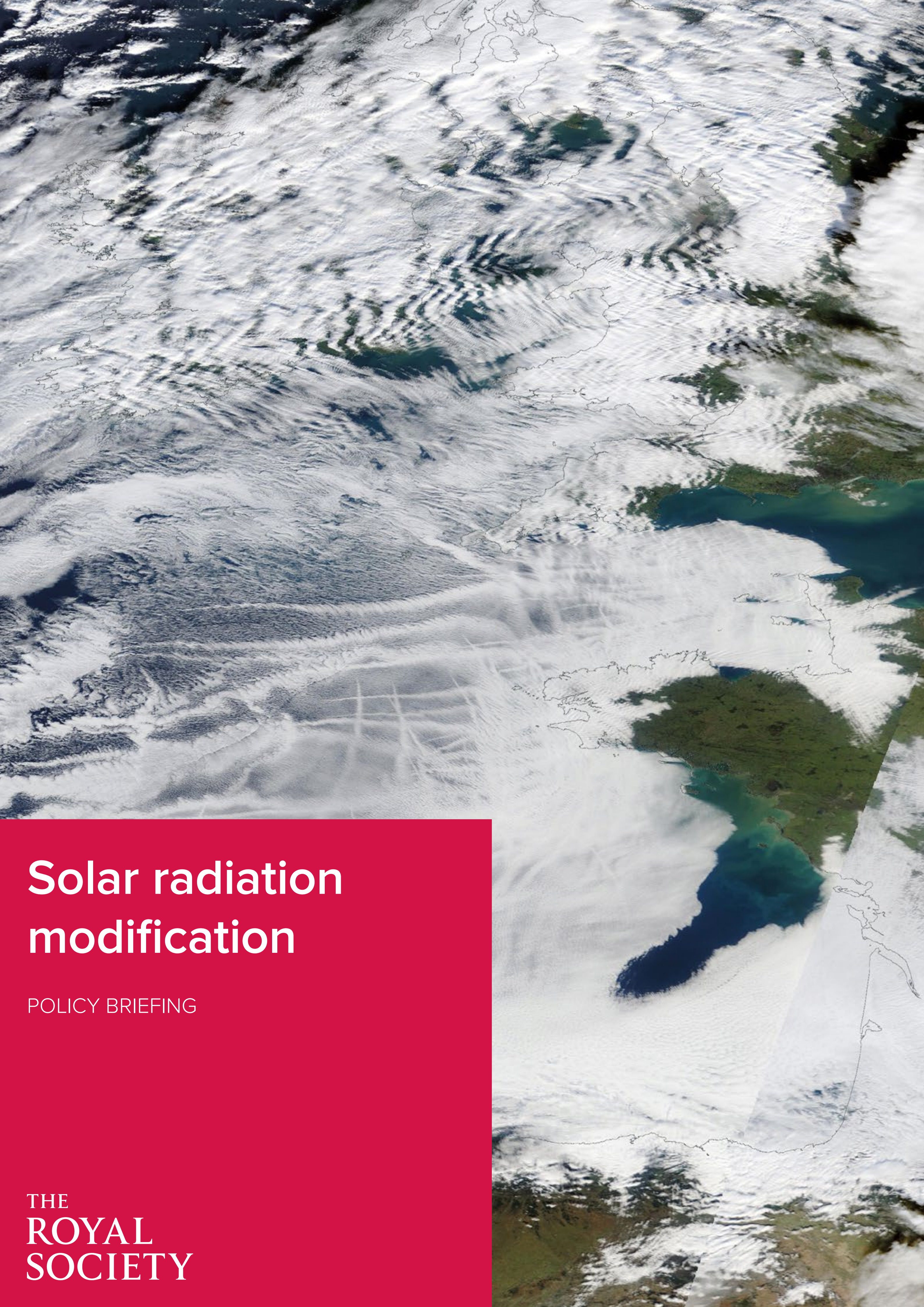

Solar radiation modification

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Cover image: Satellite image showing examples of real world analogues, from the NASA Worldview application, part of the NASA Earth Science Data and Information System (ESDIS). For more information visit: worldview.earthdata.nasa.gov.

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Abbreviations

Climate and atmospheric science

SRM Solar Radiation Modification

SAI Stratospheric Aerosol Injection

MCB Marine Cloud Brightening

MSB Marine Sky Brightening

CDR Carbon Dioxide Removal

CO_2 Carbon Dioxide

CH_4 Methane

SO_2 Sulfur Dioxide

SS Sea Salt

PAR Photosynthetically Active Radiation

NPP Net Primary Productivity

ERF Effective Radiative Forcing

LOSU Level of Scientific Understanding

Tg Teragram, 1 million metric tonnes

SST Sea Surface Temperature

Climate models and scenarios

ESM Earth System Model

UKESM1 UK Earth System Model version 1

CESM2 Community Earth System Model version 2

E3SMv2 Energy Exascale Earth System Model version 2

WACCM6 Whole Atmosphere Community Climate Model version 6

MIP Model Intercomparison Project

GeoMIP Geoengineering Model Intercomparison Project

SSP Shared Socioeconomic Pathways

SSP2-4.5 SSP scenario with intermediate emissions

RCP Representative Concentration Pathways

RCP4.5 RCP scenario with intermediate emissions

CMIP5/CMIP6 Coupled Model Intercomparison Project Phase 5/6

Earth system components

AMOC Atlantic Meridional Overturning Circulation

ITCZ Intertropical Convergence Zone

ENSO El Niño Southern Oscillation

NAO North Atlantic Oscillation

QBO Quasi-Biennial Oscillation

CCT Cirrus Cloud Thinning

CCN Cloud Condensation Nuclei

Monitoring and observational tools

CERES Clouds and the Earth's Radiant Energy System

MODIS Moderate Resolution Imaging Spectrometer

GloSSAC Global Space-based Stratospheric Aerosol Climatology

FACE Free-Air Carbon Dioxide Enrichment

Organisations and programmes

IPCC Intergovernmental Panel on Climate Change

IPCC AR6 IPCC Sixth Assessment Report

UNEP United Nations Environment Programme

UNFCCC United Nations Framework Convention on Climate Change

UNCBD United Nations Convention on Biological Diversity

UNEA United Nations Environment Assembly

WMO World Meteorological Organization

WCRP World Climate Research Programme

SAPEA Science Advice for Policy by European Academies

NASEM US National Academies of Sciences, Engineering and Medicine

ARIA Advanced Research and Invention Agency

NERC Natural Environment Research Council

QCF Quadrature Climate Foundation

Executive summary

Currently implemented policies on greenhouse gas emissions are projected to lead to a peak global-mean warming this century of about 3.1°C[1]. Such warming would have high to very high risks of potential adverse consequences[2]. Even with additional mitigation actions, UNEP[3] has indicated a high probability that there will be a sustained breach of the UNFCCC Paris Agreement to pursue efforts to limit global-average surface temperature warming to 1.5°C above pre-industrial levels.

This mismatch between current mitigation policies and the Paris Agreement goals has led to renewed research and commercial attention on deliberate intervention in the climate system to limit warming to levels lower than expected with current mitigation efforts.

In this briefing we explore the science relating to the characteristics and risks of one such possible form of intervention, Solar Radiation Modification (SRM), and conclude with the following key messages for policymakers:

1. Several SRM techniques have been proposed. Two have received particular attention in the scientific literature: Stratospheric Aerosol Injection (SAI) and Marine Cloud Brightening (MCB).
2. The influence of SAI on the climate is currently much better understood than MCB, although climate effects of both methods are less well understood than greenhouse-gas driven climate change.
3. The primary source of evidence for the effect of SRM comes from computer-based climate models, which represent a subset of the same models used in Intergovernmental Panel on Climate Change (IPCC) projections of future climate change. These models are supported, to an extent, by understanding of real-world analogues to SAI and MCB, such as volcanic eruptions or sulfur dioxide emissions from shipping.
4. If deployed in an informed and globally-coordinated[4] way, SRM could ameliorate many, but not all, of the adverse impacts of climate change. However, if deployed without due diligence, SRM could exacerbate regional climate change.
5. There is robust evidence that globally-coordinated deployment of SRM could reduce global-mean surface temperature, and associated impacts such as sea-level rise, wildfires and extreme precipitation, and so mask part of human-induced climate change. Significant uncertainties remain in how much cooling would be achieved for a given deployment of SRM.
6. Other impacts of climate change are likely to respond to SRM in different ways to global temperature. Globally-averaged precipitation would be lower with globally-coordinated SRM than without it. This reduction would be greater than that caused by the same reduction in temperature achieved by mitigating greenhouse-gas concentrations. Ocean acidification due to increased CO_2 concentrations would not be offset by SRM.

1 United Nations. 2024 Emissions Gap Report 2024: No more hot air … please! Nairobi, Kenya. 24 October 2024. See: https://doi.org/10.59117/20.500.11822/46404 (accessed 1 October 2025).

2 Arias *et al*. 2021 Technical Summary. In *Climate Change 2021: The Physical Science Basis. Contributions of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. [Masson-Delmotte *et al*. (eds).]. Cambridge, United Kingdom and New York, NY. See: https://doi.org/10.1017/9781009157896.002 (accessed 1 October 2025).

3 *Op. cit.* 1.

4 The term 'globally-coordinated' refers to the need to deploy SRM in a scientifically-informed and coordinated, multilateral way in both hemispheres, with wide international agreement and with a commitment to maintaining SRM for decades or even centuries. This is by no means the only conceivable model of SRM implementation. Individual nations or entities might decide, in their own self-interest, to attempt SRM, which could lead to large regional climate effects that impacted on third parties.

7. There are limits to the extent to which climate models can predict, with confidence, regional climate change, with or without SRM. This is particularly so for SRM given that relatively few models have been used to simulate its effects. SRM could exacerbate rather than ameliorate some regional changes in climate, such as patterns of rainfall change, and it is uncertain which regions would be so affected.
8. The duration of SRM deployments required to reduce global temperatures to a given target level would be unknown when any deployment starts. It would depend on future greenhouse gas mitigation measures and uncertain aspects of the climate system, but could be many decades or even centuries.
9. The short atmospheric lifetimes of SRM aerosols means that maintaining their cooling effect would require regular replenishment of the aerosols to mask the climate effect of long-lived greenhouse-gas emissions.
10. If deployment of SRM were halted, or significantly reduced, the climate would return to close to its non-SRM state in one to two decades. If the SRM-induced cooling was substantial, the resulting rate of change of temperature would likely have strong impacts.

Deploying SRM alongside other climate policies could lead to fewer risks than climate change without SRM, although there are significant challenges in quantifying these relative risks to inform any policy choice. Scientific evidence assessed in this Briefing indicates that SRM, if it was ever deemed necessary, could be used to mask global-mean warming due to greenhouse gases. The intended extent and duration of that masking would be a policy choice. Many impacts of climate change associated with global-mean temperature rise (including sea-level rise, wildfires and extreme precipitation) would be expected, on average, to be reduced in a world with such relatively lower temperatures.

SRM would not offset all aspects of climate change, for example it will not directly abate ocean acidification due to CO_2, and its associated adverse impacts on marine ecosystems.

The most-researched methods for SRM (SAI and MCB) utilise atmospheric aerosol particles to reflect a portion of incoming sunlight back to space. The climate effects of SAI have been subject to significantly more research and are currently better understood than MCB.

Understanding of SRM's climate effects is mostly based on research using climate models supported, to an extent, by understanding of real-world analogues to SAI and MCB. This research indicates that the extent of changes to regional temperature or other climate variables, such as precipitation and regional circulation patterns, would not be simply proportional to the magnitude of masking of global-mean surface temperature increase by SRM.

Climate models indicate that the way in which SRM is deployed will be critical to minimise large, potentially undesirable, regional climate changes. It might be applied in a globally co-ordinated and scientifically informed way to reduce some undesirable global and regional impacts. Alternatively, it might be applied in an uncoordinated way, perhaps by a single nation or other entity, that could lead to large regional climate responses. For example, if it were to be applied just near the equator or in only one hemisphere, models show that it could lead to large changes in tropical rainfall patterns with associated adverse consequences. This indicates that international governance of any SRM deployment would be essential if risks of such adverse consequences were to be reduced. At the international level, governance discussions remain at an early stage, and few countries have commenced national discussions.

Aerosols that cause SRM's cooling effect are much shorter-lived in the atmosphere than gases most responsible for global warming. Hence, regular injections of the relevant aerosols would be necessary to maintain the cooling effect. Depending on the intended extent of the moderation of global-mean surface temperature increase, and the success or otherwise of efforts to mitigate the greenhouse gas emissions, this implies that a long-term commitment to SRM would be necessary. Should injections be abruptly halted or significantly reduced in extent, there would be a termination effect where the climate would return to its state without SRM in about a decade or two. If temperatures would have continued to rise significantly without SRM, due to a continuing rise in atmospheric greenhouse gas concentrations, this termination effect would very likely have strong impacts on sensitive planetary systems that cannot adapt quickly, such as natural ecosystems.

Much progress has been made in understanding the climate impact of SRM in recent years, but many knowledge gaps have been identified[5]. Some of these gaps apply more generally to understanding of climate change; others are more specific to the deployment of SRM. These gaps include:

- Uncertainties in the quantity of aerosol required to cause a given cooling. This is associated (a) with limitations in the ability of the current generation of climate models to represent small scale-processes associated with aerosols and clouds – this in itself is limited by incomplete understanding of those small-scale processes and by insufficient observations to test and improve that understanding; and (b) with a more fundamental uncertainty in the sensitivity of global-mean temperatures to changing concentrations of (for example) greenhouse gases and aerosols.
- Uncertainties in the representation of regional responses (for example in temperature and rainfall, including local extremes) to climate change. These uncertainties arise from long-standing model biases in large-scale circulation patterns and recurrent variations in these patterns, and difficulties in representing small scale features and processes in models with relatively coarse spatial resolution. There is little confidence in the ability of current models to predict how some circulation patterns will change as climate changes (with or without SRM). Because of this, it cannot be ruled out that SRM could, in some locations, exacerbate the impacts of climate change.

5 Haywood J M, Boucher O, Lennard C, Storelvmo T, Tilmes S, Visioni D. 2025 World Climate Research Program Lighthouse Activity: An Assessment of Major Research Gaps in Solar Radiation Modification Research. *Frontiers in Climate* **7**, See: http://doi.org/10.3389/fclim.2025.1507479 (accessed 1 October 2025).

- Monitoring of the climate effects of SRM at both global and regional scales. An adequate and sustained global climate observing system, and robust techniques to detect and attribute the effects of any deployment, would be needed. Because of the natural variability of climate, which is more marked at regional scales, confident detection of the impact of SRM on surface temperatures might take decades. It is also important to maintain continuity in current global observational capacity to monitor ongoing global change and to provide essential data to test and improve climate models.
- Uncertainties in the possible wider effects of SRM on the wider Earth System, including stratospheric ozone, ocean circulation, the cryosphere, and natural and managed terrestrial and marine ecosystems.

If greenhouse gas emissions continue to rise, or do not fall rapidly enough to avoid prolonged adverse consequences of climate change, at some point in the future policymakers may decide that the risks associated with SRM deployment are smaller than those associated with climate change without SRM.

In addition to the governance issues highlighted above, there are many other important issues beyond climate science that must be considered prior to any decision to deploy SRM. These include engineering feasibility, economic costs, public perception, transparency, ethics and inclusivity. Concerns have also been expressed that even considering SRM could undermine international and domestic efforts to reduce greenhouse gas emissions. This indicates that a thorough international multidisciplinary assessment of all aspects of SRM would be necessary.

The many uncertainties associated with the climate effect of SRM deployment, and the fact that it would only partially mask the climate effects of increased greenhouse gas concentrations for the duration of its deployment, lead us to reaffirm the view expressed in the IPCC's Sixth Assessment Report: if it is decided that the risks associated with climate change need to be reduced, then SRM should not be the main policy response to climate change; it would, at best, be a supplement to action to further mitigate greenhouse gas emissions.

What is Solar Radiation Modification and why is it of current interest?

In its Sixth, and most recent, Assessment Report in 2021, the Intergovernmental Panel on Climate Change (IPCC AR6) stated that it was "unequivocal that human influence has warmed the atmosphere, ocean and land"[6].

The observed global mean surface temperature (hereon, surface temperature) for the most recent decade (2015 – 2024) was about 1.24°C higher than pre-industrial levels, with 2024 itself about 1.6°C higher[7]. Whilst temperatures in an individual year or group of years may be influenced by natural variability[8, 9] and natural drivers of climate change, the overall persistent warming trend continues (Figure 1).

This warming is primarily attributed to increased concentrations of greenhouse gases (mostly carbon dioxide (CO_2) and methane (CH_4)) due to human activity; about 25% of the greenhouse gas warming is offset by the cooling influence of aerosols also due to human activity[10]. Aerosols are tiny particles that result from human activities such as fossil fuel use and biomass burning, and natural sources such as volcanic eruptions.

IPCC AR6 uses a range of pathways of possible future climate change due to human activity (see Annex B). Depending on which pathway is followed, these lead to warmings in 2100 ranging from about 1.4°C to 4.7°C relative to pre-industrial. The United Nations Environment Programme (UNEP) Emissions Gap Report[11] estimated that current climate policies aimed at mitigating greenhouse gas emissions would be in the middle of this range and lead to a peak warming this century of approximately 3.1°C.

6 *Op. cit*. 2.

7 Forster *et al*. 2025 Indicators of Global Climate Change 2024: annual update of key indicators of the state of the climate system and human influence, *Earth Systems Science Data*, **17**, 2641–2680. See: https://doi.org/10.5194/essd-17-2641-2025 (accessed 1 October 2025).

8 *Op. cit.* 7.

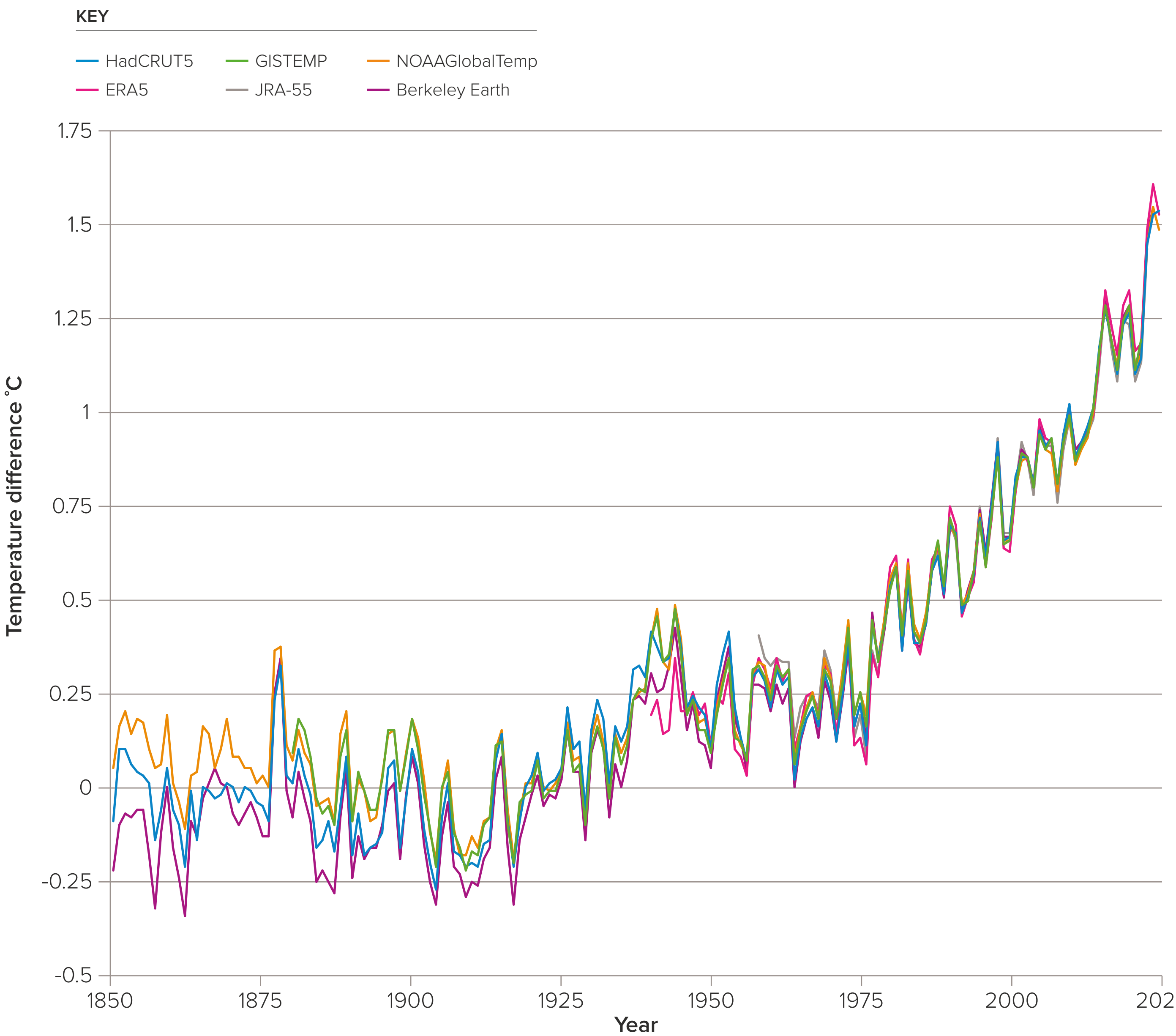
9 Samset, B H, Lund M T, Fuglestvedt J S, Wilcox L J. 2024 2023 temperatures reflect steady global warming and internal sea surface temperature variability. *Communications Earth and Environment* **5**, 460. See: https://doi.org/10.1038/s43247-024-01637-8 (accessed 1 October 2025).

10 Forster *et al*. 2021 The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom and New York, USA: Cambridge University Press

11 *Op. cit.* 1.

FIGURE 1

Annual and global mean surface temperature expressed as a difference from pre-industrial levels (defined as the period 1850 – 1900). Results are shown from six different analyses and combine near-surface air temperatures over land and sea surface temperatures over oceans[12].



Source: © Crown copyright, Met Office (2025).

12 Met Office Climate Dashboard: Global Temperature. See https://climate.metoffice.cloud/temperature.html (accessed 15 September 2025 (accessed 1 October 2025).

Such warming would significantly exceed the goals of the 2016 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC)[13] which were to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels". O'Neill *et al*. (2022)[14] identified five integrative "Global Reasons for Concerns" covering, for example, unique biological and human systems, extreme climate events, uneven distributions of climate impacts, ecosystem and biodiversity loss, and abrupt and possibly irreversible large-scale changes in the Earth System. It concluded that risks increased with every increment of warming, and would be categorised as high or very high for a global-mean warming of more than 2.5°C.

The gap between current policies and those required to limit global warming to 1.5°C[15] means that meeting the Paris Agreement temperature goal is highly challenging. It would require greenhouse gas, and in particular CO_2 emissions, to peak in 2025, fall by more than 40% by 2030 and achieve 'net-zero' (when greenhouse gas emissions from human activity and their removal from the atmosphere are in balance) by 2050. The gap also makes it more difficult to meet the Paris Agreement's goal to increase "the ability to adapt to the adverse impacts of climate change".

This mismatch between current mitigation policies and the Paris Agreement goals has led to renewed research and commercial attention on deliberate intervention in the climate system to limit warming to levels lower than expected with current mitigation efforts alone. Many projected climate-change pathways (see Annex B) envisage that even if Paris Agreement goals could be met at some point in the future, there would be a period of temperature overshoot, the duration and magnitude of which affects the impacts of climate change. Time-limited interventions, explained later in this report, have been proposed to moderate warming during this period of overshoot, but this is only one of many possible intervention scenarios.

13 The Paris Agreement. See https://unfccc.int/process-and-meetings/the-paris-agreement (accessed 15 September 2025)

14 O'Neill *et al*. 2022 Key Risks Across Sectors and Regions. In: Pörtner HO *et al* (eds.) *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, USA: Cambridge University Press

15 *Op. cit*. 1.

1.1 Climate interventions

Deliberate climate interventions to limit warming fall under the general heading of 'geoengineering' or 'climate engineering'. A 2009 Royal Society report *Geoengineering the climate: science, governance and uncertainty*[16] considered two possible complementary approaches. One was active removal of CO_2 from the atmosphere (Carbon Dioxide Removal (CDR)), which was considered in the Royal Society's report on Greenhouse Gas Removal[17] (see also Annex B); the other was Solar Radiation Management (SRM), which aims to implement measures to reflect additional sunlight back into space to counter warming due to increasing greenhouse gas concentrations. Following recent widespread practice, we use the same acronym (SRM) but refer to it as 'Solar Radiation Modification'; 'management' might imply a degree of control that, given current understanding, is impossible.

SRM comes with particular characteristics and risks, and is the focus of this Briefing. SRM is distinct from CDR in that SRM aims to mask some part of human-induced climate change, rather than being part of a solution to reduce greenhouse gas concentrations in the atmosphere. It also fails to address issues such as ocean acidification, which result directly from uptake of anthropogenic CO_2 in the oceans.

Since the Royal Society's 2009 report, a much wider base of research literature on SRM has become available. SRM has been discussed in several recent international and national assessments that support its conclusions. For example, IPCC AR6[18, 19], which concluded that "SRM cannot be the main policy response to climate change and is, at best, a supplement to [actions aimed at] achieving sustained net-zero or net negative CO_2 emissions globally". The World Meteorological Organization's 2022 *Scientific Assessment of Ozone Depletion*[20] considered one particular SRM technique (Stratospheric Aerosol Injection – see below), concluding that it "has the potential to reduce global mean temperatures" but it "cannot fully offset the widespread effects of global warming and produces unintended consequences, including effects on ozone".

16 The Royal Society. 2009 Geoengineering the climate: science, governance and uncertainty. See https://royalsociety.org/news-resources/publications/2009/geoengineering-climate/ (accessed 15 September 2025).

17 The Royal Society. 2018 Greenhouse gas removal. See https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf (accessed 15 September 2025).

18 *Op. cit*. 14.

19 Patt *et al*. 2022 International cooperation. In: Shuklaet PR *et al* (eds.) *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,* Cambridge, UK and New York, USA: Cambridge University Press

20 World Meteorological Organization (WMO) 2022. Scientific Assessment of Ozone Depletion: 2022 Geneva, Switzerland. 09 January 2023. See https://www.unep.org/resources/publication/scientific-assessment-ozone-layer-depletion-2022 (accessed 15 September 2025).

Other more recent assessments include the US National Academies of Sciences, Engineering and Medicine[21], UNEP[22] and the European Commission[23] (see also SAPEA[24]). As part of a World Climate Research Programme activity, Haywood *et al*.[25] presented an assessment of major SRM research gaps.

In the same period, more research funding has become available from a variety of sources, including national funding agencies and philanthropic organisations. Current UK national funding includes the Natural Environment Research Council's £10 million programme 'Modelling the environmental responses to SRM'[26] and the Advanced Research and Invention Agency's (ARIA) £57 million programme 'Exploring Climate Cooling'[27] which includes a component for small-scale outdoor experiments (considered further in Chapter 8). It is believed that together, these constitute the world's largest national funding commitment to SRM research.

Among the philanthropic donors active in this space, London-based Quadrature Climate Foundation (QCF) is planning to invest US$ 40 million over three years in solar geoengineering research[28].

1.2 Briefing focus

This Briefing provides an update on current scientific understanding of SRM, emphasising the nature and extent of uncertainties. SRM is a controversial topic, with concerns raised that SRM research lacks a robust governance framework, and that such research might distract from international efforts to mitigate greenhouse gas emissions. Even if deemed scientifically feasible, any decision to deploy SRM would require detailed consideration of many other important aspects including international governance, engineering feasibility, economic costs, transparency, public perception, ethics, and inclusivity. Some aspects of research governance, feasibility and costs will be briefly covered here; many of the wider issues are considered by NASEM[29], UNEP[30] and European Commission[31].

21 National Academies of Sciences, Engineering, and Medicine (NASEM). 2021 Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance. Washington, DC, USA. 2021. See https://nap.nationalacademies.org/catalog/25762/reflecting-sunlight-recommendations-for-solar-geoengineering-research-and-research-governance (accessed 15 September 2025).

22 United Nations Environment Programme. 2023 One Atmosphere: An independent expert review on Solar Radiation Modification research and deployment. Kenya, Nairobi. 28 February 2023. See https://www.unep.org/resources/report/Solar-Radiation-Modification-research-deployment (accessed 15 September 2025).

23 European Commission: Directorate-General for Research and Innovation and Group of Chief Scientific Advisors. 2024 Solar radiation modification. Brussels, Belgium. 9 December 2024. See: https://data.europa.eu/doi/10.2777/391614 (accessed 15 September 2025).

24 SAPEA (Science Advice for Policy by European Academies). 2024 Solar radiation modification: evidence review report. European Commission. Berlin, Germany. 9 December 2024. See https://doi.org/10.5281/zenodo.14283096 (accessed 15 September 2025).

25 *Op. cit*. 5.

26 UK Research and Innovation. Modelling environmental responses to solar radiation management. See https://www.ukri.org/opportunity/modelling-environmental-responses-to-solar-radiation-management/ (accessed 15 September 2025).

27 Advanced Research and Invention Agency. Exploring Climate Cooling. See https://www.aria.org.uk/opportunity-spaces/future-proofing-our-climate-and-weather/exploring-climate-cooling (accessed 15 September 2025).

28 Skinner G, De Temmerman G, Setiya S. 2024 Quadrature commits $40 million to solar geoengineering research. *Philanthropy News Digest*. 23 June 2024. See https://philanthropynewsdigest.org/news/quadrature-commits-40-million-to-solar-geoengineering-research (accessed 15 September 2025).

29 *Op. cit*. 21.

30 *Op. cit*. 22.

31 *Op. cit*. 23.

An underlying assumption in much of the research assessed in this Briefing is that SRM would be deployed in a scientifically-informed and coordinated multilateral way in both hemispheres, with wide international agreement and with a commitment to maintaining SRM for decades or even centuries. This is by no means the only conceivable model of SRM deployment. Individual nations or entities might decide, in their own self-interest, to attempt SRM, which could lead to large regional climate effects that impacted on third parties.

Here, we focus only on large-scale interventions designed to cause global-scale cooling, and for which there is sufficient scientific evidence to allow an assessment. We do not consider in any detail local climate interventions, for example, aiming to offset Arctic sea-ice loss[32], nor do we consider short-term and localised weather modification (for example, to increase rainfall for agricultural purposes).

One possible framing of SRM is through a risk-risk framework[33, 34]. Such a risk-risk framework at least recognises the future significant impacts of climate change that have been widely documented[35]. In practice, it is challenging to apply methods for quantifying competing risks, which often entail value judgements. It would need to consider risks associated with a range of possible climate futures, including those with and without the use of SRM.

A further difficulty in applying this framework is that, if SRM were to be deployed, it would be very challenging to assert, for sure, how much worse things might have been had it not been applied. A specific example is that even under SRM, the risk of extreme weather events will remain. While there have been some advances in attributing individual extreme events to climate change, current climate models would only provide limited guidance as to how much worse such events might have been had it not been deployed.

1.3 Introduction to SRM Techniques

The basic principle of SRM is that a proportion of the heat-trapping effect of increased greenhouse gas concentrations could be counter-balanced (ie masked) by reflecting an additional small amount of sunlight back into space (Figure 2). Two SRM techniques have received particular attention in the scientific literature, stratospheric aerosol injection (SAI) and marine cloud brightening (MCB) (with less attention on the related marine sky brightening (MSB)).

SAI

In SAI, aerosol particles (or gases that lead to aerosol formation) would be injected into the stratosphere, the region of the atmosphere at altitudes above about 8 km in high latitudes and 20 km in the tropics. Provided these particles are of the appropriate (small) size, they can be efficient at scattering and so reflecting some sunlight back into space, thus cooling the planet.

32 Pauling A G, Bitz C M. 2021 Arctic sea ice response to flooding of the snow layer in future warming scenarios. *Earth's Future* **9**. See: https://doi.org/10.1029/2021EF002136 (accessed 1 October 2025).

33 *Op. cit*. 21.

34 *Op. cit*. 24.

35 *Op. cit*. 2.

MCB
MCB would also exploit aerosols to increase planetary reflectivity (albedo), but in a distinct way to SAI. Aerosols would be injected into the lowest kilometre or so of the atmosphere. Cloud droplet formation is reliant on the presence of aerosols of an appropriate size and chemical composition; the quantity of such aerosols determines the number and size of cloud (water) droplets. All else being equal, a larger number of aerosol particles results in a larger number of smaller cloud droplets, which reflect more sunlight and hence exert a cooling influence on climate.

Other suggestions for reducing the fraction of absorbed sunlight, such as placing mirrors in space and altering land surface, ocean surface, or vegetation characteristics to increase their reflectivity are discussed, more briefly, in later chapters.

1.4 Synopsis

The following chapters present a more detailed analysis of the current state of scientific understanding of SRM and emphasise knowledge gaps. A brief synopsis is given here.

Chapter 2 presents the background science of SRM and some illustrative scenarios as to how it might be applied; it also includes two boxes, one outlining various timescales relevant to SRM climate science and one that introduces climate models referred to throughout this report.

Chapter 3 presents a systematic discussion of proposed SRM techniques, including the challenges in technological developments, the feasibility of large-scale deployment, and possible deployment strategies.

Chapter 4 discusses, in more detail, how observations of real-world analogues provide important information on the underlying physical processes of SRM techniques, and test, to an extent, the ability of climate models to represent them.

Chapter 5 focuses on how effective SRM techniques are at cooling the planet, from a global-average perspective. This chapter will also discuss the important issue of monitoring and detecting the impact of any SRM deployment.

Chapter 6 discusses regional aspects of climate change and moves beyond global-mean surface temperature as the only variable of interest. It is now well appreciated that impacts on the global hydrological cycle (including rainfall) and patterns of regional temperature change resulting from greenhouse gas forcing would differ from those resulting from the application of SRM, with consequences for the local impacts of climate change.

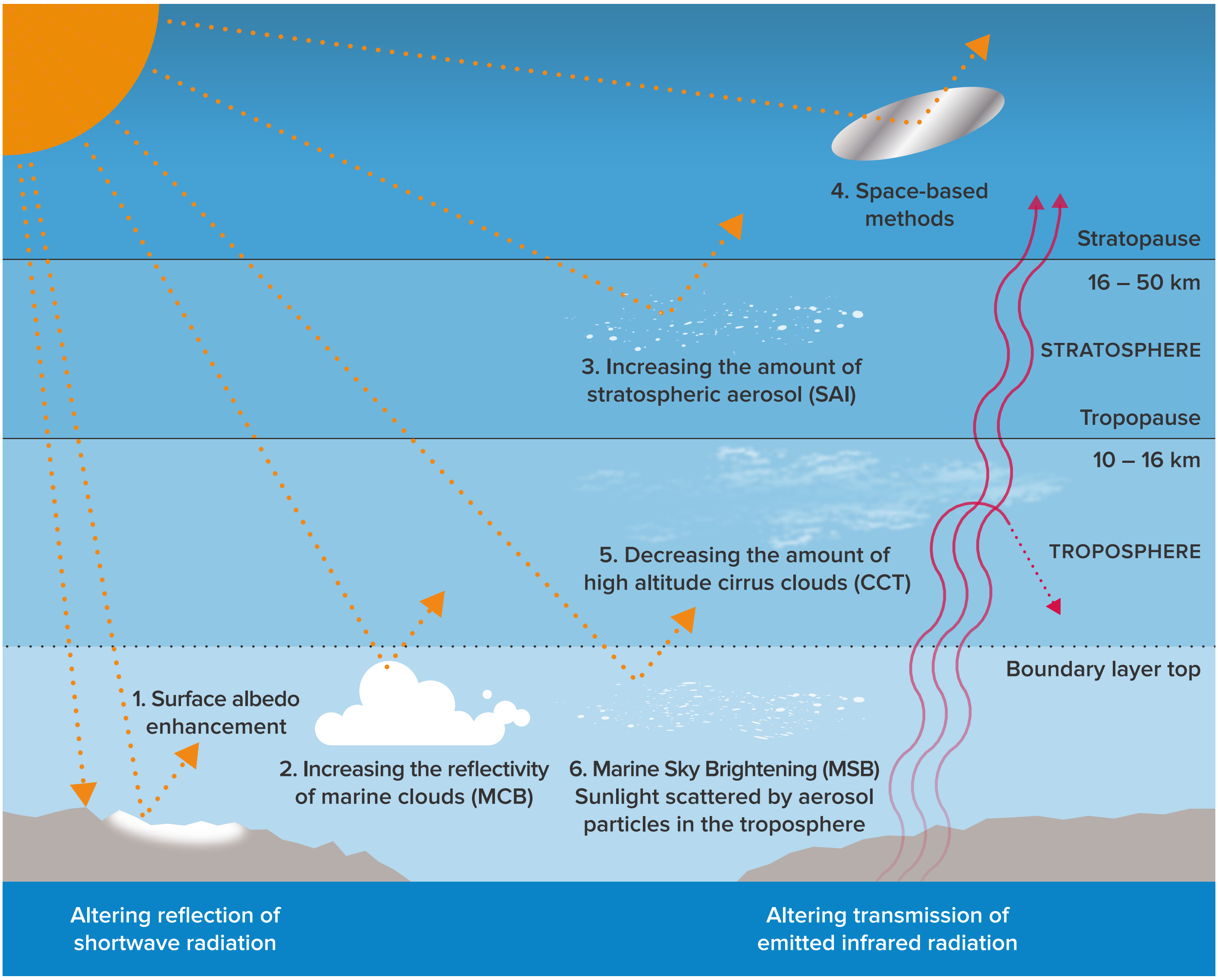
Chapter 7 addresses wider Earth system responses to SRM, including the terrestrial and marine ecosystems (both natural and managed) and the cryosphere. Many knowledge gaps are identified and the dependence of impacts on the way SRM might be applied are noted.

Chapter 8 discusses many important governance issues related to the application of SRM. It covers governance of research, including putative field experiments, as well as the governance of any operational application of SRM.

Brief concluding comments are made in the Conclusions.

FIGURE 2

Schematic diagram showing the interaction of solar radiation (yellow arrows) and emitted infrared radiation (wavy red arrows) with the various proposed SRM techniques[36].



Adapted from WMO (2022).

36 *Op. cit.* 20.

SRM basic science and scenarios

2.1 The basic science of SRM

SRM involves modification of Earth's energy budget[37, 38, 39]. That budget consists of two components: (i) absorbed sunlight, and (ii) infrared radiation emitted by the Earth and atmosphere into space, see Figure 2[40]. About 30% (the planetary albedo) of sunlight reaching the Earth is reflected into space by clouds, aerosols, atmospheric gases and the Earth's surface and plays no role in warming the planet. Approximately half of the sunlight reaching the Earth is absorbed at the surface; the rest is absorbed by atmospheric gases, clouds and aerosols. The emitted infrared radiation is heavily influenced by greenhouse gases in the atmosphere (mostly water vapour and CO_2) and clouds, such that the amount emitted to space is only about 60% of that emitted by the Earth's surface. The 'trapping' of infrared radiation due to natural concentrations of greenhouse gases maintains surface temperatures at levels suitable for life as we know it. Human activity is enhancing the concentrations of many greenhouse gases, resulting in an increase in the amount of trapped infrared radiation, which in turn causes additional warming.

For a climate system in long-term equilibrium (Box 1), the absorbed sunlight and emitted infrared radiation must approximately balance, when averaged over the globe. The major climate change mechanisms disturb this equilibrium. Increased concentrations of greenhouse gases reduce the emission of infrared radiation into space. The resulting initial imbalance in the energy budget is termed radiative forcing and is the main driver of climate change[41]. Radiative forcing is reported in units of watts per square metre (W m^{-2}); to give a sense of typical values, the increased concentrations of CO_2 since pre-industrial times have caused a forcing of about 2.3 W m^{-2} [42].

The Earth system responds to greenhouse gas increases by warming, thus increasing emitted infrared radiation. If greenhouse gas concentrations increased only by a fixed amount, energy balance would gradually be restored, and a new higher equilibrium temperature would be established after a period of decades to centuries (Box 1). This warming is influenced by Earth system feedbacks. For example, higher surface temperatures lead to higher concentrations of water vapour which accentuates the warming (ie, a positive feedback). Some climate feedbacks, such as those associated with changing cloud properties, have large uncertainties[43].

One indicator of uncertainty in climate feedbacks is the equilibrium climate sensitivity, often quoted as the eventual global-mean surface warming in response to a doubling of CO_2 concentrations from a pre-industrial baseline of around 280 ppm[44] after the system has equilibrated. The IPCC AR6 best estimate is 3°C with a very likely (ie greater than 90% chance) range of warming of 2 to 5°C. This uncertainty is reflected in the uncertainty ranges in future climate change for given emission pathways (Annex B). It also impacts estimates of how much SRM would be needed to achieve a given cooling.

37 *Op. cit*. 16.
38 *Op. cit*. 21.
39 *Op. cit*. 22.
40 *Op. cit*. 20.
41 *Op. cit*. 10.
42 *Op. cit*. 10.
43 *Op. cit*. 10.
44 *Op. cit*. 10.

2.2 Idealised scenarios of SRM deployment

Figure 3 is a schematic of possible SRM approaches. Three scenarios are illustrated in frames A – C; frame D shows a schematic of the amount of aerosol, or its precursor, injected to meet each scenario.

In each case A – C, the black line shows schematically the temperature evolution assuming limited or no mitigation of emissions and no application of SRM; in practice it could represent any scenario in which anthropogenic emissions have not reached net-zero.

The predicted effect of SRM on future climate is characterised here by two aspects. It depends on the scenario; ie the assumed future greenhouse gas emission pathway to which SRM is applied, and the target climate response that SRM aims to achieve. It also depends on the implementation strategy – when, where, and how SRM is deployed. In any modelling study, the choice of scenario and strategy together determines the predicted outcomes of any deployment.

In Case A in Figure 3, the orange line shows a temperature evolution assuming aggressive mitigation of greenhouse gas (GHG) emissions plus CDR, such that temperatures peak and then start to fall. In this scenario, despite aggressive mitigation, temperatures overshoot a stabilisation target (eg, as defined by the Paris Agreement). SRM is assumed to be applied in a peak-shaving way so that the temperature is returned to the target level (as indicated by the blue arrows) via SRM for the period of overshoot (as illustrated in frame D).

The duration of such a peak-shaving scenario could be anywhere from decades to centuries depending on the target temperature, the underlying emission pathway, the availability of large-scale CDR technologies, and the sensitivity of the climate system[45]. Many of these are unlikely to be known at the start of SRM deployment and potentially imply a multi-generational commitment.

In Case B, there is limited mitigation so that temperatures continue to increase. As noted in Chapter 1, current climate policies can be regarded as such a case. To bring temperatures down to a given stabilisation target, progressively greater amounts of SRM would be needed (see frame D). In Case C, partial SRM is applied to moderate the warming to a given extent, rather than aiming for some pre-specified target. A number of variants on these three cases have also been considered in SRM research.

A key aspect of both SAI and MCB is that the aerosols driving these SRM techniques are short-lived in the atmosphere and so contrast with the long lifetimes of many greenhouse gases, and of CO_2 in particular. To maintain the masking effect of SAI and MCB requires frequent replenishment of the aerosols for as long as the SRM is deemed to be needed. See Box 1 for further discussion.

A serious concern about SRM is what would happen if it were suddenly halted or significantly reduced in future (for example, if one partner in a multilateral implementation withdrew). Because SRM just masks the impact of greenhouse gas warming for the duration of the deployment, temperatures would rapidly rise unless SRM was restarted[46].

45 Baur S, Nauels A, Nicholls Z, Sanderson B M, Schleussner C F. 2023 The deployment length of solar radiation modification: an interplay of mitigation, net-negative emissions and climate uncertainty. *Earth System Dynamics* **14**, 367–381. See: https://doi.org/10.5194/esd-14-367-2023 (accessed 1 October 2025).

46 Parker A, Irvine P J. 2018 The Risk of Termination Shock From Solar Geoengineering. *Earth's Future* **6**, 456–467. See: https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2017EF000735 (accessed 1 October 2025).

FIGURE 3

Schematic diagram representing the concept of three policy-relevant SRM scenarios: peak-shaving scenario, strong SRM scenario and medium SRM scenario.

Different lines in frames A to C illustrate global mean surface temperatures for future scenarios[47]. Frame D shows the time variation of the SRM aerosol injection.

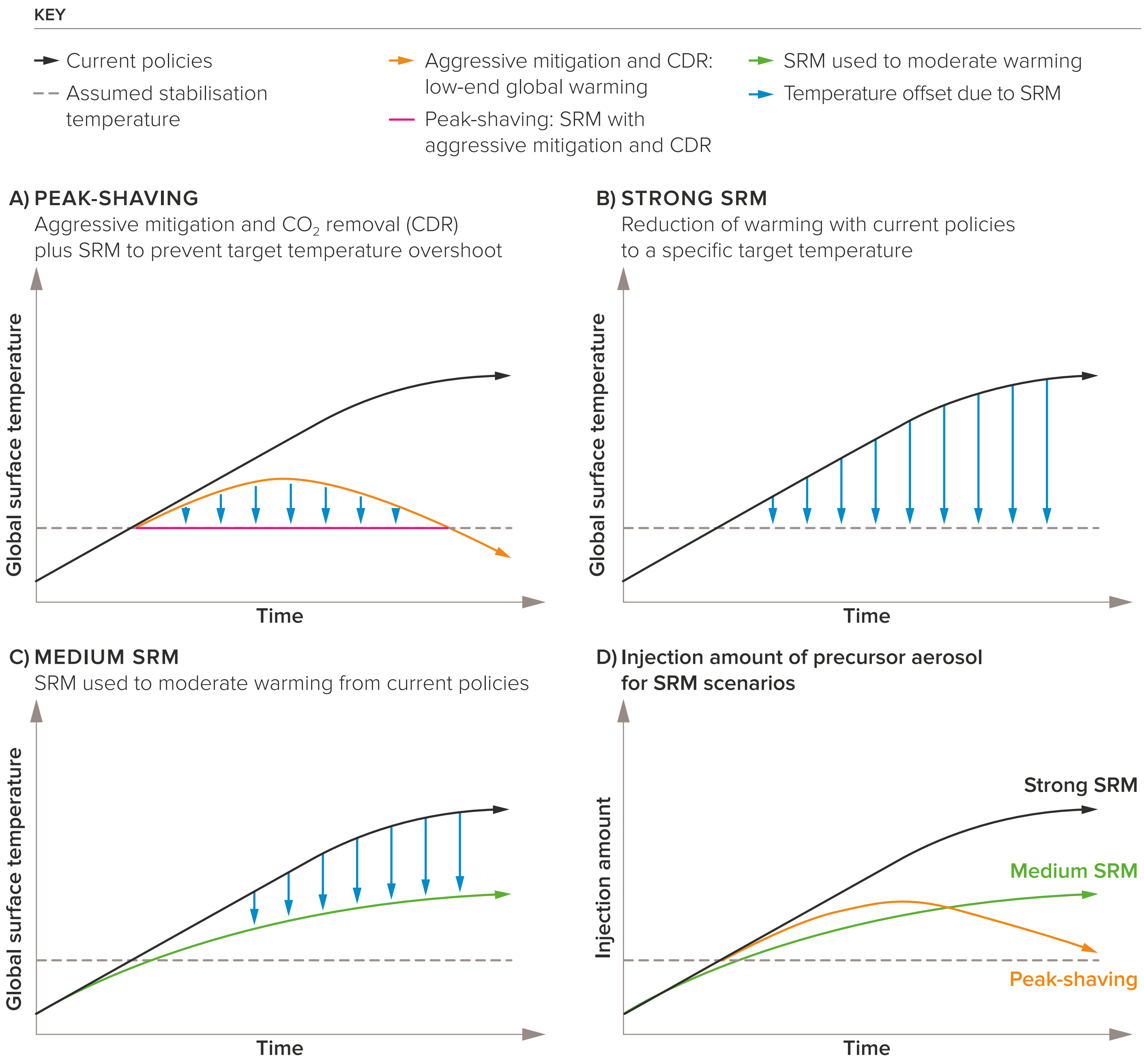


Figure adapted from Haywood and Tilmes 2022.

47 Haywood J, Tilmes S. 2022 Chapter 6: Stratospheric aerosol injection and its potential effect on the stratospheric ozone layer. In: World Meteorological Organization (ed.) *Scientific assessment of ozone depletion*. Geneva, Switzerland, See: https://csl.noaa.gov/assessments/ozone/2022/downloads/Chapter6_2022OzoneAssessment.pdf (accessed 1 October 2025).

More than half of this rise would likely occur within the first decade after SRM was halted (see Box 1. for timescales). This rapid rise in temperature is referred to as a termination effect and is indicated by the size of the blue arrows in Figure 3 at the time of termination. It would be most severe in Cases B and C. Section 5.4 considers the termination effect in more detail.

The SRM deployment strategy is important because a similar reduction in global average temperature could be achieved using different SRM techniques and by applying the same technology at different locations. However regional climate responses might differ significantly. If it was applied in a naive way (for example by a single party in a limited location) it could lead to large and undesirable regional climate responses. For example, early modelling studies of SAI focused on equatorial injection, as aerosols injected at the equator persist longer in the stratosphere due to the characteristics of stratospheric circulation. However, as discussed in Chapter 6, this would lead to significant reductions in precipitation around the equator and the latitudinal variation of cooling would be distinctly different to that due to greenhouse gas driven warming.

On the other hand, as will be discussed, modelling indicates that if it is applied in a coordinated and scientifically-informed way, some of the risks of these undesirable responses could be ameliorated. We refer to such deployments as ‘globally-coordinated’, as they seek to minimise changes in specified climate metrics whilst still reducing global temperature as effectively as possible, but we stress that their exact nature is a subject of ongoing research. For example, modelling studies indicate that a multi-location off-equatorial strategy (eg 30° North and South) results in a more uniform global cooling[48, 49] than an equatorial injection.

48 Henry M, Bednarz E M, Haywood J. 2024 How does the latitude of stratospheric aerosol injection affect the climate in UKESM1? *Atmospheric Chemistry and Physics* **24**, 13253–13268. See: https://doi.org/10.5194/acp-24-13253-2024 (accessed 1 October 2025).

49 Visioni *et al*. 2024 G6-1.5K-SAI: a new Geoengineering Model Intercomparison Project (GeoMIP) experiment integrating recent advances in solar radiation modification studies. *Geoscientific Model Dev*elopment **17**, 2583–2596. See: https://doi.org/10.5194/gmd-17-2583-2024 (accessed 1 October 2025).

BOX 1

Timescales of climate response to climate forcing agents

Various distinct timescales affect the climate system response to a forcing agent, such as carbon dioxide (CO_2) or SRM aerosols. This is a simplified introduction to these timescales; in practice there are many nuances.

The first timescale is the atmospheric persistence time of the forcing agent. For SRM, a major determinant is the altitude of the aerosols. For SAI (or an explosive volcanic eruption), the typical aerosol lifetime[50] is around one year, but it depends on the altitude and latitude of injection[51]. For MCB, in which aerosols are injected in the lower troposphere, lifetimes may be only days or less[52] because cloud and precipitation processes more quickly remove aerosols. To sustain SRM requires frequent replenishment of the aerosols to maintain their cooling effect; and the shorter the aerosol lifetime the higher the required rate of replenishment.

In contrast to aerosols, and most other anthropogenic emissions, CO_2 is very different in the way it is removed by a complex of different land and ocean processes. Following a pulse emission of CO_2, about 40% is removed in 20 years, a further 20% in a century, but even after 1,000 years, 20% remains in the atmosphere[53].

The second timescale involves how winds spread a forcing agent. If SAI were deployed via injection at a single location (like an individual volcanic eruption), the timescales to spread the aerosol across the hemisphere of injection are a few months. Stratospheric circulation patterns mean that an injection in one hemisphere is unlikely to spread significantly into the other hemisphere unless it is near the equator[54]. The relationship between this dispersion timescale and lifetime is important. Tropospheric aerosols emitted in a specific location are restricted to regions close to the emission point because their lifetime is short compared to the dispersion timescale. They can still generate a climate response further away via their impact on winds and temperatures. However, the pattern of climate response to an inhomogeneous forcing agent such as aerosol differs to that from a more homogeneous forcing agent such as CO_2 (see Chapter 6).

50 In atmospheric science, 'lifetime' is normally the e-folding lifetime for concentrations to decay to about 37% of its original concentration, if the concentration is not being refreshed by other mechanisms. It takes about 3 lifetimes for concentration to decay to less than 5% of the original concentration. There are various nuances associated with the definition of lifetime. CO_2 concentrations do not decay in such a simple way, as they are impacted by distinct processes acting on very different timescales.

51 Tilmes *et al*. 2017 Sensitivity of aerosol distribution and climate response to stratospheric SO_2 injection locations. *Journal of Geophysical Research: Atmospheres* **122**, 12591–12615. See: https://doi.org/10.1002/2017JD026888 (accessed 1 October 2025).

52 Feingold *et al*. 2024 Physical science research needed to evaluate the viability and risks of marine cloud brightening. *Science Advances* **10**. See: https://doi.org/10.1126/sciadv.adi8594 (accessed 1 October 2025).

53 Joos *et al.* 2013 Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmospheric Chemistry and Physics* **13**, 2793–2825. See: https://doi.org/10.5194/acp-13-2793-2013 (accessed 1 October 2025).

54 Op. *cit.* 51.

The initial effect of a forcing agent on the planetary energy budget can be almost immediate[55] and can lead to adjustments to other atmospheric components (eg, temperature, humidity and clouds) on timescales from days to months. These changes can, on the same timescale, alter precipitation; this is relevant to SRM as greenhouse gases and aerosols impact precipitation in distinct ways[56, 57].

The timescale over which global surface temperatures respond is largely determined by the time required to warm the oceans. Upper ocean layers warm within years, but deep oceans respond on centennial timescales. In response to a sustained application (or removal) of a forcing, climate model simulations show that around 50% of the full temperature response occurs within 10 years and about two-thirds after 100 years[58]. The observed response of the climate system to volcanic eruptions broadly supports these modelled timescales[59].

Ice sheet responses, and associated changes in sea level from ice melt, occur on centennial timescales. While temperature changes needed to cause dramatic changes in the ice sheets might occur in the coming decades, it would still take centuries for the full response to be realised.

These differing timescales are important in understanding the climate effect of an SRM implementation. Aerosols associated with individual volcanic eruptions are present for a short time, so the climate only partially responds to them; SAI might be sustained for decades and lead to a distinct climate response.

55 SRM implementation does not necessarily operate by injection of a forcing agent. For SAI, the most widely researched method is the injection of sulfur dioxide gas, which has a lifetime of about one month as it is converted to the aerosols that cause the increased albedo. For MCB, the most widely researched injection is sea salt particles. Increased albedo mostly results from its impact on cloud droplet size, which is estimated to occur on a timescale of around 10 minutes (*Op. cit.* 52.).

56 Irvine *et al*. 2019 Halving warming with idealized solar geoengineering moderates key climate hazards. *Nature Climate Change* 9, 295–299. See: https://doi.org/10.1038/s41558-019-0398-8 (accessed 1 October 2025).

57 Stjern *et al*. 2023 The Time Scales of Climate Responses to Carbon Dioxide and Aerosols. *Journal of Climate* **36**, 3537-3551. See: https://doi.org/10.1175/JCLI-D-22-0513.1 (accessed 1 October 2025).

58 Knutti R, Rugenstein M A. 2015 Feedbacks, climate sensitivity and the limits of linear models. *Philosophical Transactions of the Royal Society A* **373**. See: https://royalsocietypublishing.org/doi/10.1098/rsta.2015.0146 (accessed 1 October 2025).

59 Lücke L J, Schurer A P, Toohey M, Marshall L R, Hegerl G C. 2023 The effect of uncertainties in natural forcing records on simulated temperature during the last millennium. *Climate of the Past* **19**, 959–978. See: https://doi.org/10.5194/cp-19-959-2023 (accessed 1 October 2025).

BOX 2

Climate models

Climate models are a key tool for aiding understanding of the possible effects of SRM. Climate models come in many different forms. For example, computationally-fast models, whose prime output is global-mean surface temperature, are much used in exploring the range of future emissions pathways. For the most part, this briefing focuses on results from more complex models; these will be referred to as either 'climate models' generally or specifically 'Earth System Models (ESMs)' depending on the range of processes included in them[60].

Climate models are computer programs that represent the fundamental laws of physics applied to the atmosphere, ocean, ice and land, and the interactions between these components. They simulate variables such as temperature, moisture, winds (or currents in the ocean), and cloudiness, on grids covering the entire globe with a typical spacing of 100 km in the horizontal and 1 to 5 km the vertical, extending to around 50 km altitude (ie encompassing the stratosphere) and sometimes higher, and extending into the deep oceans.

Increasingly, these models include other climate system components, including chemical and biological processes, at which point they are generally classed as ESMs. As computational power increases, modellers face choices as to whether to exploit this power on increasing the horizontal and vertical resolution, exploring longer timescales, increasing the complexity by which processes are represented, and/or including additional processes.

Many processes occur on smaller spatial scales than the grid being used; these include aerosol and cloud processes which are important for proposed SRM techniques and interactions with the Earth surface (including the representation of orography). Uncertainty in how to represent these small-scale processes is one reason why simulations from different models disagree in key aspects. There are several tens of such models being used by research groups around the world. Some models are variants of each other and differ only in their horizontal and vertical resolution or in how they represent small-scale processes.

60 Eyring *et al*. 2021. Human Influence on the Climate System (Chapter 3). In: Masson-Delmotte *et al.* (eds) *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*. Cambridge, United Kingdom and New York, USA: Cambridge University Press.

Models are assessed by comparison with observations and with each other, often as part of formal model intercomparison projects (MIPs), where each modelling group performs identical sets of calculations; these have provided important input to IPCC assessments[61]. Several MIPs have focused on SRM, although fewer models have taken part in these. There have also been MIPs on volcanic effects which are relevant and have been relatively well participated in[62]. The spread in model results from MIPs is a key (but incomplete) indicator of confidence in, for example, climate sensitivity or regional climate change.

Climate models have important limitations in representing regional responses, which impacts how reliable they are in representing regional impacts of SRM. An important and long-standing bias in climate models is their representation of the Asian Summer Monsoon, which directly affects billions of people. The circulation is often too weak, and does not extend far enough north, so models can fail to capture the associated precipitation pattern. Such a bias can limit confidence in climate projections for a region. Understanding of regional responses can also be limited by model spatial resolution, with ESMs often having grid cells that are around 100 km wide. This means that they can struggle to capture the details of regional patterns, and have to rely on simplified representations of regional processes. Natural variability is also larger at regional scales, which can hamper detection and understanding of forced changes. To address these issues, multiple models are often used to run the same experiment to reduce the influence of biases, and many realisations of the same experiment are performed to aid the distinction between natural variability and forced changes. Regional models are often used alongside ESMs to better predict regional climate changes. Resources to do this are often more limited for SRM studies, which further limits the confidence in regional responses to SRM compared to regional responses to climate change.

61 *Op. cit.* 60.

62 Zanchettin *et al.* 2022 Effects of forcing differences and initial conditions on inter-model agreement in the VolMIP volc-pinatubo-full experiment. *Geoscientific Model Development* **15**, 2265–2292. See: https://doi.org/10.5194/gmd-15-2265-2022 (accessed 1 October 2025).

What are the different SRM techniques?

This chapter reviews the principal characteristics of the main proposed SRM techniques and briefly considers other techniques. To motivate the focus, as part of this briefing, an expert evaluation was performed (see Annex A for details) where a number of active SRM researchers were polled to give their judgement on the ability of possible SRM techniques to achieve a 1°C global-mean surface cooling, and the technical barriers and level of scientific understanding associated with each technique. While necessarily subjective, it can be considered as an evolution of a similar figure (Figure 5.1) in the 2009 Royal Society report[63] (but without CDR). Figure 4 shows the outcome of this expert evaluation; it indicates a clear separation between the potential of SAI, MCB and MSB from other techniques, based on current understanding.

3.1 Main SRM techniques

3.1.1 SAI – Stratospheric Aerosol Injection

Definition

SAI proposes injecting aerosol particles or their gaseous precursors into the stratosphere, the region of the atmosphere at altitudes above about 8 km in high latitudes and 20 km in the tropics, to reflect sunlight and reduce the amount of solar radiation reaching the Earth's surface[64]. Most commonly sulfate aerosols have been modelled, but alternate materials have been suggested[65, 66, 67, 68, 69, 70]. The concept is supported, to an extent, by the surface cooling effects observed after explosive volcanic eruptions[71].

A prime reason that SAI has been proposed is that aerosol particles in the stratosphere have a much longer lifetime (typically 1 to 2 years) than those in the underlying troposphere (days to weeks) (see Box 1). The relatively long stratospheric lifetime means that winds associated with the atmospheric circulation can spread aerosols over large regions, and less replenishment would be needed. Even with a lifetime of 1 – 2 years, however, the SAI aerosol layer would need to be regularly refreshed to maintain its climate effect.

63 *Op. cit.* 16.

64 *Op. cit.* 5.

65 Keith D W. 2010 Photophoretic levitation of engineered aerosols for geoengineering. *Proceedings of the National Academy of Sciences of the United States of America* **107**, 16428–16431. See: https://doi.org/10.1073/pnas.1009519107 (accessed 1 October 2025).

66 Weisenstein *et al*. 2015 Solar geoengineering using solid aerosol in the stratosphere. *Atmospheric Chemistry and Physics* **15**, 11835–11859. See: https://doi.org/10.5194/acp-15-11835-2015 (accessed 1 October 2025).

67 Ferraro A J, Highwood E J, Charlton-Perez A J. 2011 Stratospheric heating by potential geoengineering aerosols. *Geophysical Research Letters* **38**. See: https://doi.org.10.1029/2011GL049761 (accessed 1 October 2025).

68 Jones A C, Haywood J M, Jones A. 2016 Climatic Impacts of Stratospheric Geoengineering with Sulfate, Black Carbon and Titania Injection. *Atmospheric Chemistry and Physics* **16**, 2843–2862. See: https://doi.org/10.5194/acp-16-2843-2016 (accessed 1 October 2025).

69 Dykema J A, Keith D W, Keutsch F N. 2016 Improved aerosol radiative properties as a foundation for solar geoengineering risk assessment. *Geophysical Research Letters* **43**, 7758–7766. See: https://doi.org/10.1002/2016GL069258 (accessed 1 October 2025).

70 Stefanetti *et al*. 2024 Stratospheric injection of solid particles reduces side effects on circulation and climate compared to SO_2 injections. *Environmental Research: Climate* **3**. See: https://doi.org/10.1088/2752-5295/ad9f93 (accessed 1 October 2025).

71 Robock A, MacMartin D G, Duren R, Christensen M W. 2013 Studying geoengineering with natural and anthropogenic analogs. *Climate Change* **121**, 445–458. See: https://doi.org/10.1007/s10584-013-0777-5 (accessed 1 October 2025).

FIGURE 4

Expert evaluation of proposed SRM techniques, summarised in terms of perceived technical barriers, effectiveness in achieving a 1°C global-mean cooling and level of scientific understanding (LOSU).

Each point represents the mean rating of all responses. Error bars indicate two standard errors of the mean. All responses were collected using a 1 – 6 Likert scale. See Annex A for data collection details.

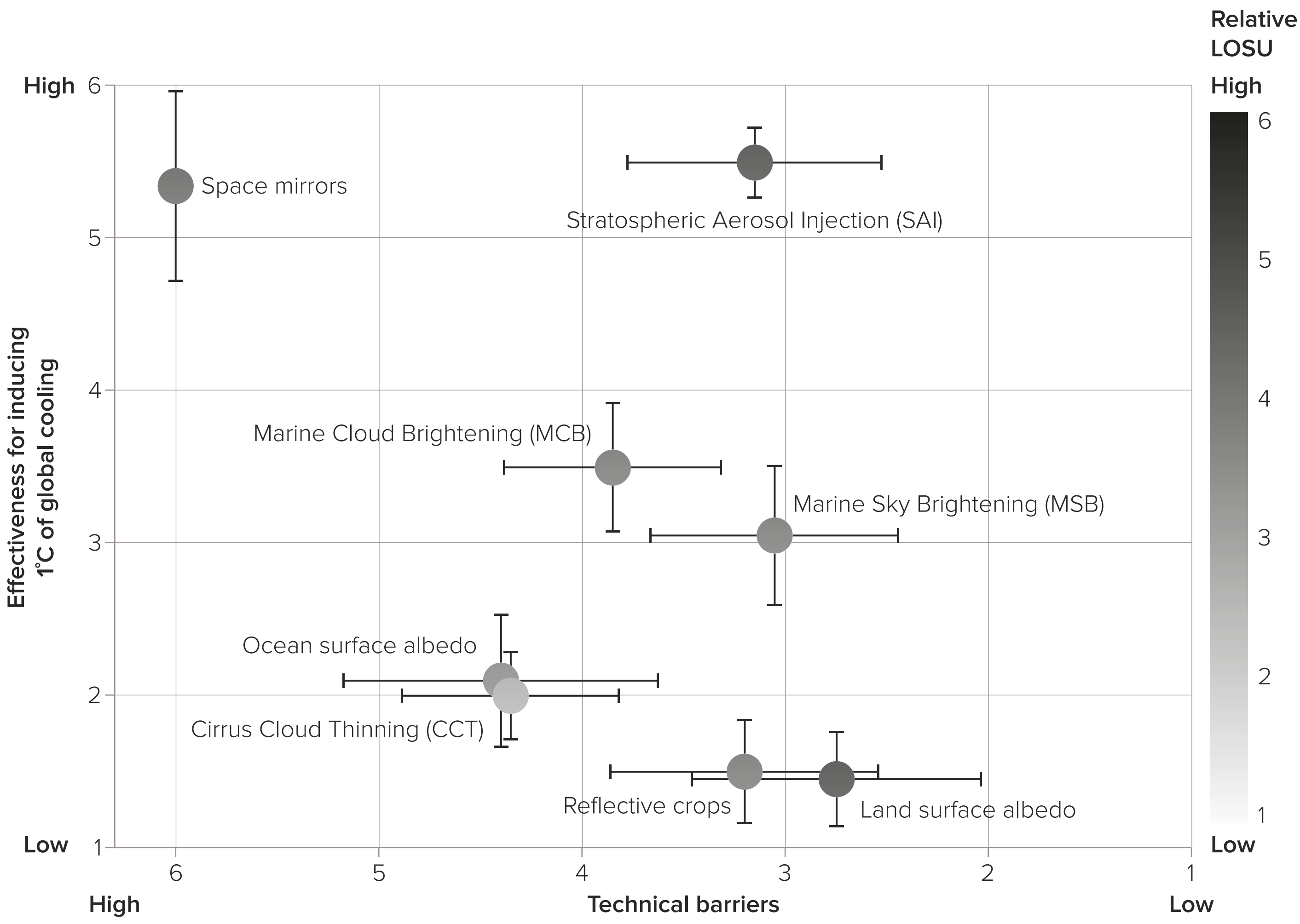


Figure produced by Josh Smith (University of Exeter).

Analogues

Real-world analogues for SAI include explosive volcanic eruptions, such as the 1991 Mt. Pinatubo eruption, which released large quantities of gas-phase sulfur dioxide (SO_2) into the stratosphere (Figure 5). This led to the formation of sulfate aerosol particles and a measurable peak global surface cooling of around 0.3°C for a few years[72]. To achieve a long-lasting surface cooling from a short-lived volcanic eruption (ie emission pulse), aerosols, or their gaseous precursors, need to reach the stratosphere[73]. Meteorological conditions determine the spread of the aerosol plume. Explosive tropical eruptions can result in plumes that spread into both hemispheres (eg, 1991 Mt. Pinatubo), or more into the northern hemisphere (eg, El Chichón eruption in 1982) or the southern hemisphere (eg, Agung eruption in 1963). Plumes from eruptions outside the tropics tend to remain in the same hemisphere as the eruption.

Explosive volcanic eruptions demonstrate the potential of sulfate aerosols to reduce incoming solar radiation but the forcing from volcanic eruptions is transient (ie it decays over the course of a few years) because it is the result of a one-off ‘pulse’ emission flux to the stratosphere.

In contrast, SAI would likely involve sustained emissions, which leads to a sustained forcing (ie longer-lived and no or little decay of forcing magnitude compared to explosive volcanic eruptions). This sustained emission increases would increase the size of the particles which are less efficient at scattering sunlight and are removed from the atmosphere more quickly[74]. A further limitation of the pulse nature of explosive eruptions, and its short-lived forcing relative to any SAI deployments, is that the responses differ[75, 76]. Land cools down much more quickly than the ocean following a pulse injection owing to the slow response of ocean temperature[77]. Pulse-like volcanic events thus provide little or no information on how long-term SAI may affect recurrent large-scale variations in atmospheric circulation such as El Niño Southern Oscillation (ENSO), further discussed in Chapter 6. The climate response to SAI cannot therefore be directly inferred from the observed response to volcanic eruptions. Overall, explosive volcanic eruptions are limited, but nevertheless useful, analogues for SAI, because they provide unique opportunities to test and validate climate models against observed responses to enhanced stratospheric aerosol loadings.

72 Robock A. 2000 Volcanic eruptions and climate. *Reviews of Geophysics* **38**, 191–219. See: https://doi.org/10.1029/1998RG000054 (accessed 1 October 2025).

73 Marshall L, Johnson J S, Mann G W, Lee L, Dhomse S S, Regayre L. 2019 Exploring how eruption source parameters affect volcanic radiative forcing using statistical emulation. *Journal of Geophysical Research: Atmospheres* **124**, 964–985. See: https://doi.org/10.1029/2018JD028675 (accessed 1 October 2025).

74 Laakso A, Korhonen H, Romakkaniemi S, Kokkola H. 2017 Radiative and climate effects of stratospheric sulfur geoengineering using seasonally varying injection areas. *Atmospheric Chemistry and Physics* **17**, 6957–6974. See: https://doi.org/10.5194/acp-17-6957-2017 (accessed 1 October 2025).

75 *Op. cit.*71.

76 Duan L, Cao L, Bala G, Caldeira K. 2019 Climate Response to Pulse Versus Sustained Stratospheric Aerosol Forcing. *Geophysical Research Letters* **46**, 8976–8984. See: https://doi.org/10.1029/2019GL083701 (accessed 1 October 2025).

77 Op. *cit. 76*

There have also been some suggestions that black carbon that heats the surrounding air and 'self-lofts' into the stratosphere could act as an 'elevator' for other scattering aerosol species[78]. The most dramatic evidence is associated with wildfires that occurred in S.E. Australia in 2019/2020 which lofted smoke plumes to altitudes of up to 35 km[79], resulting in the largest global mean stratospheric temperature perturbation since the eruption of Pinatubo[80].

Technology development

Technology for SAI primarily involves the injection of aerosol particles or their gaseous precursors into the stratosphere. The earliest suggestions for deployment included the use of high-altitude aircraft, artillery shells or balloons[81]. Currently, high-altitude aircraft appear the most feasible and cost-effective delivery method, but substantial development costs would be needed to maximise the efficiency of any deployment[82, 83, 84, 85].

Research into specific materials such as sulfate, calcium carbonate, titanium dioxide, or other reflective particles is ongoing to identify options with minimal undesirable effects (for a review see Haywood *et al*., 2025[86] and references therein). The feasibility of delivery methods that relies on gaseous precursors such as SO_2 is relatively straightforward and well-studied through volcanic analogues. However, knowledge of the consequences of the interaction of the additionally introduced gaseous precursor species or particles with background aerosols is very limited[87]. Planned small-scale deployments to study these aspects such as the Stratospheric Controlled Perturbation Experiment (SCoPEx) have been cancelled (see Chapter 8 for more details). For context, the 1991 Mt. Pinatubo eruption emitted around 15 Tg of SO_2[88], the gaseous precursor species for sulfate aerosol particles[89], which is billions of times larger than was proposed in SCoPEx.

78 Gao *et al*. 2021 Toward practical stratospheric aerosol albedo modification: Solar-powered lofting. *Science Advances* **7**. See: https://doi.org/10.1126/sciadv.abe3416 (accessed 1 October 2025).

79 Khaykin *et al*. 2020 The 2019/20 Australian wildfires generated a persistent smoke-charged vortex rising up to 35 km altitude. *Communications Earth and Environment*, **1**, 22. See: https://doi.org/10.1038/s43247-020-00022-5 (accessed 1 October 2025).

80 Damany-Pearce *et al*. 2022. Australian wildfires cause the largest stratospheric warming since Pinatubo and extends the lifetime of the Antarctic ozone hole. *Scientific Reports* **12**, 12665. See: https://doi.org/10.1038/s41598-022-15794-3 (accessed 1 October 2025).

81 Robock A, Marquardt A, Kravitz B, Stenchikov G. 2009 Benefits, risks, and costs of stratospheric geoengineering. *Geophysical Research Letters* **36**. See: https://doi.org/10.1029/2009GL039209 (accessed 1 October 2025).

82 Laakso A, Partanen AI, Kokkola H, Laaksonen A, Lehtinen KE, Korhonen H 2012 Stratospheric passenger flights are likely an inefficient geoengineering strategy. *Environmental Research Letters* **7**, 034021. See: https://doi.org/10.1088/1748-9326/7/3/034021 (accessed 1 October 2025).

83 Smith W. 2020 The cost of stratospheric aerosol injection through 2100. *Environmental Research Letters* **15**. See: https://doi.org/10.1088/1748-9326/aba7e7 (accessed 1 October 2025).

84 Smith W. 2024 An assessment of the infrastructural and temporal barriers constraining a near-term implementation of a global stratospheric aerosol injection program. *Environmental Research Communications* **6**. See: https://doi.org/10.1088/2515-7620/ad4f5c (accessed 1 October 2025).

85 Duffey A, Henry M, Smith W, Tsamados M, Irvine P J. 2025 Low-Altitude High-Latitude Stratospheric Aerosol Injection Is Feasible With Existing Aircraft. *Earth's Future* **13**. See: https://doi.org/10.1029/2024EF005567 (accessed 1 October 2025).

86 *Op. cit*. 5.

87 *Op. cit.* 5.

88 1 Teragram (Tg) is equivalent to 1 million metric tonnes

89 McCormick M, Thomason L, Trepte C. 1995 Atmospheric effects of the Mt Pinatubo eruption. *Nature* **373**, 399–404. See: https://doi.org/10.1038/373399a0 (accessed 1 October 2025).

Feasibility to scale up

Scaling up SAI is considered technically feasible, as it could leverage and develop existing technologies like high-altitude aircraft to deliver gaseous precursors species or aerosol particles. However, existing large-payload aircraft can only deliver aerosol particles or their gaseous precursors into the stratosphere at high latitudes, as the tropopause is lower there compared to the tropics[90, 91]. Delivering aerosol particles at polar latitudes would significantly reduce deployment efficiency due to their shorter atmospheric lifetime. Even without considering this issue, scaling up is a challenge. For 1°C cooling, around 1,800 take-offs per day with a payload of 15 metric tonnes (t) per flight would be required[92]. For context, at London Heathrow airport there are around 650 combined take-offs per day. In addition, significant scientific challenges remain, including uncertainties in aerosol composition, dispersion strategies, and long-term effects on the stratospheric composition, the ozone layer, and regional climate. Costs of deployment are projected to be relatively low compared to other SRM strategies (see Section 3.4).

Deployment strategies

An SAI strategy involving the injection of SO_2 gas into the lower stratosphere would involve chemical processing there to convert the gas into sulfate aerosol particles with a time-evolving size distribution that affects their interaction with sunlight (ie how reflective they are). Strategies must consider the continuous deployment, optimal altitude, particle type, season, and geographic locations to achieve desired cooling effects while trying to minimise undesirable side effects such as large regional climate changes[93, 94], also see Chapter 6. Climate model simulations of both explosive volcanic eruptions and SAI have demonstrated that the climate response to increasing SO_2 emissions is non-linear, which results in a diminishing change in surface temperature per unit of SO_2 emitted as emissions increase[95, 96]. This is because higher SO_2 emissions lead to larger-sized sulfate aerosol particles, which are less efficient at scattering sunlight and are removed from the atmosphere more quickly due to their higher settling velocity. SAI simulations suggest that these limiting factors may only be significant under large injection rates exceeding 10 – 20 Tg of SO_2 per year[97], which is corroborated by studies of explosive volcanic eruptions[98].

90 *Op. cit*. 82.

91 *Op. cit*. 85.

92 *Op. cit*. 83.

93 *Op. cit*. 81.

94 Tilmes *et al*. 2020 Reaching 1.5 and 2.0°C global surface temperature targets using stratospheric aerosol geoengineering. *Earth System Dynamics* **11**, 579–601. See: https://doi.org/10.5194/esd-11-579-2020 (accessed 1 October 2025).

95 Schmidt A, Black B A 2022. Reckoning with the Rocky Relationship Between Eruption Size and Climate Response: Toward a Volcano-Climate Index. *Annual Review of Earth and Planetary Sciences* **50**, 627–661. See: https://doi.org/10.1146/annurev-earth-080921-052816 (accessed 1 October 2025).

96 *Op. cit*. 20.

97 Niemeier U, Timmreck C. 2015 What is the limit of climate engineering by stratospheric injections of SO_2? *Atmospheric Chemistry and Physics* **15**, 9129-9141. See: https://doi.org/10.5194/acp-15-9129-2015 (accessed 1 October 2025).

98 *Op. cit*. 95.

3.1.2 MCB – Marine Cloud Brightening

Definition

MCB aims at increasing the reflectivity of low-lying marine clouds, in the lowest kilometre or so of the atmosphere. It proposes introducing small-sized aerosol particles, such as sea salt aerosol particles, to serve as additional cloud condensation nuclei. Low-lying marine clouds are suggested as targets because they frequently consist of relatively pristine liquid water droplets. Such clouds are more susceptible to the injection of additional aerosol particles; these increase the number of cloud droplets but reduce their size which has the effect of increasing cloud brightness[99]. This brightening is particularly effective over low-reflectance surfaces such as the ocean. Sea salt is frequently suggested as the source of aerosols because it is a naturally occurring component of marine aerosols, and considered relatively benign when compared to the possible significant effects on health from aerosols such as sulfates formed from the combustion of shipping fuel. MCB alters cloud properties and lifetime (ie the number and the size of cloud droplets and possibly also the thickness and horizontal extent of clouds), thereby indirectly enhancing cloud albedo and increasing the amount of reflected sunlight.

However, because MCB relies on complex aerosol-cloud interactions rather than direct aerosol-radiation effects, it is much harder to quantify and significantly more uncertain than aerosol-radiation interactions, which are better understood and more reliably measured using, for example, satellite instruments[100, 101]. Aerosol-cloud interactions are a major source of uncertainty in understanding current climate change (see Chapter 5) and that uncertainty carries over to MCB.

Overall, the effects of MCB on cloud properties and regional climate are still poorly understood (see Chapter 6 for details). In some conditions, injecting aerosols into low-lying clouds could even lead to cloud darkening rather than brightening, reducing its overall intended cooling effect[102].

99 Malavelle F F. 2017 Strong constraints on aerosol–cloud interactions from volcanic eruptions. *Nature* **546**, 485–491. See: https://doi.org/10.1038/nature22974 (accessed 1 October 2025).

100 Bellouin *et al*. 2020. Bounding global aerosol radiative forcing of climate change. *Review of Geophysics* **58**. See: https://doi.org/10.1029/2019RG000660 (accessed 1 October 2025).

101 *Op. cit.* 52.

102 *Op. cit.* 52.

Analogues

Ship tracks provide a real-world analogue for MCB. These are bright streaks in marine clouds caused by aerosol particles formed from ship exhausts that act as cloud condensation nuclei, increasing cloud brightness (Figure 5). However, not all ships produce visible ship tracks, and even in their absence, ships may still contribute to a more diffuse cloud brightening effect[103]. Observations of ship tracks offer insights into how aerosols can influence cloud properties and albedo, but uncertainties are large (see Chapter 4), and the spatial and temporal scales differ significantly from climate model simulations of large-scale MCB deployments.

MCB also has some parallels to the aerosol indirect effects induced by both effusive volcanic eruptions and continuously degassing volcanoes that inject sulfate aerosol precursor species into the lowermost troposphere[104, 105, 106, 107, 108]. Some of these eruptions result in long-lasting (weeks to months) and large-scale (10s to 100s of km) perturbations of the background atmosphere and cloud properties[109], which allow the quantification of the magnitude of the aerosol-induced cloud and climate response using measurements and global climate models. However, as for SAI, the sustained deployment and regionally targeted nature of MCB (towards stratocumulus clouds) somewhat limits the applicability of effusive eruptions as analogues.

103 *Op. cit*. 52.

104 Gasso S. 2008 Satellite observations of the impact of weak volcanic activity on marine clouds. *Journal of Geophysical Research: Atmospheres* **113**. See: https://doi.org/10.1029/2007JD009106 (accessed 1 October 2025).

105 Yuan T, Remer L A, Yu H. 2011 Microphysical, macrophysical and radiative signatures of volcanic aerosols in trade wind cumulus observed by the A-Train. *Atmospheric Chemistry and Physics* **11**, 7119–7132. See: https://doi.org/10.5194/acp-11-7119-2011 (accessed 1 October 2025).

106 Schmidt *et al*. 2012 Importance of tropospheric volcanic aerosol for indirect radiative forcing of climate. *Atmospheric Chemistry and Physics* **12**, 7321–7339. See: https://doi.org/10.5194/acp-12-7321-2012 (accessed 1 October 2025).

107 McCoy D T, Hartmann DL. 2015 Observations of a substantial cloud-aerosol indirect effect during the 2014–2015 Bárðarbunga-Veiðivötn fissure eruption in Iceland. *Geophysical Research Lett*ers **42**, 10–409. See: https://doi.org/10.1002/2015GL067070 (accessed 1 October 2025).

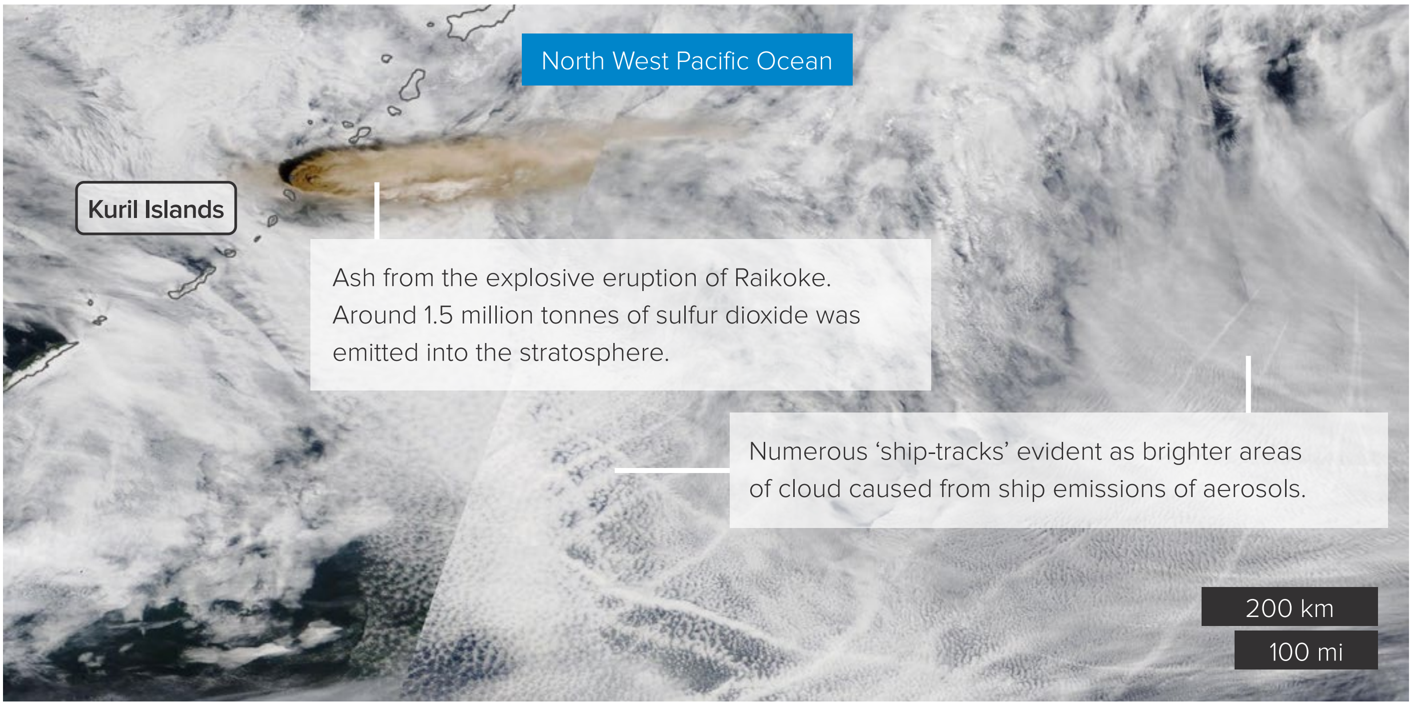
108 *Op. cit*. 99.

109 Schmidt *et al*. 2015 Satellite detection, long-range transport, and air quality impacts of volcanic sulfur dioxide from the 2014–2015 flood lava eruption at Bárðarbunga (Iceland). *Journal of Geophysical Research: Atmospheres* **120**, 9739–9757. See: https://doi.org/10.1002/2015JD023638 (accessed 1 October 2025).

FIGURE 5

Satellite image showing examples of the real-world analogues

i) stratospheric aerosol injection – the eruption of the Raikoke volcano in the Kuri Islands in June 2019,
ii) marine cloud brightening – 'ship-tracks' evident as bright lines from the injection of pollution aerosols into low lying clouds, on 22 June 2019.



Source: NASA Worldview[110]

110 NASA Worldview application, part of the NASA Earth Science Data and Information System (ESDIS). See https://worldview.earthdata.nasa.gov/ (accessed 15 September 2025).

Further evidence of the impact of aerosol-cloud interactions comes from the implementation of regulations designed to reduce local air pollution by the International Maritime Organization (IMO) which reduced fuel sulfur content from 3.5% to 0.5% in 2020. Assessment of the effect of this on ship tracks is complicated by the coincident reduction in shipping due to COVID-19. Accounting for COVID-19 reductions, studies have found a 25% reduction in ship-tracks for an estimated 80% reduction in sulfur emissions. Observations have also revealed that IMO regulations influence clouds more generally beyond the impact of ship-tracks[111]. Studies show an increase in seasonal mean radiative forcing due to IMO regulations in major shipping corridors, resulting in small changes in the global mean radiative forcing (approximately +0.1 W m^{-2})[112, 113, 114, 115].

Technology development

Technology for MCB is focused on creating vast numbers of very small aerosol particles, typically sea salt from the underlying ocean, that can enhance the reflectivity of clouds. Prototype equipment such as spray systems mounted on ships[116] has been developed for small-scale experiments. However, a key challenge is the inefficiency of current sprayers in producing the required number of appropriately sized particles. The energy requirements for large-scale deployment are currently estimated to be orders of magnitude beyond practical feasibility[117]. Additionally, challenges remain in achieving consistent aerosol production at precise size ranges and dispersion over large marine areas[118]. One recent field experiment has indicated that sea salt injections from the ocean surface can influence aerosol concentrations at cloud base[119]. However, the influence of such injections on cloud droplet sizes or cloud brightness has not yet been demonstrated and will likely depend upon the prevailing meteorological and cloud regimes.

111 Manshausen P, Watson-Parris D, Christensen M W, Jalkanen J P, Stier P. 2023 Rapid saturation of cloud water adjustments to shipping emissions. *Atmospheric Chemistry and Physics* **23**, 12545–12555. See: https://doi.org/10.5194/acp-23-12545-2023 (accessed 1 October 2025).

112 Gettelman *et al*. 2024 Has reducing ship emissions brought forward global warming? *Geophysical Research Letters* **51**. See: https://doi.org/10.1029/2024GL109077 (accessed 1 October 2025).

113 Jordan G, Henry M. 2024 IMO2020 regulations accelerate global warming by up to 3 years in UKESM1. *Earth's Future* **12**. See: https://doi.org/10.1029/2024EF005011 (accessed 1 October 2025).

114 Quaglia I, Visioni D. 2024 Modeling 2020 regulatory changes in international shipping emissions helps explain anomalous 2023 warming. *Earth System Dynamics* **15**, 1527–1541. See: https://doi.org/10.5194/esd-15-1527-2024 (accessed 1 October 2025).

115 Watson-Parris *et al*. 2025 Weak surface temperature effects of recent reductions in shipping SO_2 emissions are within internal variability. *Atmospheric Chemistry and Physics* 25, 4443–4454. See: https://doi.org/10.5194/egusphere-2024-1946 (accessed 1 October 2025).

116 Harrison D P. 2024 An Overview of Environmental Engineering Methods for Reducing Coral Bleaching Stress. In: Wolanski E, Kingsford MK (eds) *Oceanographic Processes of Coral Reefs*, 2nd edn. Florida, USA: CRC Press.

117 Parson E A, Keith D W. 2024 Solar Geoengineering: History, Methods, Governance, Prospects. *Annual Review of Environment and Resources* **49**, 337–366. See: https://doi.org/10.1146/annurev-environ-112321-081911 (accessed 1 October 2025).

118 Cooper *et al*. 2013 A Review of Some Experimental Spray Methods for Marine Cloud Brightening. *International Journal of Geosciences* **4**, 78-97. See: https://doi.org/10.4236/ijg.2013.41009 (accessed 1 October 2025).

119 Hernandez-Jaramillo *et al*. 2025 First generation outdoor marine cloud brightening trial increases aerosol concentration at cloud base height. *Environmental Research Letters* **20**. See: https://doi.org/10.1088/1748-9326/adccd7 (accessed 1 October 2025).

Feasibility to scale up

Scaling up MCB faces significant technological and scientific challenges[120, 121]. A key difference is the much shorter aerosol lifetime for MCB compared to SAI (see Box 1). And as will be discussed in Chapter 5, the amount of aerosol required to achieve a given climate effect is very uncertain.

Generating and dispersing enough sea salt or other aerosol types uniformly and within a specific size range over large marine areas requires the development of specialised equipment or vessels, which at present exist only as prototypes and conceptual designs[122]. Additionally, the susceptibility of clouds to brightening depends on background aerosol concentrations and meteorological conditions, which influence the effectiveness of MCB[123]. For context, using figures given in Haywood *et al*. (2025)[124] achieving a global cooling of roughly 1°C might require approximately 27,000 sprayers operating at 100% efficiency, 24 hours a day, at a spray rate of 100 litres per minute. The scale of deployment needed for MCB remains a significant barrier to feasibility.

Deployment strategies

The most susceptible marine clouds are typically found on the eastern side of large oceanic basins where there is considerable upwelling of cold water leading to lower sea-surface temperatures that are associated with marine stratocumulus clouds. On the face of it, deployment strategies for MCB could initially focus on injecting aerosol particles in such regions to maximise the cloud brightening per unit mass injection for a particular technology[125]. However, as discussed in more detail in Chapter 6, model simulations clearly suggest that inhomogeneous forcings will lead to inhomogeneous regional responses in temperature and precipitation. Any practical deployment strategy would likely seek to avoid such responses[126]. One modelling study has shown that while MCB becomes progressively less effective, per unit of sea salt injected, as injection rates increase, this is counterbalanced by a concurrent increase in MSB (see Section 3.2) which, in that model, comes to dominate the radiative forcing for injection rates exceeding about 50 Tg of sea salt per year[127].

120 *Op. cit*. 5.

121 *Op. cit*. 52.

122 *Op. cit*. 116.

123 *Op. cit.* 52.

124 *Op. cit*. 5.

125 *Op. cit.* 52.

126 *Op. cit.* 52.

127 Haywood J M, Jones A, Jones A C, Halloran P, Rasch P J. 2023 Climate intervention using marine cloud brightening (MCB) compared with stratospheric aerosol injection (SAI) in the UKESM1 climate model. *Atmospheric Chemistry and Physics* **23**, 15305–15324. See: https://doi.org/10.5194/acp-23-15305-2023 (accessed 1 October 2025).

3.2 Other SRM techniques

A range of other SRM techniques have been proposed and are discussed in more detail elsewhere[128, 129, 130, 131]. As shown by Figure 4, expert elicitation of their potential to achieve a 1°C global surface cooling is low for all of these, except for space mirrors; in that case the technical barriers and costs (see Section 3.3) are considered very high. For these reasons, these other techniques are only briefly discussed.

Marine Sky Brightening

MSB aims to inject additional scattering aerosol particles in marine areas to reflect additional sunlight to space. In contrast to MCB, which results from aerosol-cloud interactions, MSB (like SAI) directly increases reflection by aerosols (ie, without affecting clouds). Overall, MSB has been recognised as a major cooling component in studies that originally examined the effects of sea salt injections into low-lying marine clouds focused on MCB[132, 133, 134] and it could be applied in regions without extensive cloud.

Like MCB, MSB can draw analogues from ship emissions and from natural sea salt aerosol-radiation interactions. In general, aerosol-radiation interactions important for MSB are better understood and have lower uncertainty compared to aerosol-cloud interactions important for MCB[135, 136].

The technology for MSB would require developing systems capable of dispersing appropriately-sized aerosols (of a certain size range but rather larger in size than for MCB) that remain airborne over vast marine areas long enough to reflect significant amounts of sunlight. Research on the appropriate types of aerosols, including their interaction with radiation, is still in its early stages.

While the level of scientific understanding (LOSU) of MSB is at least on a par with that for MCB and the technical barriers appear somewhat lower (Figure 4), research suggests that the forcing efficiency (ie, the cooling per unit of injected aerosol) is significantly lower than for MCB[137] and so the same cooling would require much higher injection rates compared to MCB. Because MSB has generally been regarded as a by-product of MCB, deployment strategies have not yet been developed. However, it is very likely that many concerns that apply to MCB will apply equally to MSB.

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128 *Op. cit.* 127.

129 *Op. cit*. 21.

130 *Op. cit*. 22.

131 *Op. cit*. 23.

132 Jones A, Haywood J M. 2012 Sea-spray geoengineering in the HadGEM2-ES earth-system model: radiative impact and climate response. *Atmospheric Chemistry and Physics* **12**, 10887–10898. See: https://doi.org/10.5194/acp-12-10887-2012 (accessed 1 October 2025).

133 Ahlm L, Jones A, Stjern C W, Muri H, Kravitz B, Kristjánsson J E. 2017 Marine cloud brightening – as effective without clouds. *Atmospheric Chemistry and Physics* **17**, 13071–13087. See: https://doi.org/10.5194/acp-17-13071-2017 (accessed 1 October 2025).

134 *Op. cit*. 127.

135 Carslaw *et al*. 2013 Large contribution of natural aerosols to uncertainty in indirect forcing. *Nature* **503**, 67–71. See: https://doi.org/10.1038/nature12674 (accessed 1 October 2025).

136 *Op. cit*. 100.

137 *Op. cit.* 127.

Surface albedo modification

This SRM technique aims to increase the reflectivity (albedo) of the Earth's surface by altering natural or artificial materials[138]. Examples include painting rooftops white or covering areas with reflective materials. Such techniques are generally considered too small in terms of the application area to create a significant global mean temperature cooling but may help in reducing the local temperatures within urban areas and are thus frequently considered adaptation strategies to increasing temperatures rather than geoengineering techniques[139]. Creating more reflective crop varieties could potentially be larger scale, but research is in its infancy.

An alternative approach is a suggestion to cause a global-scale cooling via an increase in ocean surface albedo by generating foam or microbubbles at the ocean surface[140, 141, 142]; research on this, from both climate effects and technical feasibility, is still in its infancy, but the costs and environmental impacts of chemicals (eg surfactants) that may be needed to create long-lived bubbles are likely to be a major concern.

Cirrus cloud thinning

High-altitude cirrus clouds trap heat by absorbing outgoing infrared radiation. Strictly speaking, cirrus cloud thinning is not an SRM technique, but it is closely related as it seeks to reduce the thickness and/or coverage of high-altitude cirrus clouds, increasing the amount of infrared radiation that can escape into space, which would lead to a surface cooling. Recent work in this area has been reviewed by Haywood *et al*. (2025)[143] and the technical barriers are high and the LOSU low compared to more prominent SRM methods (Figure 4) although it is recognised that this is an area in its infancy.

Space mirrors

This SRM concept involves deploying large, reflective mirrors or sunshades in space to block or reflect a portion of incoming solar radiation before it reaches Earth. Although conceptually straightforward, recent assessments have concluded that technical barriers, including development timescales and costs, are prohibitive compared to other proposed SRM methods[144, 145].

138 *Op. cit*. 5.

139 *Op. cit.* 5.

140 *Op. cit.* 5.

141 Crook J A, Jackson L S, Forster P M. 2016 Can increasing albedo of existing ship wake reduce climate change? *JGR Atmospheres* **121**, 1549–1558. See: https://doi.org/10.1002/2015JD024201 (accessed 1 October 2025).

142 Gabriel C J, Robock A, Xia L, Zambri B, Kravitz B. 2017 The G4Foam experiment: global climate impacts of regional ocean albedo modification. *Atmospheric Chemistry and Physics* **17**, 595–613. See: https://doi.org/10.5194/acp-17-595-2017 (accessed 1 October 2025).

143 *Op. cit.* 5.

144 *Op. cit*. 22.

145 *Op. cit.* 24.

3.3 Estimated costs of different SRM techniques

We do not provide our own estimates of costs of deploying different SRM techniques; rather, we use estimates from recent assessments. These costs are necessarily approximate and open to challenge. As well as physical science uncertainties, such as the amount of injected material needed to provide a given radiative forcing, and the climate sensitivity (ie, the surface temperature change per unit radiative forcing), there are many underlying economic and technological uncertainties and assumptions. Values reported in the literature often use different bases (eg, costs of a given mass of injected material, costs of a given radiative forcing, costs per degree of cooling, and whether development costs are included), and so cannot be compared in a straightforward manner.

We provide indicative numbers here of costs for a 1°C global surface cooling, where these are available in recent assessments. Deployment and development costs might not scale linearly with the target cooling. Of the few recent detailed estimates, the majority are specifically for SAI.

SAI

Recent estimates[146, 147] which assume SAI is deployed using a fleet of high-flying aircraft, indicate typical costs of a few tens of US$ billions per year per degree cooling, a figure that accounts for development costs. This is broadly consistent with the assessment of the NASEM[148], UNEP[149], and SAPEA[150], although they share some of the same underlying literature.

MCB

Estimates of the amount of injected sea salt needed to cause a given cooling vary by an order of magnitude making cost estimates difficult, even before technological aspects are addressed. There is little specific literature on costs. SAPEA refrains from presenting a cost estimate. UNEP provides an estimate equivalent to around US$ 1 to 2 billion per year per degree cooling, based on one brief older study[151, 152]. NASEM notes the lack of thorough cost estimates but speculates that they may be broadly similar to SAI[153].

146 Smith *et al*. 2022 A subpolar-focused stratospheric aerosol injection deployment scenario. *Environmental Research Communications* **4**, 095009. See: https://doi.org/10.1088/2515-7620/ac8cd3 (accessed 1 October 2025).

147 *Op. cit.* 83.

148 *Op. cit*. 21.

149 *Op. cit*. 22.

150 *Op. cit*. 24.

151 *Op. cit.* 24.

152 *Op. cit.* 22.

153 *Op. cit.* 21.

Other SRM

With the exception of space mirrors, estimates of costs for other SRM mechanisms are either absent from recent assessments, or lack support from the underlying literature. SAPEA[154] estimates that research, development and deployment costs for space mirrors are US$ 1 to 20 trillion, making "it significantly more expensive than SAI".

If these estimates are at least broadly correct, SAI and MCB costs appear relatively modest compared to other aspects of the global economy. Questions of governance and ethics, coupled with the need for improved understanding of scientifically-informed deployment strategies that minimise residual climate impacts, are hence likely to be more important questions around SRM development than financial limitations.

154 *Op. cit.* 24.

How accurately can we understand the effects of SRM?

The modelling of the climate effects of SRM uses the same state-of-the-art climate models used in projections of future climate change. However, the processes involved in SRM are more complex than those associated with increased concentrations of greenhouse gases. Both SAI and MCB propose using aerosols to directly or indirectly increase the planetary albedo and cool the planet; successive IPCC reports have highlighted aerosol climate interactions as a leading uncertainty in climate change.

Understanding the processes and effects of SAI and MCB, and the model fidelity (ability of the models to represent them), is aided by analogues such as volcanic eruptions, intense wildfires, ship-tracks and step-changes in anthropogenic emissions. These analogues are imperfect, as the emissions can occur as rapid pulses, and detailed emission rates for volcanic eruptions and wildfires are often poorly quantified. The complex chemistry of the emissions and co-emitted gaseous and aerosol species in natural analogues further complicates their utility. While imperfect, these analogues can be used to improve the ability of our current climate models to represent critical processes relevant to SRM. The uses and limitations of these analogues are discussed below.

4.1. Stratospheric Aerosol Injection

4.1.1 Explosive volcanic eruptions

SAI is inspired by observations of naturally occurring large explosive volcanic eruptions that sporadically inject millions of tonnes of gaseous sulfur dioxide (SO_2) into the stratosphere. There it forms a layer of sulfate aerosols in the form of sulfuric acid that reflect a portion of incoming sunlight back to space. The chemistry involves simple reactions with the hydroxyl radical (OH^-) and is well represented in climate models: $SO_2 + 2OH^- \rightarrow H_2SO_4$.

The gaseous sulfuric acid (H_2SO_4) formed by this reaction then readily nucleates and/or condenses to form reflective aerosols, that are frequently referred to as sulfates.

Throughout the historical records, there is clear evidence that large explosive volcanic eruptions tend to cool climate[155]. Anomalously cold conditions have been attributed to the massive eruptions of Tambora in 1815[156, 157] and Krakatoa in 1883[158]. More recently a clearly detectable global cooling occurred after the explosive eruption of Mt. Pinatubo in 1991. It injected around 10 – 15 Tg of SO_2 into the stratosphere[159, 160], leading to a peak global mean cooling of 0.3 to 0.5°C by mid-1992[161].

155 Lücke L J, Schurer A P, Toohey M, Marshall L R, Hegerl G C. 2023 The effect of uncertainties in natural forcing records on simulated temperature during the last millennium, *Climate of the Past* **19**, 959–978. See: https://doi.org/10.5194/cp-19-959-2023 (accessed 1 October 2025).

156 Raible *et al*. 2016 Tambora 1815 as a test case for high impact volcanic eruptions: Earth system effects. *Wiley Interdisciplinary Reviews: Climate Change* **7**, 569–589. See: https://doi.org/10.1002/wcc.407 (accessed 1 October 2025).

157 Schurer *et al*. 2019 Disentangling the causes of the 1816 European year without a summer. *Environmental Research Letters* **14**, 094019. See: https://doi.org/10.1088/1748-9326/ab3a10 (accessed 1 October 2025).

158 Gleckler P J, Wigley T M L, Santer B D, Gregory J M, AchutaRao K, Taylor K E. 2006 Krakatoa's signature persists in the ocean. *Nature*. **439**, 675. See: https://doi.org/10.1038/439675a (accessed 1 October 2025).

159 Mills *et al*. 2017 Radiative and chemical response to interactive stratospheric sulfate aerosols in fully coupled CESM1 (WACCM). *Journal of Geophysical Research: Atmo*spheres **122**, 13,061–13,078. See: https://doi.org/10.1002/2017JD027006 (accessed 1 October 2025).

160 Fisher *et al*. 2019 A new discrete wavelength backscattered ultraviolet algorithm for consistent volcanic SO_2 retrievals from multiple satellite missions. *Atmospheric Measurement Tech*niques **12**, 5137–5153. See: https://doi.org/10.5194/amt-12-5137-2019 (accessed 1 October 2025).

161 Soden B J, Wetherald R T, Stenchikov G L, Robock A. 2002. Global cooling after the eruption of mount Pinatubo: a test of climate feedback by water vapor. *Science* **296**, 727–730. See: https://doi.org/10.1126/science.296.5568 (accessed 1 October 2025).

The more minor explosive eruptions of Kasatochi in 2008, Sarychev in 2009, Nabro in 2011[162, 163], and Raikoke in 2019[164] each injected around 1.5 Tg of SO_2 into the lowermost stratosphere. Although the cooling effects of such eruptions are difficult to detect in the climate record, these smaller, well observed, eruptions provide opportunities for model evaluation[165].

Because of the need to understand the effects of volcanic eruptions on climate, most climate models include representation of the stratospheric sulfur cycle. These representations can be assessed using satellite, surface-based and local observations. Figure 6 shows a comparison of the evolution of the SO_2 plume in satellite observations and in a climate model for the 2019 Raikoke eruption. Such modelling allows evaluation of key chemical processes, such as the rate of SO_2 oxidation, and the formation of sulfate aerosols and their stratospheric lifetime. Note that these simulations use observed rather than model-produced winds to minimise differences in the patterns of observed and modelled spatial distributions of SO_2; this enables chemical processes to be better assessed. However, in SAI simulations of future scenarios, models generate their own meteorological winds. Calculated winds differ considerably between models which leads to quite different distributions of stratospheric aerosols, particularly for injections in the tropics[166, 167].

The transformation into sulfate aerosol is generally reasonably well captured by modelling studies[168, 169]. The latest climate models include representations of aerosol microphysical processes (ie aerosol schemes) of varying complexity, ranging from those that consider just the total mass of aerosol[170], to those that also represent the aerosol particle sizes[171, 172]. These represent how the sizes of sulfate aerosol particles change with time with reasonable to high accuracy[173, 174] enabling estimates of the amount of sunlight interacting with aerosols (ie the aerosol optical depth).

162 Solomon S, Daniel J S, Neely R R III, Vernier J P, Dutton E G, Thomason L W. 2011 The persistently variable 'background' stratospheric aerosol layer and global climate change. *Science* **333**, 866–870. See: https://doi.org/10.1126/science.1206027 (accessed 1 October 2025).

163 Santer *et al*. 2014. Volcanic contribution to decadal changes in tropospheric temperature. *Nature Geoscience*. **7**, 185–189. See: https://doi.org/10.1038/ngeo2098 (accessed 1 October 2025).

164 Wells *et al*. 2023 Including ash in UKESM1 model simulations of the Raikoke volcanic eruption reveal improved agreement with observations. *Atmospheric Chemistry and Physics* **23**, 3985–4007. See: https://doi.org/10.5194/acp-23-3985-2023 (accessed 1 October 2025).

165 Schmidt *et al*. 2018. Volcanic radiative forcing from 1979 to 2015. *Journal of Geophysical Research: Atmos*pheres **123**, 12,491–12,508. See: https://doi.org/10.1029/2018JD028776 (accessed 1 October 2025).

166 Visioni *et al*. 2023 Climate response to off-equatorial stratospheric sulfur injections in three Earth system models – Part 1: Experimental protocols and surface changes. *Atmospheric Chemistry and Phys*ics **23**, 663–685. See: https://doi.org/10.5194/acp-23-663-2023 (accessed 1 October 2025).

167 Bednarz E M, Butler A H, Visioni D, Zhang Y, Kravitz B, MacMartin DG. 2023. Injection strategy – a driver of atmospheric circulation and ozone response to stratospheric aerosol geoengineering. *Atmospheric Chemistry and Physics*. **23**, 13665–13684. See: https://doi.org/10.5194/acp-23-13665-2023 (accessed 1 October 2025).

168 Haywood *et al*. 2010 Observations of the eruption of the Sarychev volcano and simulations using the HadGEM2 climate model. *Journal of Geophysical Research: Atmospheres* **115**. See: https://doi.org/10.1029/2010JD014447 (accessed 1 October 2025).

169 *Op. cit.* 164.

170 *Op. cit*. 168.

171 *Op. cit.* 164.

172 Tilmes *et al*. 2023 Description and performance of a sectional aerosol microphysical model in the Community Earth System Model (CESM2). *Geoscientific Model Development* **16**, 6087–6125. See: https://doi.org/10.5194/gmd-16-6087-2023 (accessed 1 October 2025).

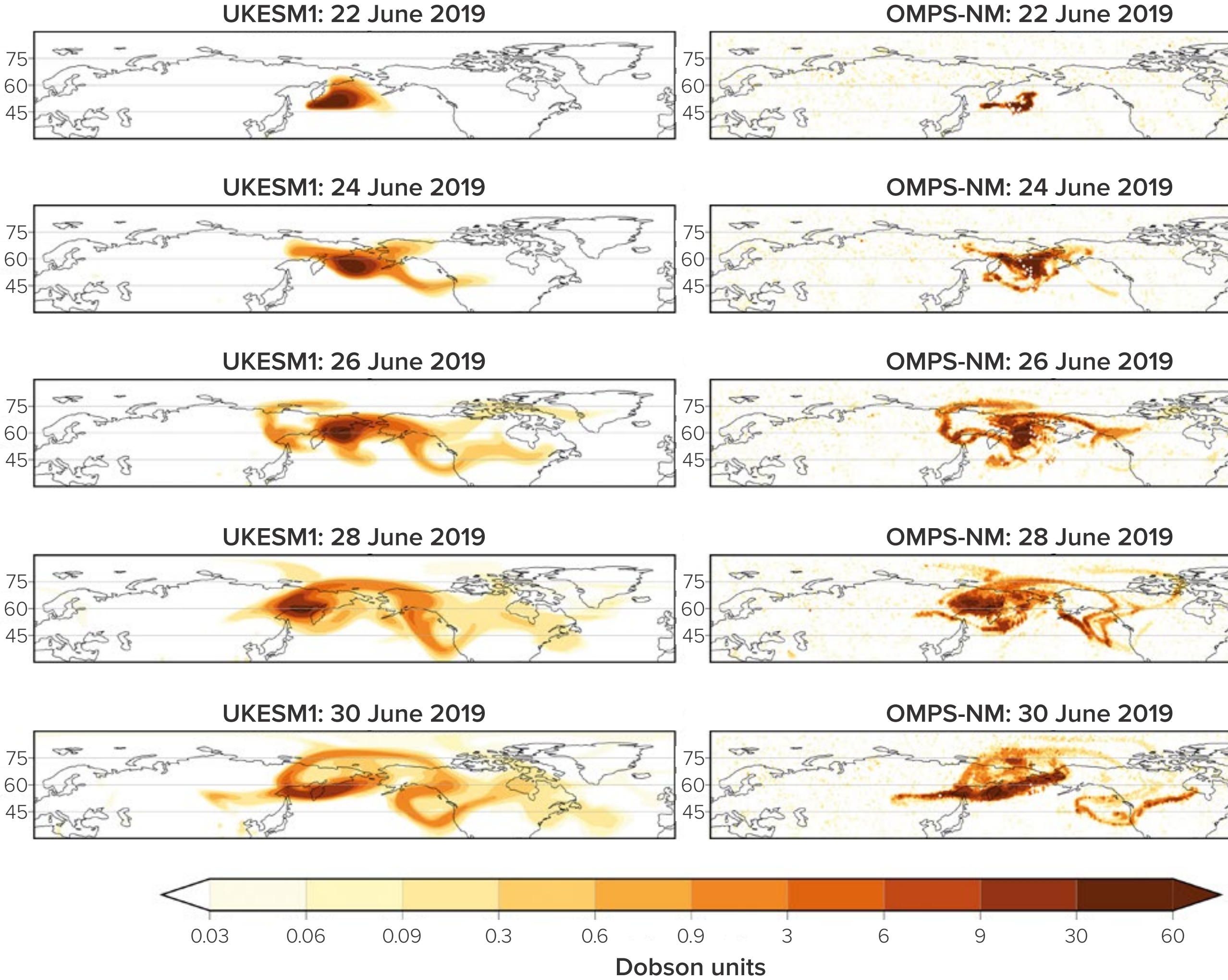
173 *Op. cit*. 165.

174 *Op. cit*. 172.

FIGURE 6

The evolution of SO_2 from the 2019 Raikoke volcanic eruption over an eight-day period immediately after the eruption.

The left-hand column shows simulations from a climate model (UKESM1) using observed winds, so that chemical processes affecting SO_2 can be more clearly assessed. The right-hand column shows satellite observations from the Ozone Mapping Photo-Spectrometer Nadir Mapper (OMPS-NM). The figure shows the SO_2 amount integrated through the depth of the stratosphere[175].



Source: After Wells *et al*. (2023).

175 *Op. cit*. 164.

Figure 7a shows the recent time variation of stratospheric aerosol optical depth; this results mainly from volcanic eruptions and determines their radiative forcing and can be well simulated by models[176]. The aerosols also absorb infrared radiation, causing a well-observed warming of the stratosphere (Figure 7b). This in turn determines features of the climate response to volcanic eruptions with implications for SRM (see Sections 6.4 and 6.5.4). Figure 7c shows the surface temperature variation over the same period. Natural climate variability means that the surface temperature response to eruptions is less readily detectable than optical depth and stratospheric temperature; this is significant for the monitoring of the effects of SRM (see Section 5.3).

Large equatorial volcanic eruptions such as the 1991 Mt. Pinatubo eruption reduced the average rate of precipitation and evaporation over land[177] and reduced river flow[178]. Model simulations of both volcanic eruptions and sustained SAI replicate this slow down of the hydrological cycle[179, 180, 181] providing some qualitative assurance of model fidelity. Stratospheric aerosols impact solar radiation at the surface, reducing evaporation and increasing atmospheric stability whereas greenhouse gases primarily impact infrared radiation. The resulting impacts on sensible and latent heat fluxes therefore differ with SAI impacts on the hydrological cycle being stronger than for greenhouse gases. As a result, balancing both the global mean temperatures and global mean precipitation simultaneously via SAI deployment is not possible (see Section 6.3)[182, 183, 184].

176 *Op. cit.* 165.

177 Trenberth K E, Dai A. 2007 Effects of mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering. *Geophysical Research Lett*ers **34**. See: https://doi.org/10.1029/2007GL030524 (accessed 1 October 2025).

178 Iles C E, Hegerl G C. 2015 Systematic change in global patterns of streamflow following volcanic eruptions. *Nature Geoscience* **8**, 838–842. See: https://doi.org/10.1038/ngeo2545 (accessed 1 October 2025).

179 Haywood J M, Jones A, Bellouin N, Stephenson D B. 2013. Asymmetric forcing from stratospheric aerosols impacts Sahelian drought. *Nature Climate Change* **3**, 660–665. See: https://doi.org/10.1038/NCLIMATE1857 (accessed 1 October 2025).

180 Tilmes *et al*. 2013 The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmosphere* **118**, 11036–11058. See: https://doi.org/10.1002/jgrd.50868 (accessed 1 October 2025).

181 Visioni *et al*. 2021. Identifying the sources of uncertainty in climate model simulations of solar radiation modification with the G6sulfur and G6solar geoengineering model Intercomparison project. *Atmospheric Chemistry and Physics* **21**, 10039–10063. See: https://doi.org/10.5194/acp-21-10039-2021 (accessed 1 October 2025).

182 Allen M R, Ingram W J. 2002 Constraints on future changes in climate and the hydrologic cycle. *Nature* **419**, 224-232. See: https://doi.org/10.1038/nature01092 (accessed 1 October 2025).

183 *Op. cit.* 178.

184 *Op. cit.* 56.

Any practical deployment of SAI would require models with significantly better spatial resolution than existing climate models; such modelling capability is already available and has been utilised for modelling the evolution of volcanic plumes[185]. However, there is not yet the computing capability to run high-resolution models (with grid spacing of around 1 km) over multidecadal periods and in ensemble mode (across multiple climate models), necessary to fully assess the possible multi-year impacts of SAI on regional climate around the world. Practical deployments would also need to take account of the prevailing meteorological conditions and injection location. Modelling studies show that meteorological variability leads to variations of more than a factor of two in the stratospheric aerosol burden and optical depth for SAI injections near the tropopause[186, 187].

4.2 Marine cloud brightening

As discussed in Section 3.1.2, there is long-standing satellite evidence from ship-tracks of the observed brightening of clouds from the injection of aerosols or their precursors into pristine, unpolluted clouds[188] (see also Figure 5).

More recently, the long (20+ years) and continuous satellite record of cloud properties from the Moderate Resolution Imaging Spectrometer (MODIS) satellite instrument allowed clear attribution of large-scale changes in cloud properties from large effusive volcanic eruptions[189, 190, 191, 192]. Observations of the large 2014 – 2015 Holuhraun effusive eruption in Iceland have been used to assess the representation of aerosol-cloud-interaction in models which simulate cloud convection (cloud-resolving models)[193] and climate models[194, 195]. The impacts on reduction of cloud droplet size, which increases cloud reflectivity, is reasonably well represented across models[196, 197].

185 de Leeuw *et al*., 2021 The 2019 Raikoke volcanic eruption – Part 1: Dispersion model simulations and satellite retrievals of volcanic sulfur dioxide. *Atmospheric Chemistry and Physics* **21**, 10851–10879. See: https://doi.org/10.5194/acp-21-10851-2021 (accessed 1 October 2025).

186 Jones A C, Haywood J M, Jones A, Aquila V. 2016 Sensitivity of volcanic aerosol dispersion to meteorological conditions: A Pinatubo case study. *Journal of Geophysical Research: Atmosphere* **121**, 6892–6908. See: https://doi.org/10.1002/2016JD025001 (accessed 1 October 2025).

187 Sun H, Bourguet S, Eastham S, Keith D. 2023 Optimizing Injection Locations Relaxes Altitude-Lifetime Trade-Off for Stratospheric Aerosol Injection. *Geophysical Research Letters* **50**. See: https://doi.org/10.1029/2023GL105371 (accessed 1 October 2025).

188 Conover J H. 1966 Anomalous cloud lines. *Journal of the Atmospheric Sciences* **23**, 778–785. See: https://doi.org/10.1175/1520-0469(1966)023%3C0778:ACL%3E2.0.CO;2 (accessed 1 October 2025).

189 *Op. cit*. 107.

190 *Op. cit*. 99.

191 Chen *et al*. 2022 Machine learning reveals climate forcing from aerosols is dominated by increased cloud cover. *Nature Geosciences* **15**, 609–614. See: https://doi.org/10.1038/s41561-022-00991-6 (accessed 1 October 2025).

192 Chen Y *et al*. 2024 Substantial cooling effect from aerosol-induced increase in tropical marine cloud cover. *Nature Geosciences* **17**, 404–410. See: https://doi.org/10.1038/s41561-024-01427-z (accessed 1 October 2025).

193 Haghighatnasab M, Kretzschmar J, Block K, Quaas J. 2022 Impact of Holuhraun volcano aerosols on clouds in cloud-systemresolving simulations. *Atmospheric Chemistry and Physics* **22**, 8457–8472. See: https://doi.org/10.5194/acp-22-8457-2022 (accessed 1 October 2025).

194 Peace *et al*. 2024 In-plume and out-of-plume analysis of aerosol–cloud interactions derived from the 2014–2015 Holuhraun volcanic eruption. *Atmospheric Chemistry and Physics* **24**, 9533–9553. See: https://doi.org/10.5194/acp-24-9533-2024 (accessed 1 October 2025).

195 Jordan *et al*. 2024 How well are aerosol–cloud interactions represented in climate models? – Part 1: Understanding the sulfate aerosol production from the 2014–15 Holuhraun eruption. *Atmospheric Chemistry and Physics* **24**, 1939–1960. See: https://doi.org/10.5194/acp-24-1939-2024 (accessed 1 October 2025).

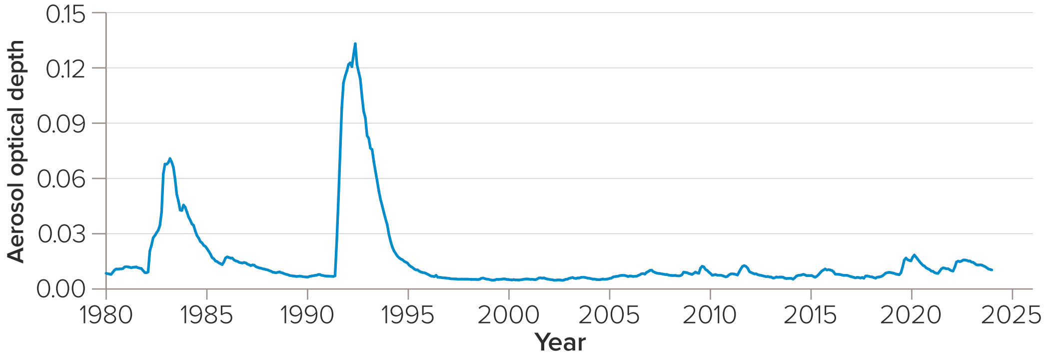
196 *Op. cit*. 99.

197 *Op. cit.* 199.

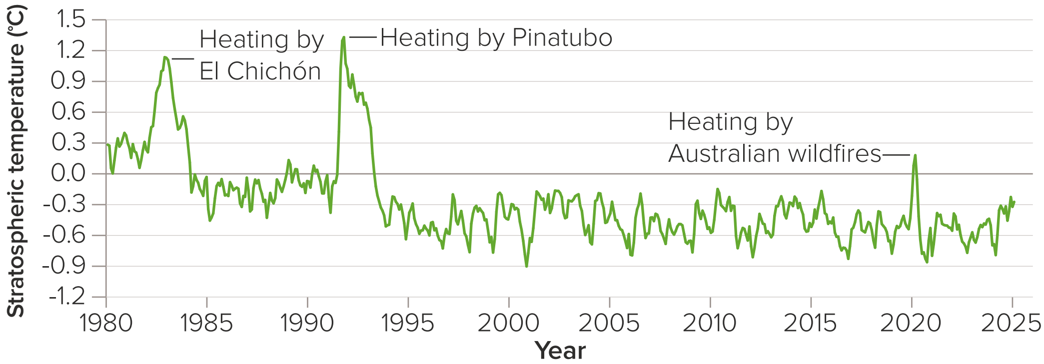
FIGURE 7

Time variation, since 1980, of observations of global-average stratospheric optical depth at a wavelength of 525 nm (a), lower stratospheric temperature (b) and surface temperature (c).

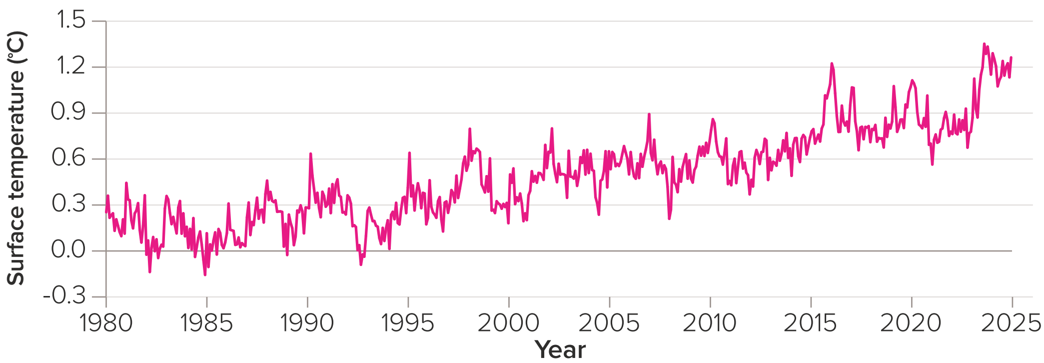
a) Monthly- and global-mean stratospheric aerosol optical depth at a wavelength of 525 nm from the Global Space-based Stratospheric Aerosol Climatology (GloSSAC)[198]



b) Monthly- and global-mean lower stratospheric temperature (°C) derived from microwave sounders plotted as the difference from the 1979 – 1998 mean*



c) Monthly- and global-mean surface temperature from the HadCRUT5 dataset plotted as differences from the 1961 – 1990 mean[201]



* Adapted from Damany-Pearce *et al.* 2022[199]. Primary source of data Mears and Wentz 2009[200].

198 ASA/LARC/SD/ASDC. Global Space-based Stratospheric Aerosol Climatology Version 2.22 [Data set]. NASA Langley Atmospheric Science Data Center DAAC. See: https://doi.org/10.5067/GLOSSAC-L3-V2.22 (accessed 1 October 2025).

199 *Op. cit.* 80.

200 Mears C A, Wentz F J. 2009 Construction of the Remote Sensing Systems V3.2 Atmospheric Temperature Records From the MSU and AMSU Microwave Sounders, *Journal of Atmospheric and Oceanic Technology* **26**, 1040-1056. See: https://doi.org/10.1175/2008JTECHA1176.1 (accessed 1 October 2025).

201 Morice *et al*. 2021 An updated assessment of near-surface temperature change from 1850: the HadCRUT5 data set. *Journal of Geophysical Research: Atmospheres* **126**, e2019JD032361. See: https://doi.org/10.1029/2019JD032361 (accessed 1 October 2025).

Observations suggest that the eruption had little impact on the amount of water (which is important in determining cloud reflectivity) within the affected clouds. However, machine learning methods indicate the eruption caused a significant increase in the cloud amount [202, 203]. Climate models generally fail to reproduce such increases suggesting that aerosol-cloud interactions may be significantly underestimated in current models. Thus, climate models can simulate some, but not all of the complexities of aerosol-cloud-interactions that lead to changes in the sunlight reflected by clouds.

Further evidence of the impact of aerosol-cloud interactions comes from the implementation of regulations designed to reduce local air pollution by the IMO which reduced fuel sulfur content from 3.5% to 0.5% in 2020, as introduced in Chapter 3.

Model studies assessing the climate effect of the IMO regulations[204, 205, 206, 207] suggest that global warming has been brought forward by up to approximately 0.03 – 0.08°C (around two to four years) over timescales of a decade. A study suggesting a significantly larger temperature response of 0.16°C[208] has been criticised[209].

Definitive attribution of the climate effect of IMO regulations is difficult owing to uncertainties in representing aerosol processes in climate models. The fidelity of commonly used representations of such clouds in climate models has been questioned for marine environments[210, 211]. Additionally, assumptions must be made about processes controlling the amount of sulfate reaching the cloud from ships[212] and must account for rapid changes in anthropogenic aerosol emissions from land areas, particularly in Asia. Claims that the IMO shipping regulations have led to an acceleration in the rate of global warming[213] are currently hotly debated[214, 215], with shipping regulations likely to be just one factor in the observed acceleration.

202 *Op. cit.* 195.

203 *Op. cit.* 196.

204 *Op. cit.* 199.

205 *Op. cit.* 112.

206 *Op. cit.* 114.

207 *Op. cit.* 115.

208 Yuan *et al*. 2024 Abrupt reduction in shipping emission as an inadvertent geoengineering termination shock produces substantial radiative warming. *Communications Earth and Environment* **5**, 281. See: https://doi.org/10.1038/s43247-024-01442-3 (accessed 1 October 2025).

209 *Op. cit.* 115.

210 Nenes A, Seinfeld J H. 2003 Parameterization of cloud droplet formation in global climate models. *Journal of Geophysical Research: Atmospheres.* **108**, 4415. See: https://doi.org/10.1029/2002JD002911 (accessed 1 October 2025).

211 Ming Y, Ramaswamy V, Donner L J, Phillips V T J. 2006 A new parameterization of cloud droplet activation applicable to general circulation models. Journal of the Atmospheric Sciences **63**, 1348–1356. See: https://doi.org/10.1175/JAS3686.1 (accessed 1 October 2025).

212 *Op. cit.* 199.

213 Hansen *et al*. 2025 Global Warming Has Accelerated: Are the United Nations and the Public Well-Informed? *Environment : Science and Policy for Sustainable Development* 67, 6–44. See: https://doi.org/10.1080/00139157.2025.2434494 (accessed 1 October 2025).

214 *Op. cit*. 7.

215 Goessling *et al*. 2024. Recent global temperature surge intensified by record-low planetary albedo. *Science* **387**, 68–73. See: https://www.science.org/doi/10.1126/science.adq7280 (accessed 1 October 2025).

Limitations of analogues in determining the validity of MCB model studies include that most studies assume emissions of sea salt aerosols while ship-track, IMO and volcanic analogues generally refer to SO_2 emissions. Whilst numerous studies have demonstrated that aerosol composition has a relatively small effect compared to particle size on the cloud nucleating ability of an aerosol[216], it is challenging to separate their impacts as they are frequently intrinsically linked [217].

216 Dusek *et al*. 2006 Size Matters More than Chemistry for Cloud-Nucleating Ability of Aerosol Particles. *Science (American Association for the Advancement of Science)* **312**, 1375–1378. See: https://doi.org/10.1126/science.1125261 (accessed 1 October 2025).

217 Farmer D K, Cappa C D, Kreidenweis S M. 2015 Atmospheric Processes and Their Controlling Influence on Cloud Condensation Nuclei Activity. *Chemical Reviews* **115**, 4199–4217. See: https://doi.org/10.1021/cr5006292 (accessed 1 October 2025).

How effective could SRM techniques be at cooling the planet, and in what timeframes?

This chapter addresses current understanding of the extent to which SRM could cool the planet, addressing uncertainties and knowledge gaps, some of which could be reduced with further research and some of which are irreducible.

SRM focuses on man-made interventions that increase planetary albedo and lower global mean surface temperature. Simulations using global climate models show that SAI implemented at a scale similar to, or larger than, recent observed tropical volcanic eruptions would lower surface temperatures over global land and ocean regions (see the period between 2020 – 2070 in Figure 8). However, the effects on surface climate depend on the target SRM scenario, the modelled deployment strategy and the climate system response to the imposed SRM perturbation. These aspects are described in this chapter.

5.1 Effective radiative forcing due to SRM

The effect of different SRM techniques and strategies on cooling the planet can be quantified and compared using a measure known as effective radiative forcing (ERF)[218]. Global average ERF quantifies a change in Earth's energy balance that can be directly related to a resultant change in surface temperature[219].

There is a complex chain of physical processes that control the ERF from a given SRM strategy. All ERF estimates for SRM deployment rely on the use of complex climate models in some form given the relatively limited observational constraints (see Chapter 4). Climate models do not have a complete representation of all necessary processes, leading to inherent uncertainties even within the relatively controlled environment of a model. The amplitude of ERF and its associated uncertainties depend on the SRM strategy and the climate model used; a particular injection rate for SAI, MCB or MSB leads to a different ERF depending on location, altitude and season. This means that while we can have confidence that SRM could generate some surface cooling, the SRM strategy required to achieve a target cooling would be uncertain.

218 Sherwood *et al*. 2015 Adjustments in the Forcing-Feedback Framework for Understanding Climate Change. *Bulletin of the American Meteorological Society* **96**, 217–228. See: https://doi.org/10.1175/BAMS-D-13-00167.1 (accessed 1 October 2025).

219 *Op. cit*. 10.

If SO_2 gas was injected into the lower stratosphere as part of an SAI strategy, the gas would undergo chemical conversion into sulfate aerosol particles with a time-evolving size distribution that affects their interaction with sunlight (ie how reflective they are; see Chapter 3). The particle size distribution is not constant as over time they coagulate making fewer, larger particles. This is also dependent on the SRM strategy, with larger injection rates creating larger particles that become progressively less effective at reflecting solar radiation and have a reduced stratospheric lifetime owing to sedimentation[220]. This means that the first tonne of SO_2 gas released would be more effective than the last. Once formed, the aerosol particles are transported by atmospheric winds, spreading them to different regions, and are removed from the atmosphere on a timescale that varies by SAI deployment strategy (see Box 1). Therefore, an identical SAI deployment strategy implemented in different climate models results in different stratospheric aerosol loading, radiative properties and ERF [221, 222].

A comparison of five climate models[223] found an annual SAI injection rate of 20 Tg SO_2 gave an ERF varying from -0.8 to -2 W m^{-2}. This uncertainty is proportionately larger than the uncertainty in the present-day ERF due to greenhouse gases in Earth's atmosphere (within ± 12% for CO_2 ERF)[224]. Despite the large quantitative uncertainty, some general features have emerged:

- SAI is generally simulated to be more effective at reducing surface temperature when deployed at lower latitudes as compared to higher latitudes. This is because the aerosol remains in the stratosphere for longer when emitted in this region, and there is more sunlight on average to reflect[225]. This applies if injection occurs within the stratosphere above around 18 km altitude in the tropics.

- Injections at the equator have been shown to lead to large inter-model differences in spatial distribution of the resulting aerosol[226, 227].

220 *Op. cit.* 47.

221 Niemeier U, Richter JH, Tilmes S. 2020 Differing responses of the quasi-biennial oscillation to artificial SO_2 injections in two global models. *Atmospheric Chemistry and Physics* **20**, 8975–8987. See: https://doi.org/10.5194/acp-20-8975-2020 (accessed 1 October 2025).

222 *Op. cit*. 166.

223 *Op. cit.* 47.

224 *Op. cit*. 10

225 Henry M, Bednarz E M, Haywood J. 2024 How does the latitude of stratospheric aerosol injection affect the climate in UKESM1? *Atmospheric Chemistry and Physics* **24**, 13253–13268. See: https://doi.org/10.5194/acp-24-13253-2024 (accessed 1 October 2025).

226 *Op. cit*. 166.

227 Bednarz *et al*. 2023 Climate response to off-equatorial stratospheric sulfur injections in three Earth system models – Part 2: Stratospheric and free-tropospheric response. *Atmospheric Chemistry and Physics* **23**, 687–709. See: https://doi.org/10.5194/acp-23-687-2023 (accessed 1 October 2025).

- The most recent tranche of multi-model simulations inject at 30°N and 30°S to minimise these differences while maintaining a high cooling efficiency[228].
- The strongest SAI ERF also occurs for sulfate emissions in the mid-stratosphere (21 – 24 km)[229] and there are temporal dependencies related to the seasonal evolution of incoming sunlight.

In the case of MCB, the sea salt particles are injected within the troposphere to act as nuclei for cloud droplet formation. The particles are rapidly removed from the air by rain and settling (sedimentation) meaning they need to be continuously replenished (see Box 1). Climate models do not explicitly simulate aerosol-cloud interactions, which occur on very small spatial scales, and therefore represent their average effect on cloud properties over broad spatial scales of many 10s of km. Consequently, model estimates of aerosol-cloud interactions often have relatively larger absolute uncertainty ranges. To illustrate this, the contribution of aerosol-cloud interaction to the estimated ERF of anthropogenic aerosols has a larger uncertainty (-1.0 W m^{-2} ± 0.7 W m^{-2}) than that for aerosol-radiation interaction (–0.3 ± 0.3 W m^{-2})[230]. Since aerosol-cloud interaction is also the largest contributor to ERF for MCB, it means different climate models estimate different ERF for a similar MCB strategy[231].

An idealised model experiment involving a 50% increase in the cloud droplet number concentration of low clouds over the global oceans produced a large range of ERF (from −0.6 to −2.5 W m^{-2}) in different climate models[232]. Furthermore, the relationship between the rate of injection of sea salt (SS) particles and the resulting radiative forcing is uncertain; Rasch *et al*. (2024)[233] provide estimates from three climate models performing nominally identical deployment strategies and find values of ERF per unit emission of SS of -0.04 to -0.7 W m^{-2} / Tg SS yr^{-1}. They estimate that to achieve a net negative radiative forcing of approximately -1.8 W m^{-2} (about half the amplitude of that due to a CO_2 doubling) would require a sea salt burden ranging from around 7.5 Tg to 75 Tg of dry sea salt, equivalent to a range of 210 Tg to 2,100 Tg of seawater[234].

228 *Op. cit*. 49.

229 *Op. cit*. 73.

230 *Op. cit*. 10.

231 Stjern *et al*. 2018 Response to marine cloud brightening in a multi-model ensemble. *Atmospheric Chemistry and Physics* **18**, 621–634. See: https://doi.org/10.5194/acp-18-621-2018 (accessed 1 October 2025).

232 *Op. cit.* 231.

233 Rasch *et al*. 2024 A protocol for model intercomparison of impacts of marine cloud brightening climate intervention. *Geoscientific Model Devel*opment **17**, 7963–7994. See: https://doi.org/10.5194/gmd-17-7963-2024 (accessed 1 October 2025).

234 *Op. cit.* 233.

It is worth noting that the ERFs due to SRM are non-unique, insofar as the same ERF and the same reduction in surface temperature can be achieved through very different strategies[235] (which might depend on practical constraints related to deployment. However, even if multiple SRM strategies can in principle generate the same ERF, they may have very different consequences for other aspects of regional climate and the Earth system[236] (see also Chapter 6) so careful consideration of a suite of Earth system measures must be given when assessing the risks of different SRM strategies.

5.2 Impact of SRM on surface temperature

The response of surface temperature to an ERF can be characterised by two main timescales (see Box 1): a 'fast' response that occurs within a few years, and a 'slow' response occurring over many decades that involves gradual heat uptake by the deep ocean[237, 238, 239]. Any SRM deployment would alter the surface temperature within a couple of years. This is much faster than the timescales for mitigation and CDR, so SRM would be the only known method that could begin to reduce surface temperature within years, though it would take longer to confidently detect this signal due to background climate variability (see Section 5.3). The timescale for SRM to affect the climate would therefore mainly be determined by the technical and governance readiness for deployment (see Chapter 3).

As explained in Chapter 2.1 it is uncertain as to how much SRM would be required to hold surface temperature at a target level. Multi-model studies suggest that 8 – 16 Tg SO_2 would need to be delivered to the stratosphere every year to achieve a 1°C cooling of surface temperature[240] via SAI. For context, the 1991 Mt. Pinatubo eruption injected around 18 Tg SO_2 into the stratosphere[241]. Using optimally sized sea salt emissions, injections required to achieve a 1°C cooling via MSB vary by a factor of around 7 between models from around 7 to 50 Tg yr^{-1} of dry sea salt (or around 200 to 1,400 Tg yr^{-1} of seawater assuming 3.5% sea salt content)[242, 243]. If sea salt particles have a size distribution similar to natural sea salt, rather than having sizes that are optimised to affect clouds for MCB, the required injections are around ten times larger[244].

235 *Op. cit*. 48.

236 *Op. cit*. 48.

237 Dickinson R E, Schaudt K J. 1998 Analysis of timescales of response of a simple climate model. *Journal of Climate* **11**, 97–106. See: https://www.osti.gov/biblio/576804 (accessed 1 October 2025).

238 Held *et al*. 2010 Probing the Fast and Slow Components of Global Warming by Returning Abruptly to Preindustrial Forcing. *Journal of Climate* **23**, 2418-2427. See: https://doi.org/10.1175/2009JCLI3466.1 (accessed 1 October 2025).

239 Geoffroy O, Saint-Martin D, Bellon G, Voldoire A, Olivié D J L, Tytéca S. 2013 Transient Climate Response in a Two-Layer Energy-Balance Model. Part II: Representation of the Efficacy of Deep-Ocean Heat Uptake and Validation for CMIP5 AOGCMs. *Journal of Climate* **26**, 1859–1876. See: https://doi.org/10.1175/JCLI-D-12-00196.1. (accessed 1 October 2025).

240 *Op. cit*. 47.

241 Guo S, Bluth G J S, Rose W I, Watson I M, Prata A J. 2004 Re-evaluation of SO_2 release of the 15 June 1991 Pinatubo eruption using ultraviolet and infrared satellite sensors, *Geochemistry, Geophysics, Geosystems* **5**. See: https://doi.org/10.1029/2003GC000654 (accessed 1 October 2025).

242 *Op. cit*. 233.

243 *Op. cit*. 127.

244 *Op. cit*. 132.

5.3 Detectability of the effects of SRM

Any deployment of SRM would require monitoring of its effectiveness at three levels: the forcing agent, the ERF and the subsequent climate change. Effective monitoring will need to be large-scale in nature, require appropriate satellite instruments, and continuity of measurements will need to be maintained for an appropriate period. The ability to detect the effects of SRM in observations will depend on the size of the deployment and for how long it is sustained. For example, a larger SRM-induced ERF would generate a larger surface temperature change that would be detected above internal climate variability sooner. The unavoidable delay in detecting a signal in surface climate, and being able to attribute it to SRM with confidence, would need to be considered in communication strategies with the public. Changes in rainfall would be much more difficult to detect due to their lower signal-to-noise ratio (see Chapter 6.3).

1. **Monitoring of the forcing agent**

   For SAI, the forcing agent would be an enhanced stratospheric aerosol layer. Experience with aerosol from volcanic eruptions and wildfires indicates that this is readily measurable, for example by satellites with instruments that measure the transmission of sunlight through the atmosphere (Figure 7a). However, there are impending data gaps for satellite measurements of the stratosphere[245], so increased efforts would be required to ensure adequate monitoring to observe the effects of SAI on the stratospheric aerosol layer.

   For MCB, monitoring the sea salt aerosol would likely be unfeasible. Individual aspects of clouds (cloud droplet size, areal extent, optical depth) can be monitored from satellites; examples include observed changes in cloud properties from volcano analogue events and changes in IMO regulations for shipping fuels which have reduced the frequency of cloud ship tracks (see Chapter 3). Nevertheless, natural variability (and the impact of changes in aerosol characteristics due to other anthropogenic sources) would make clear attribution of cloud changes to MCB more difficult than detecting aerosol layer changes from SAI.

245 Salawitch *et al*. 2025 The Imminent Data Desert: The Future of Stratospheric Monitoring in a Rapidly Changing World. *Bulletin of the American Meteorological Society*. **106**, E540–E563. See: https://doi.org/10.1175/BAMS-D-23-0281.1. (accessed 1 October 2025).

2. **Monitoring of the forcing**
The driving agent of SRM is primarily the top-of-atmosphere change in absorbed solar radiation which causes an ERF. This could in principle be monitored using earth-radiation budget instruments such as from the Clouds and the Earth's Radiant Energy System (CERES) project. However, large year-to-year internal variability in Earth's energy balance would confound detection and attribution of temporal changes to SRM. One study[246] has estimated the probability of detection of a planetary albedo change from satellite observations, for both deployment and SRM field experiments. As an example, the effect on Earth's energy balance from a three-month SAI experiment in the tropics would need to be three times larger than the 1991 Pinatubo eruption to be confidently detected.

Another study asserts that because of internal variability of stratocumulus cloud decks, detecting MCB forcing might take years[247]. This would present significant difficulties in adjusting seeding strategies in any MCB deployment. In one climate model[248], the estimated ERF from the effect of IMO shipping regulations was 0.13 W m^{-2}; because of natural variability such a small forcing would take around 30 years to detect in climate model simulations[249]. In terms of future monitoring capabilities, there are concerns about the continued reliability of satellite measurements of the Earth's radiation budget, with current planned missions being subject to single points of failure or no guarantee of continuation into the 2030s[250].

3. **Monitoring of climate change**
The global observing system for monitoring surface temperature is currently adequate to monitor year-to-year changes[251]. However, over short timescales, the attribution of change is complicated by internal climate variability (Figure 7c) which can mask externally forced trends over timescales of years to decades[252, 253]. This would also apply to detecting the effects of SRM[254].

246 Seidel D, Feingold G, Jacobson A, Loeb N. 2014 Detection limits of albedo changes induced by climate engineering. *Nature Climate Change* **4**, 93–98. See: https://doi.org/10.1038/nclimate2076 (accessed 1 October 2025).

247 *Op. cit*. 52.

248 Yoshioka M, Grosvenor D P, Booth B B B, Morice C P, Carslaw K S. 2024 Warming effects of reduced sulfur emissions from shipping. *Atmospheric Chemistry and Physics* **24**, 13681–13692. See: https://doi.org/10.5194/acp-24-13681-2024 (accessed 1 October 2025).

249 Forster *et al*. 2016 Recommendations for diagnosing effective radiative forcing from climate models for CMIP6. *Journal of Geophysical Research: Atmosphere* **121**, 12,460–12,475. See: https://doi.org.10.1002/2016JD025320 (accessed 1 October 2025).

250 Mauritsen *et al*. 2025 Earth's energy imbalance more than doubled in recent decades. *AGU Advances*, **6**. See: https://doi.org/10.1029/2024AV001636 (accessed 1 October 2025).

251 Copernicus: Climate Intelligence. See https://climate.copernicus.eu/climate-intelligence (accessed 15 September 2025 (accessed 1 October 2025)..

252 Marotzke J. 2019 Quantifying the irreducible uncertainty in near-term climate projections. *WIREs Climate Change* **10**. See: https://doi.org/10.1002/wcc.563 (accessed 1 October 2025).

253 Romanzini-Bezerra G, Maycock A C. 2024 Projected rapid response of stratospheric temperature to stringent climate mitigation. *Nature Communications* **15**, 6590. See: https://doi.org/10.1038/s41467-024-50648-8 (accessed 1 October 2025).

254 MacMartin D G, Wang W, Kravitz B, Tilmes S, Richter J H, Mills M J. 2019 Timescale for detecting the climate response to stratospheric aerosol geoengineering. *Journal of Geophysical Research: Atmospheres* **124**, 1233–1247. See: https://doi.org/10.1029/2018JD028906 (accessed 1 October 2025).

For example, the estimated effect of recent changes in IMO shipping fuel regulations on surface temperature would require more than a decade to detect against internal variability[255]. Changes in regional climate variables, such as the hydrological cycle or patterns of temperature change, typically require longer datasets to detect changes because internal variability is larger at regional and local scales, and would be more difficult to characterise because of poorer data coverage. NASEM (2021)[256] point out that identifying whether SAI is causing different climate change to that which would have occurred without SAI would be difficult even on multi-decadal timescales[257, 258]. Figure 9 illustrates this issue using modelled surface temperature timeseries at a point location (Beijing, China).

All four panels include an identical background greenhouse gas scenario with SAI applied from the mid-2030s onwards with the goal of holding global average temperature at 1.5°C above pre-industrial conditions. The only difference amongst the four panels of Figure 9 is the representation of internal climate variability. Over periods of 10 years, the different timeseries show contrasting warming or cooling trends before and after SAI is implemented. This highlights the challenge of detecting the effects of SAI on regional surface temperature over short periods, which might also have consequences for the way the effect of SRM is communicated to policymakers and the wider public.

A small number of studies have used climate models to simulate a hypothetical 'feedback controller' approach, where a model is treated as pseudo-observations and the SRM strategy in the model is adjusted in near real-time with a goal of achieving pre-defined climate targets without prior knowledge of a 'no geoengineering' counterfactual state[259].

255 *Op. cit*. 248.

256 *Op. cit*. 21.

257 *Op. cit*. 254.

258 Lee *et al.* 2021 Future global climate: scenario-based projections and near-term information. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: *Cambridge University Press.* See: https://doi.org/10.1017/9781009157896.006 (accessed 1 October 2025).

259 Jackson L S *et al*. 2015 Assessing the controllability of Arctic sea ice extent by sulfate aerosol geoengineering. *Geophysical Research Letters* **42**, 1223–1231. See: https://doi.org/10.1002/2014GL062240 (accessed 1 October 2025).

While this is closer to what would occur in the real world and the conditions under which policy decisions would need to be made, some of the 'automated' feedback-controller loops for SRM[260, 261, 262] implemented in climate models use pre-calculated information about how the model responds to different SRM strategies that we do not know for the real world. The inter-model variability in the injection latitudes deemed 'optimal' by the automation strategy shows considerable variability.

4. **Possible interaction of SAI with volcanic eruptions**
Since volcanic eruptions occur sporadically, it is likely that at some point under sustained SAI deployment over at least a few decades, a large explosive tropical volcanic eruption would occur causing additional effects on surface climate for a few years. Modelling studies show that the presence of an enhanced stratospheric aerosol layer from SAI would reduce the lifetime of the volcanic sulfate aerosol and reduce the magnitude of its ERF and the associated global surface cooling response compared to the same eruption occurring in the absence of SAI[263].

Following a large tropical volcanic eruption, SAI deployment could be temporarily paused or the SAI strategy altered with a goal of ameliorating additional climatic effects caused by the eruption[264]. However, similar issues of detectability and attribution would apply to distinguishing the relative effects of SAI and the eruption.

In summary, the combination of the uncertain ERF, the uncertain total anthropogenic forced trend in surface temperature (including SRM and other climate forcings), and the difficulties of detecting climate signals over short periods, would present complex challenges for governance in the event of SRM deployment.

260 Kravitz *et al*. 2017 First simulations of designing stratospheric sulfate aerosol geoengineering to meet multiple simultaneous climate objectives. *Journal of Geophysical Research: Atmospheres* **122**, 12,616–12,634. See: https://doi.org/10.1002/2017JD026874 (accessed 1 October 2025).

261 Henry *et al*. 2023 Comparison of UKESM1 and CESM2 simulations using the same multi-target stratospheric aerosol injection strategy. *Atmospheric Chemistry and Physics* **23**, 13369-13385. See: https://doi.org/10.5194/acp-23-13369-2023 (accessed 1 October 2025).

262 Wells *et al*. 2024 Identifying climate impacts from different stratospheric aerosol injection strategies in UKESM1. *Earth's Future* **12**. See: https://doi.org/10.1029/2023EF004358 (accessed 1 October 2025).

263 Laakso A, Kokkola H, Partanen A-I, Niemeier U, Timmreck C, Lehtinen KEJ, Hakkarainen H, Korhonen H. 2016 Radiative and climate impacts of a large volcanic eruption during stratospheric sulfur geoengineering. *Atmospheric Chemistry and Physics* **16**, 305–323. See: https://doi.org/10.5194/acp-16-305-2016 (accessed 1 October 2025).

264 Quaglia I, Visioni D, Bednarz E M, MacMartin D G, Kravitz B. 2024 The potential of Stratospheric Aerosol Injection to reduce the climatic risks of explosive volcanic eruptions. *Geophysical Research Letters* **51**, e2023GL107702. See: https://doi.org/10.1029/2023GL107702 (accessed 1 October 2025).

5.4 Effects of cessation of SRM

As noted in Chapter 2, to maintain surface cooling, aerosol-based SRM techniques would require continued deployment. If SRM was significantly reduced in a sudden manner or removed altogether and not reinstated, the surface climate system would rapidly return to the baseline scenario without SRM (see the period after 2070 in Figure 8). Box 1 explained that upon sudden cessation of SRM, at least half of the surface warming being offset would reappear within the first decade. Therefore, a sudden cessation or a rapid sustained reduction of SRM that is offsetting 0.4°C or more of surface temperature increase would result in decadal warming rates larger than those observed in recent decades and which are larger than typical internal variability[265]. This rapid surface temperature warming could lead to large-scale impacts that are referred to as 'termination effects'[266] including record-breaking extremes[267]. A short-term cessation or reduction in SRM (eg, for a few months to a year) which is subsequently reinstated is not expected to cause strong termination effects.

Termination effects have the potential to push many natural and human systems outside of their adaptation limits and causing some ecosystems to collapse[268] (see also Chapter 7). These issues have led researchers to consider peak-shaving scenarios (Figure 3), in which SRM is used temporarily to reduce surface temperature while strong mitigation and CDR are scaled up, to avoid severe termination effects[269]; in principle a gradual phase out could also be administered for any SRM scenario with coordinated global action. Any non-global action that resulted in a sudden reduction or cessation of SAI in one hemisphere, eg because some countries cease deployment, would cause additional termination effects in some regions. This is because regional impacts depend on how the SRM aerosol is distributed. These are discussed in Chapter 6.

265 McKenna C M, Maycock A C, Forster P M, Smith C J, Tokarska K B 2021 Stringent mitigation substantially reduces risk of unprecedented near-term warming rates. *Nature Climate Change* **11**, 126–131. See: https://doi.org/10.1038/s41558-020-00957-9 (accessed 1 October 2025).

266 Parker A, Irvine P J. 2018 The Risk of Termination Shock From Solar Geoengineering. *Earth's Future* **6**, 456–467. See: https://doi.org/10.1002/2017EF000735 (accessed 1 October 2025).

267 Fischer E M, Sippel S, Knutti R. 2021 Increasing probability of record-shattering climate extremes. *Nature Climate Change* **11**, 689–695. See: https://doi.org/10.1038/s41558-021-01092-9 (accessed 1 October 2025).

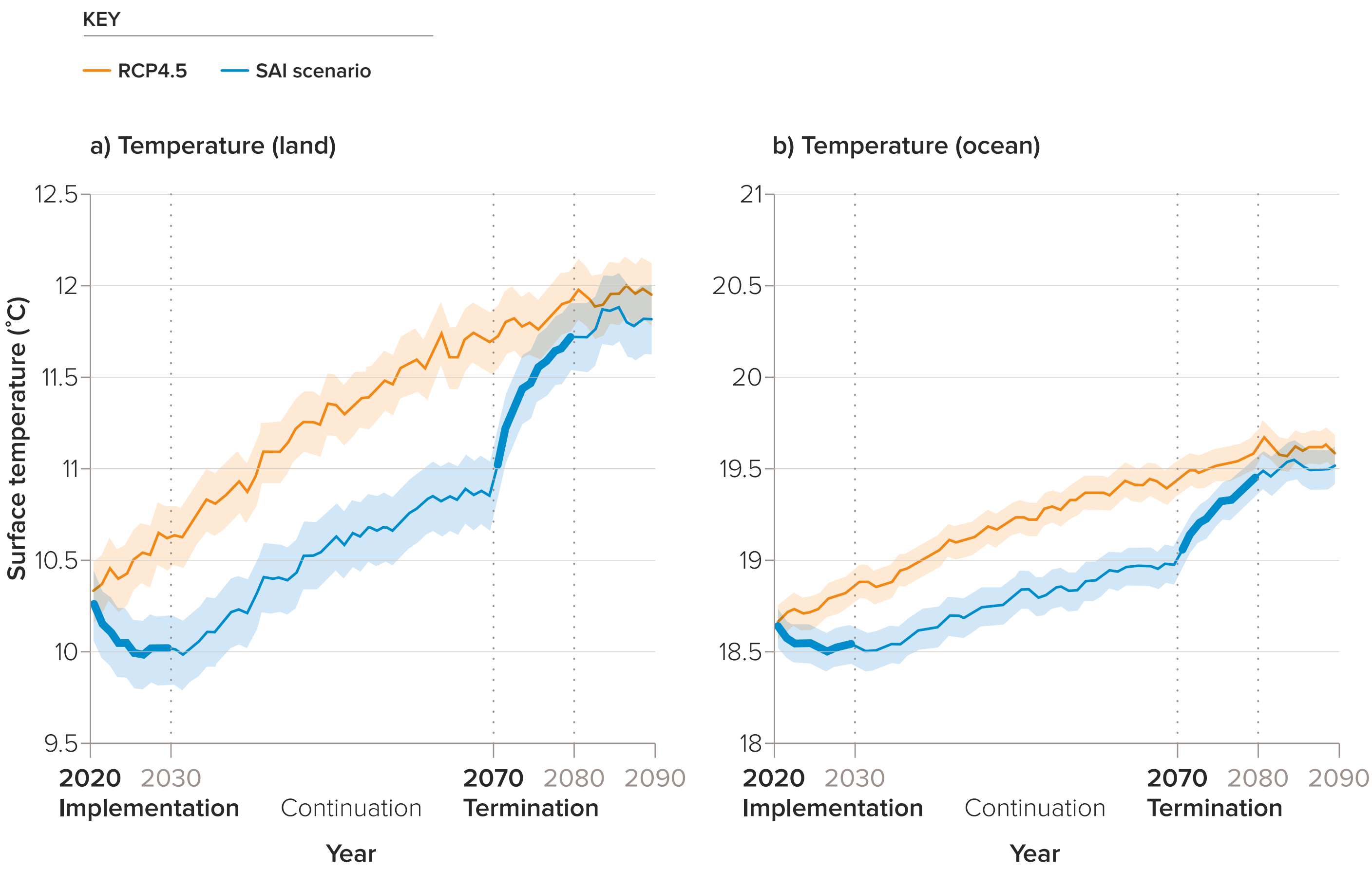
268 Trisos C H, Amatulli G, Gurevitch J, Robock A, Xia L, Zambri B 2018 Potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination. *Nature Ecology and Evolution* 2, 475–482. See: https://doi.org/10.1038/s41559-017-0431-0 (accessed 1 October 2025).

269 *Op. cit.* 47.

FIGURE 8

Timeseries of multi-model average surface temperature over (a) global land and (b) global ocean regions from 2020 – 2090.

The orange line shows a baseline climate scenario (RCP4.5 – see Annex B) that includes increases in CO_2 emissions from 2020 up to around 2050, with decreasing but still positive CO_2 emissions thereafter: this scenario produces continued global warming during the 21st century. The blue line shows a hypothetical SAI scenario (GeoMIP G4), applied in addition to RCP4.5, starting in 2020 (labelled 'implementation') with an emission of 5 Tg SO_2 per year into the equatorial lower stratosphere, which is held constant until 2070 and then suddenly halted ('termination') thereafter. The shading indicates one standard deviation above and below the multi-model average based on the spread across four climate models which each provide three simulations. The bold blue lines show the climate response for the ten-year periods immediately following implementation and termination.



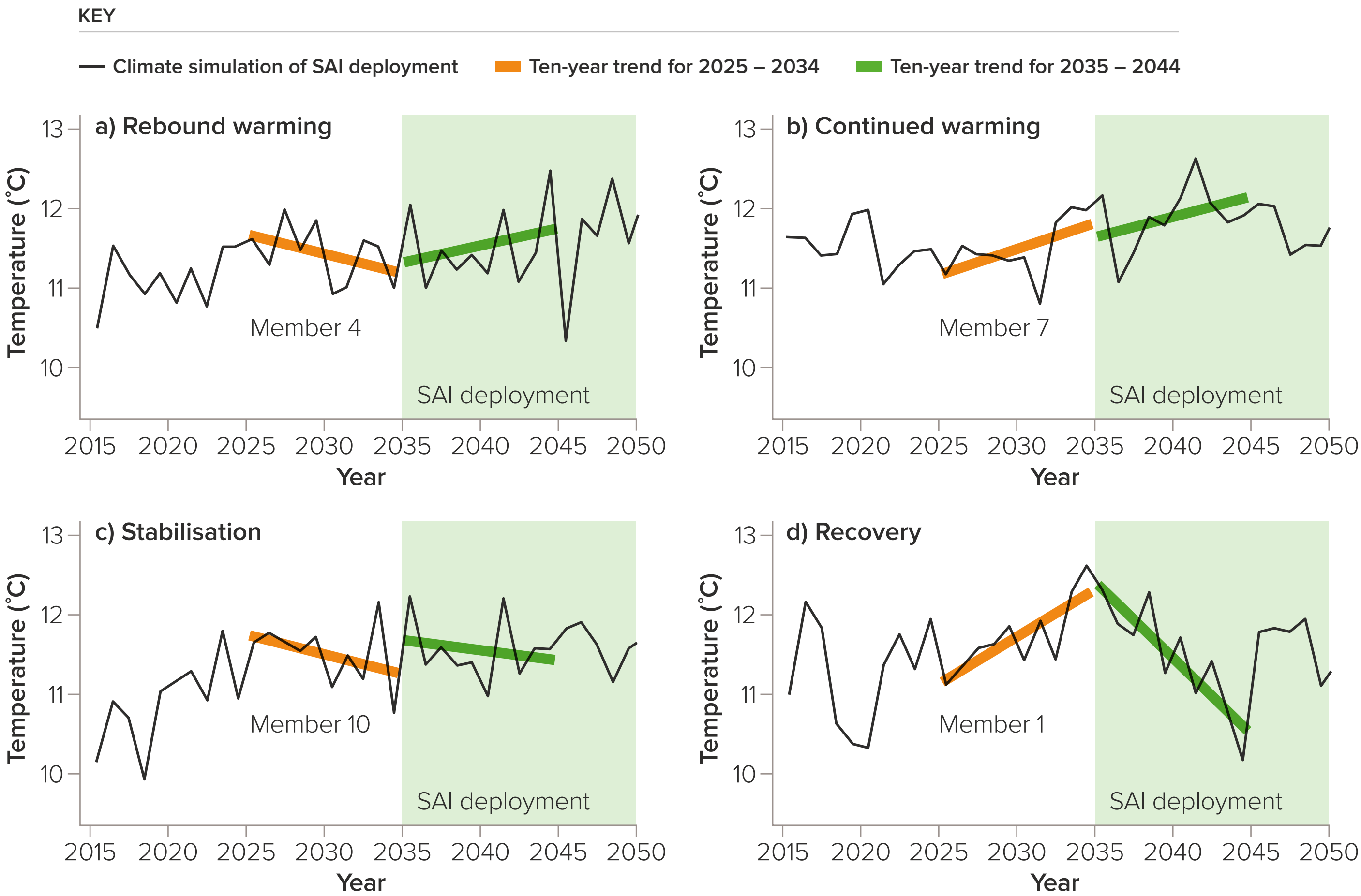
Source: Adapted from Trisos *et al*. (2018)[270].

270 *Op. cit*. 268.

FIGURE 9

Climate model simulations of surface temperature trends for Beijing, China.

Each panel displays a single climate simulation (black line) deploying SAI in a manner designed to hold global mean temperature at 1.5°C above pre-industrial conditions relative to a baseline scenario (SSP 2-4.5, see Annex B). All four panels follow an identical scenario up to SAI deployment (white, up to 2035) and following SAI deployment (green, 2035 onwards). They differ only in their sequence of internal climate variability. The differences between the black lines in the four panels gives an impression of how natural climate variability could affect the detectability of SRM at regional scales. Ten-year trends are shown for the period 2025 to 2034 (bold orange) and 2035 to 2044 (bold green). In comparing pre- and post-SRM temperature trends, the four selected simulations broadly show what may be perceived as (A) ‘Rebound warming’, (B) ‘continued warming’, (C) ‘temperature stabilisation’ and (D) ‘climate recovery’ following the deployment of SRM.



Source: Figure adapted from Keys *et al*. (2022)[271].

271 Keys P W, Barnes E A, Diffenbaugh N S, Hurrell J W, Bell C M. 2022 Potential for perceived failure of stratospheric aerosol injection deployment. *Proceedings of the National Academy of Sciences of the United States of America* **119**. See: https://doi.org/10.1073/pnas.2210036119 (accessed 1 October 2025).

What are the key risks and effects on regional climate from the use of SRM?

There is little doubt that future climate change will expose the planet to significant and increasingly wide-ranging impacts and risks; the impacts and risks of SRM must be considered relative to these. Some of the impacts that might be expected in the UK are discussed in Box 3.

6.1 Regional temperature

Climate modelling studies have demonstrated that both SAI[272] and MCB[273] can be effective at reducing global-mean temperatures (see Chapter 5). However, global warming has important regional characteristics: the Arctic is warming 3 to 4 times faster than the rest of the planet[274] and the land is warming faster than the ocean[275]. While SRM may be able to reduce global temperatures by a specified amount, the different mechanisms underlying SRM cooling and greenhouse gas warming mean SRM cannot perfectly offset greenhouse gas warming at regional (country to continental) scales (Figures 6.1 and 6.2).

Climate model simulations robustly show that SAI cools the Arctic more than the rest of the planet[276, 277] (see also Figure 10f) and is thus effective at countering Arctic amplification from global warming, though it is not always perfectly offset (Figure 10 panels d and e). Early SAI modelling studies focused on equatorial injection, as aerosols injected at the equator persist longer in the stratosphere due to the characteristics of stratospheric circulation. One feature of equatorial injection is that it leads to a less Arctic-amplified cooling resulting in more residual Arctic warming relative to a multi-location off-equatorial strategy (eg 30 degrees North and South)[278, 279].

If MCB is deployed in distinct cloud seeding regions (see Chapter 3), it would have to produce a large local forcing to have a global impact. This would potentially induce large regional climate changes, including warming in some areas through atmospheric teleconnections (climate links between geographically separated regions; Figure 6.2)[280, 281]. However, this may be avoided by having a more distributed deployment[282].

272 *Op. cit*. 166.

273 *Op. cit*. 231.

274 Rantanen *et al*. 2022. The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth and Environment*, **3**, 168. See: https://doi.org/10.1038/s43247-022-00498-3 (accessed 1 October 2025).

275 Byrne M P, O'Gorman P A. 2018. Trends in continental temperature and humidity directly linked to ocean warming. *Proceedings of the National Academy of Sciences* **115**, 4863–4868. See: https://doi.org/10.1073/pnas.1722312115 (accessed 1 October 2025).

276 *Op. cit.* 181.

277 *Op. cit.* 261.

278 *Op. cit*. 262.

279 *Op. cit*. 48.

280 *Op. cit*. 127.

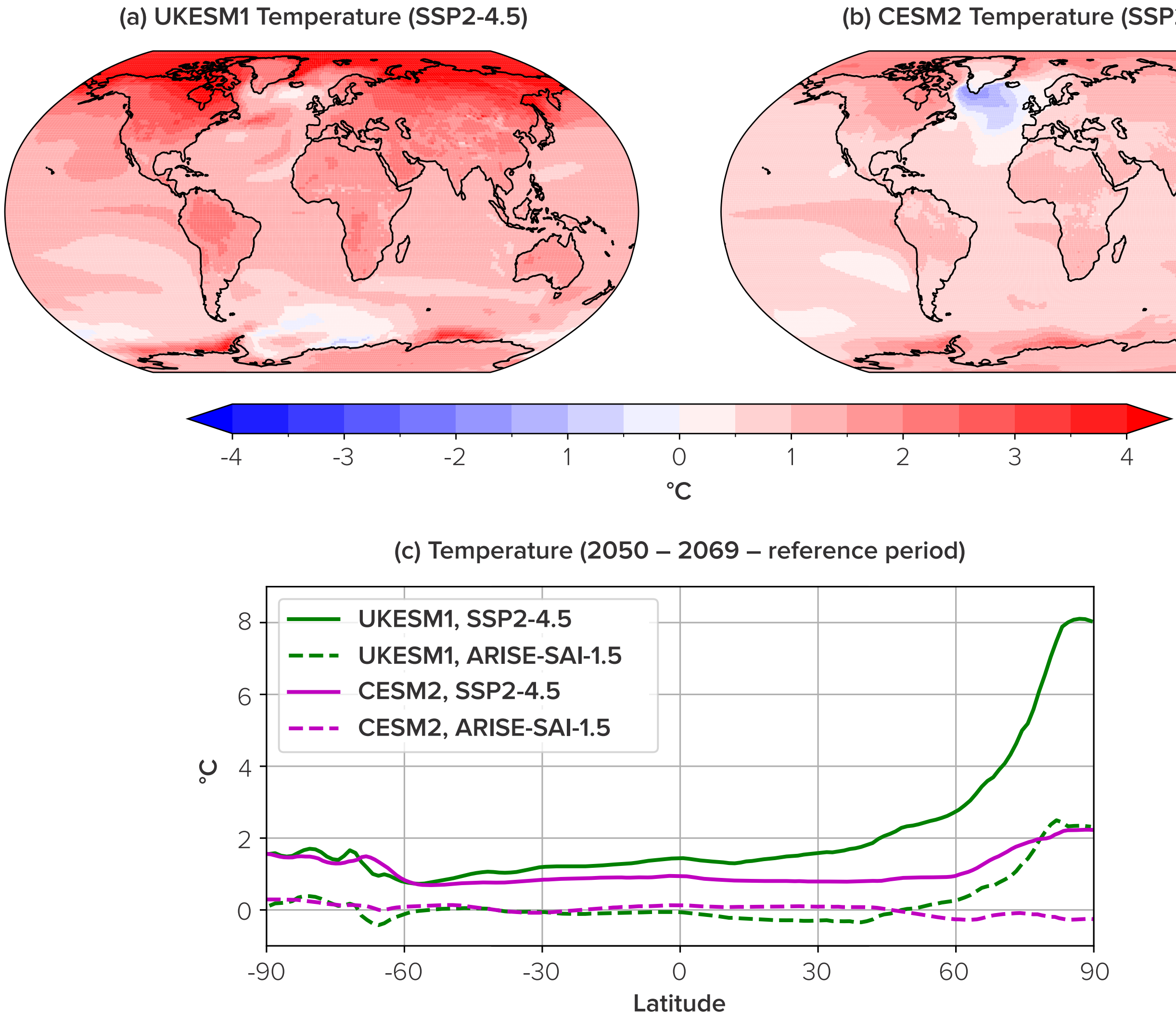
281 *Op. cit*. 233.

282 Kravitz *et al*. 2013. Climate model response from the geoengineering model intercomparison project (GeoMIP). *Journal of Geophysical Research: Atmospheres* **118**, 8320– 8332. See: https://doi.org/10.1002/jgrd.50856 (accessed 1 October 2025).

FIGURE 10

Variation in existing climate models.

(a,b) Annual-mean surface temperature change in 2050 – 2069 relative to 1.5°C above pre-industrial baseline for two state-of-the-art Earth System Models UKESM1 and CESM2 and for middle-of-the-road greenhouse gas emission scenario (SSP2-4.5 – see Annex B). (c) Zonal-mean surface temperature for both models and scenarios (solid lines shows SSP2-4.5 warming, dashed show the effect of adding SAI).



Source: Henry *et al.* 2023[283].

283 *Op. cit.* 261.

FIGURE 10 (CONTINUED)

(d,e) Surface temperature change relative to target for an SAI scenario aiming to stabilise warming at 1.5° above pre-industrial baseline (ARISE-SAI-1.5) where injection occurs at 15 and 30° North and South.
(f) Temperature (ARISE-SAI-1.5 minus SSP2-4.5 (2050 – 2069)).

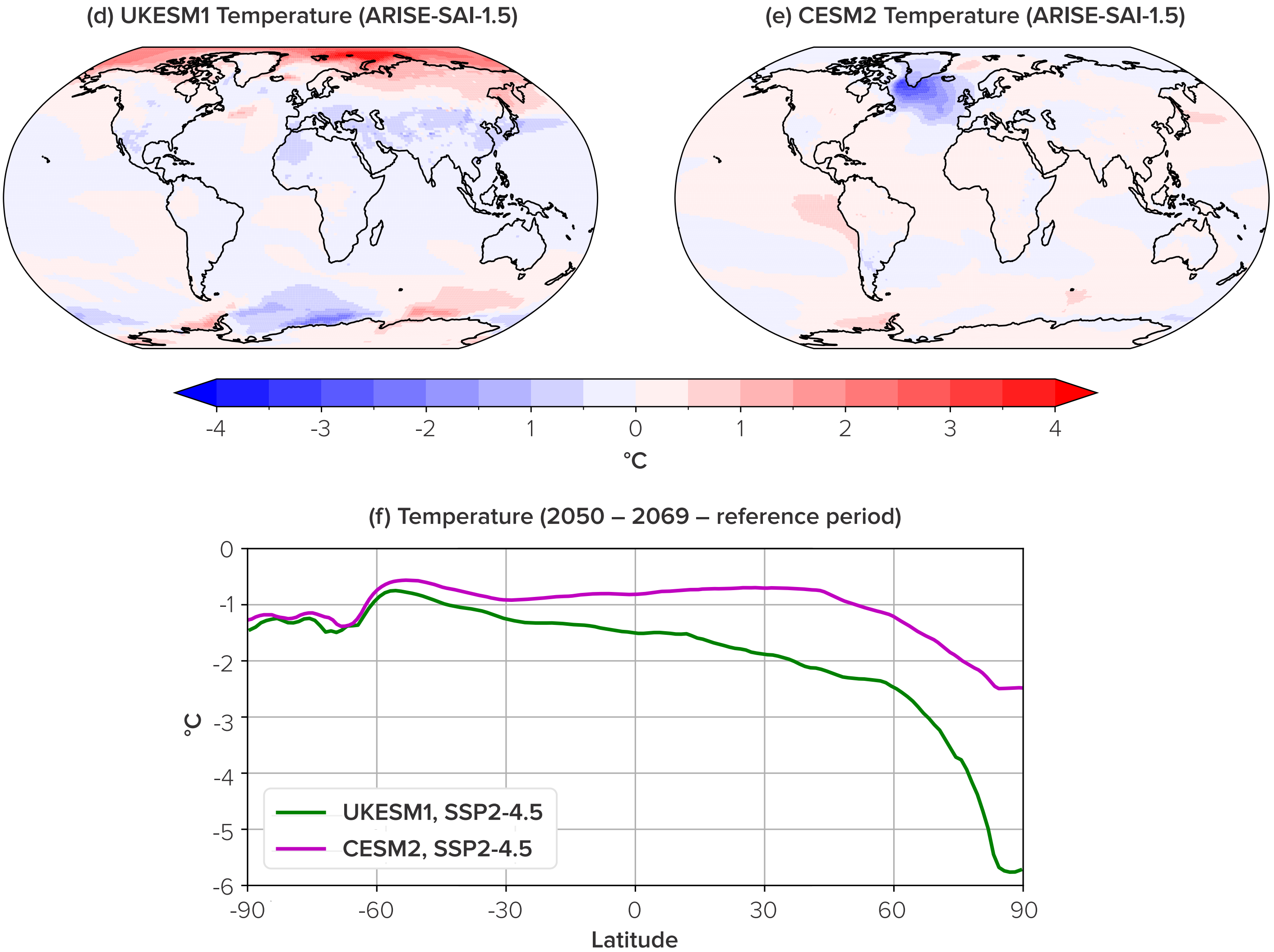
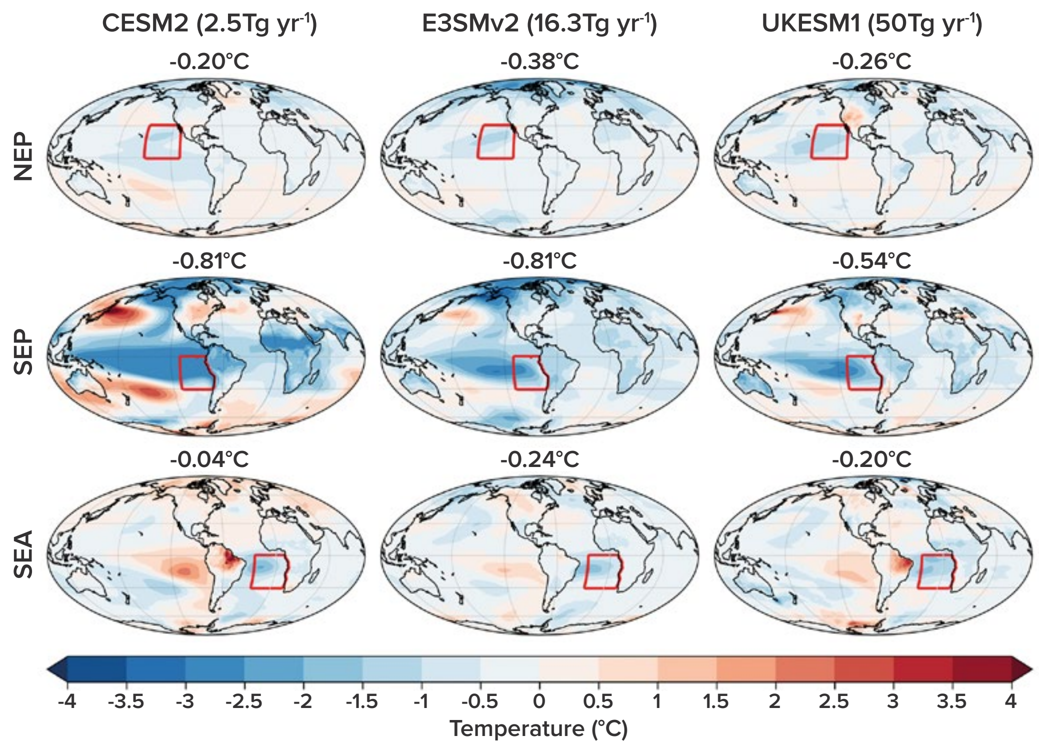


FIGURE 11

Annual-mean surface temperature response of CESM2, E3SMv2, and UKESM1 Earth System Models to MCB applied to give a global radiative forcing of -1.8 W m^{-2} for CESM2 and E3SMv2 and -2.3 W m^{-2} for UKESM1 when applied over three different regions.

The responses (the different rows) are for modelled deployments over SEP = South East Pacific, SEA = South East Atlantic, NEP = North East Pacific. The resulting global-mean temperature change for each model and each area of application is shown above each frame, and the sea salt aerosol injection rate required to achieve the given radiative forcing in each model is shown at top of each column.



Source: Adapted from Rasch *et al.* (2024)[284].

284 *Op. cit.* 233.

Figure 11 shows the temperature response to MCB applied in regions of extensive marine stratocumulus in three leading ESMs. Such regions are particularly susceptible to cloud brightening, and thus most likely to produce a large radiative forcing (see Chapter 3). The spatial pattern of the simulated temperature response depends strongly on the area of deployment (the difference between the rows), but all the models produce broadly similar spatial response patterns for a particular deployment (the similarity among models within rows). This similarity in the model responses suggests that the teleconnections and remote temperature responses are relatively consistent between models.

Note that while stratocumulus regions represent optimum sites for producing a large radiative forcing from MCB, not all such regions would be good targets for MCB deployment. For example, targeting the SEA region tends to warm the Amazon (bottom row of Figure 11). The models also show a significant reduction in precipitation over the Amazon[285, 286] leading to significant Amazon dieback (Chapter 7); thus, subsequent modelling studies have chosen not to deploy in the SEA region. Similarly, targeting the SEP region (middle row of Figure 11) produces a strong La Niña-like response (a phase of ENSO), and a global pattern of temperature response that is very different to that due to greenhouse gas driven warming. This would lead to strong residual regional climate changes.

It is reassuring to see some consistency between the pattern of the temperature response to different MCB deployments simulated in different models (Figure 11). However, it is important to note that while a similar global-mean radiative forcing is achieved for all three models and three regions, the global temperature response (shown at the top of each panel) and the necessary aerosol injection rate (shown at the top of each column) differs significantly between models and between perturbation regions, due to their different sensitivities to aerosol perturbations. The range of aerosol injection rates and global temperature responses for similar global radiative forcings shown in Figure 11 are a reflection of the diversity in the representation of aerosol-cloud interactions in climate models more generally[287].

In summary, SAI with similar amounts of aerosol in both hemispheres would cool surface temperatures with a pattern which broadly matches that of warming from greenhouse gases, though some residual undercooling of the Arctic is possible. MCB in distinct seeding regions can induce large remote temperature and precipitation changes, including warming in the Amazon and strong La Niña-like responses.

285 Jones A, Haywood J M, Boucher O. 2009 Climate impacts of geoengineering marine stratocumulus clouds. *Journal of Geophysical Research* **114**. See: https://doi.org/10.1029/2008JD011450 (accessed 1 October 2025).

286 *Op. cit.* 132.

287 *Op. cit.* 10.

6.2 Regional precipitation

SRM is robustly shown to reduce global average precipitation and to reduce it more per degree of cooling than the equivalent reduction in greenhouse gas concentrations[288, 289]. This is because the radiative forcing from the reduction in sunlight has no compensating impact on the vertical temperature structure of the atmosphere[290]. Thus precipitation will be lower in a world with SRM compared to a world without it, at a given target temperature[291, 292, 293].

Regional precipitation changes in global warming scenarios without SRM vary widely across climate models due to uncertainties in atmospheric circulation changes, climate sensitivity, and parameterisations of cloud, aerosol, and land processes (Figure 12 panels a and b). In a single climate model, internal climate variability can play a dominant role in regional precipitation change uncertainty[294].

The addition of SRM (in this case SAI) further complicates the picture, especially as the pattern and magnitude of precipitation changes vary across approaches and SRM strategies due to differing responses in atmospheric heating imbalances and radiative budgets[295] and circulation changes[296]. Even when multiple large scale temperature metrics are nearly stabilised using SAI in the 'ARISE-SAI-1.5' experiments[297], considerable uncertainty remains in the regional precipitation responses[298] (Figure 12 panels c and d). Diversity in regional precipitation responses is a common feature across all SRM scenarios[299, 300].

288 Bala G, Duffy P B, Taylor K E. 2008 Impact of geoengineering schemes on the global hydrological cycle. *Proceedings of the National Academy of Sciences of the United States of America USA* **105**, 7664–7669. See: https://doi.org.10.1073/pnas.0711648105 (accessed 1 October 2025).

289 *Op. cit*. 56.

290 Seeley J T, MacMartin D G, Keutsch F N 2021 Designing a radiative antidote to CO_2. *Geophysical Research Letters*, **48**. See: https://doi.org/10.1029/2020GL090876 (accessed 1 October 2025).

291 Niemeier U, Schmidt H, Alterskjær K, Kristjánsson JE. 2013 Solar irradiance reduction via climate engineering: Impact of different techniques on the energy balance and the hydrological cycle. *JGR Atmosphere* **118**, 11,905–11,917. See: https://doi.org/10.1002/2013JD020445 (accessed 1 October 2025).

292 *Op. cit.* 288.

293 *Op. cit*. 180.

294 Deser *et al*. 2012 Uncertainty in climate change projections: the role of internal variability. *Climate Dynamics* **38**, 527–546. See: https://doi.org/10.1007/s00382-010-0977-x (accessed 1 October 2025).

295 *Op. cit.* 291.

296 *Op. cit*. 167.

297 Richter *et al.* 2023 Stratospheric aerosol injection in CESM2-WACCM6: initial results from the GeoMIP G7 experiment. *Journal of Advances in Modeling Earth Systems* **15**, e2023MS003714. See: https://doi.org/10.1029/2023MS003714 (accessed 1 October 2025).

298 *Op. cit*. 261.

299 Simpson *et al*. 2019 The regional hydroclimate response to stratospheric sulfate geoengineering and the role of stratospheric heating. *Journal of Geophysical Research: Atmospheres* **124**, 12587–12616. See: https://doi.org/10.1029/2019JD031093 (accessed 1 October 2025).

300 Kravitz *et al*. 2019 Comparing surface and stratospheric impacts of geoengineering with different SO_2 injection strategies. *Journal of Geophysical Research: Atmos*pheres **124**, 7900–7918. See: https://doi.org10.1029/2019JD030329 (accessed 1 October 2025).

The balance between precipitation and evaporation is important for the biosphere, and evaporation is also influenced by climate change and SRM. Evaporation changes are typically more uniform than precipitation changes, and evaporation increases in a warming world are better offset by SAI than precipitation changes[301]. In summary, SRM is robustly shown to reduce global average precipitation and reduces it more per degree of cooling than the equivalent reduction in greenhouse gas concentrations. Regional precipitation changes in global warming scenarios without SRM vary widely across climate models. The addition of SRM further complicates the picture, as the pattern and magnitude of precipitation changes vary across models, SRM techniques and SRM strategies. Diversity in regional precipitation responses is a common feature across all SRM scenarios.

6.2.1 Intertropical Convergence Zone

The Intertropical Convergence Zone (ITCZ) is a belt of high precipitation situated near the equator and is subject to latitudinal shifts under certain SRM scenarios. The ITCZ moves north-south with the seasonal cycle. It stays in the summer hemisphere, and is responsible for much of the seasonal monsoon precipitation upon which equatorial areas such as the Sahel, the Indian sub-continent, South East Asia, and South America depend.

In future climate scenarios, ESMs have low agreement on precipitation change over tropical land even in the absence of SRM, underlining uncertainties inherent in these processes[302].

The injection of stratospheric aerosols in one hemisphere (either deliberately or by a volcanic eruption) cools that hemisphere but not the other, shifting the ITCZ towards the warmer hemisphere, leading to droughts in the cooler hemisphere. Northern hemisphere volcanic eruptions have, for example, been shown to be a leading cause of droughts in the Sahel. Similarly, if SAI was applied in one hemisphere it could lead to impactful crop failures[303] (see Chapters 4 and 7). These impacts could be avoided by ensuring a hemispherically symmetric deployment scenario as per those modelled in the many different multi-model scenarios that have been developed by GeoMIP[304].

Early modelling of equatorial SAI[305] led to significant reductions in precipitation around the equator. This undesirable side effect is significantly diminished with injection in subtropical areas instead of the equator[306]. The same injection strategy in terms of injection height and latitude can lead to ITCZ shifts of different magnitude in different models[307, 308].

301 *Op. cit.* 299.

302 *Op. cit.* 2.

303 *Op. cit.* 179.

304 *Op. cit.* 49.

305 *Op. cit.* 181.

306 *Op. cit.* 262.

307 Zhang Y, MacMartin D G, Visioni D, Bednarz E M, Kravitz B. 2024 Hemispherically symmetric strategies for stratospheric aerosol injection. *Earth System Dynamics* **15**, 191–212. See: https://doi.org/10.5194/esd-15-191-2024 (accessed 1 October 2025).

308 *Op. cit.* 48.

However, within one model, it is possible to control the global-mean temperature while minimising the changes in the ITCZ by adjusting the injection amount in each hemisphere[309].

The balance of evidence suggests that injection of aerosols off the equator and of approximately equal amounts in both hemispheres would be required to minimise undesirable shifts in the ITCZ. Understanding to what extent the ITCZ and its associated precipitation can be controlled by adjusting aerosol injection in each hemisphere is still a topic of research.

For MCB, the ITCZ is generally found to shift away from the hemisphere in which it is applied, but details on how injection in different regions, and at different latitudes, affect the ITCZ is still an open research question.

6.2.2 Monsoon precipitation

In monsoon regions, the majority of the annual total rainfall is supplied by the summer monsoon. The Indian and West African summer monsoons deliver around 80% of the total annual rainfall in these regions. Around 60% of the world's population live in the Northern Hemisphere land monsoon regions, so small changes in monsoon characteristics can result in considerable socio-economic impacts.

Changes in the monsoons are tied to changes in the ITCZ and in the temperature gradient between land and ocean. Northern Hemisphere monsoon precipitation is expected to increase under global warming, as the Northern Hemisphere warms relative to the South, and the land warms relative to the ocean, causing a northward shift of the ITCZ and the monsoons[310]. Simulated monsoon responses to SRM can vary between models, as do the simulated responses to all anthropogenic forcing, since the representation of the monsoons is a long-standing challenge in climate science[311].

309 Lee W, MacMartin D, Visioni D, Kravitz B. 2020 Expanding the design space of stratospheric aerosol geoengineering to include precipitation-based objectives and explore trade-offs. *Earth System Dynamics* **11**, 1051–1072. See: https://doi.org/10.5194/esd-11-1051-2020 (accessed 1 October 2025).

310 Douville *et al*. 2021: Water Cycle Changes. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte *et al*. (eds.)]. *Cambridge University Press*, Cambridge, United Kingdom and New York, NY, USA, pp. 1055–1210, See: https://doi.org/10.1017/9781009157896.010 (accessed 1 October 2025).

311 IPCC. 2021 Annex V: Monsoons [Cherchi A, Turner A (eds.)] In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte *et al*. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, USA, 2193–2204. See: https://doi.org/10.1017/9781009157896 (accessed 1 October 2025).

SAI is expected to weaken the monsoon circulations and decrease monsoon precipitation[312, 313, 314, 315], although there is a degree of dependence on deployment strategy and model to this: globally-coordinated deployments can result in insignificant precipitation responses over India, for example Figure 12 panels d and e. Tropical teleconnections mean that MCB can lead to large modelled precipitation changes in some regions; for example, large increases in Indian monsoon precipitation in response to east Pacific deployments, or large decreases in the South American monsoon in response to east Atlantic deployments[316]. MCB strategies can also lead to increased precipitation over Sub-Saharan Africa and India[317, 318, 319, 320, 321].

6.2.3 Tropical cyclones

Tropical cyclones are expected to have increased rainfall rates and intensities under anthropogenic warming as a result of higher sea surface temperatures and higher humidity supplying more energy to the storms. Additionally, the proportion of tropical cyclones reaching very intense levels is projected to increase, though changes in the total number of storms are less certain. Finally, sea level rise will cause higher coastal inundation levels when tropical cyclones do occur, all else being equal[322].

Model projections of global SAI consistently show a decrease in tropical cyclone intensity[323]. Northern hemisphere SAI has been shown to decrease North Atlantic storm frequency, whereas southern hemisphere SAI increases North Atlantic storm frequency relative to global SAI[324]. Latham *et al*. (2012)[325] showed that, in principle, MCB could lower sea surface temperatures in tropical cyclone genesis regions thus lowering their intensity.

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312 *Op. cit*. 81.

313 Krishnamohan K S, Bala G, Cao L, Caldeira K. 2022 Sensitivity of tropical monsoon precipitation to the latitude of stratospheric aerosol injections. *Climate Dynamics* **59**, 151-168. See: https://doi.org/10.1007/s00382-021-06121-z (accessed 1 October 2025).

314 *Op. cit*. 299.

315 Da-Allada *et al*. 2020 Changes in west African summer monsoon precipitation under stratospheric aerosol geoengineering. *Earth's Future* **8**. See: https://doi.org/10.1029/2020EF001595 (accessed 1 October 2025).

316 *Op. cit*. 233.

317 *Op. cit*. 132.

318 *Op. cit*. 285.

319 Latham *et al*. 2012 Marine cloud brightening. *Philosophical Transactions of the Royal Society A:* Mathematical, *Physical and Engineering Sciences* **370**, 4217–4262. See: https://doi.org/10.1098/rsta.2012.0086 (accessed 1 October 2025).

320 Alterskjær *et al.* 2013 Geoengineering Model Intercomparison Project (GeoMIP): Initial analysis of G3 and G4 simulations for cirrus cloud response and climate impacts. *Journal of Geophysical Research: Atmospheres* **118**, 101–118. See: https://doi.org/10.1002/jgrd.50766 (accessed 1 October 2025).

321 *Op. cit*. 231.

322 *Op. cit*. 2.

323 *Op. cit*. 56.

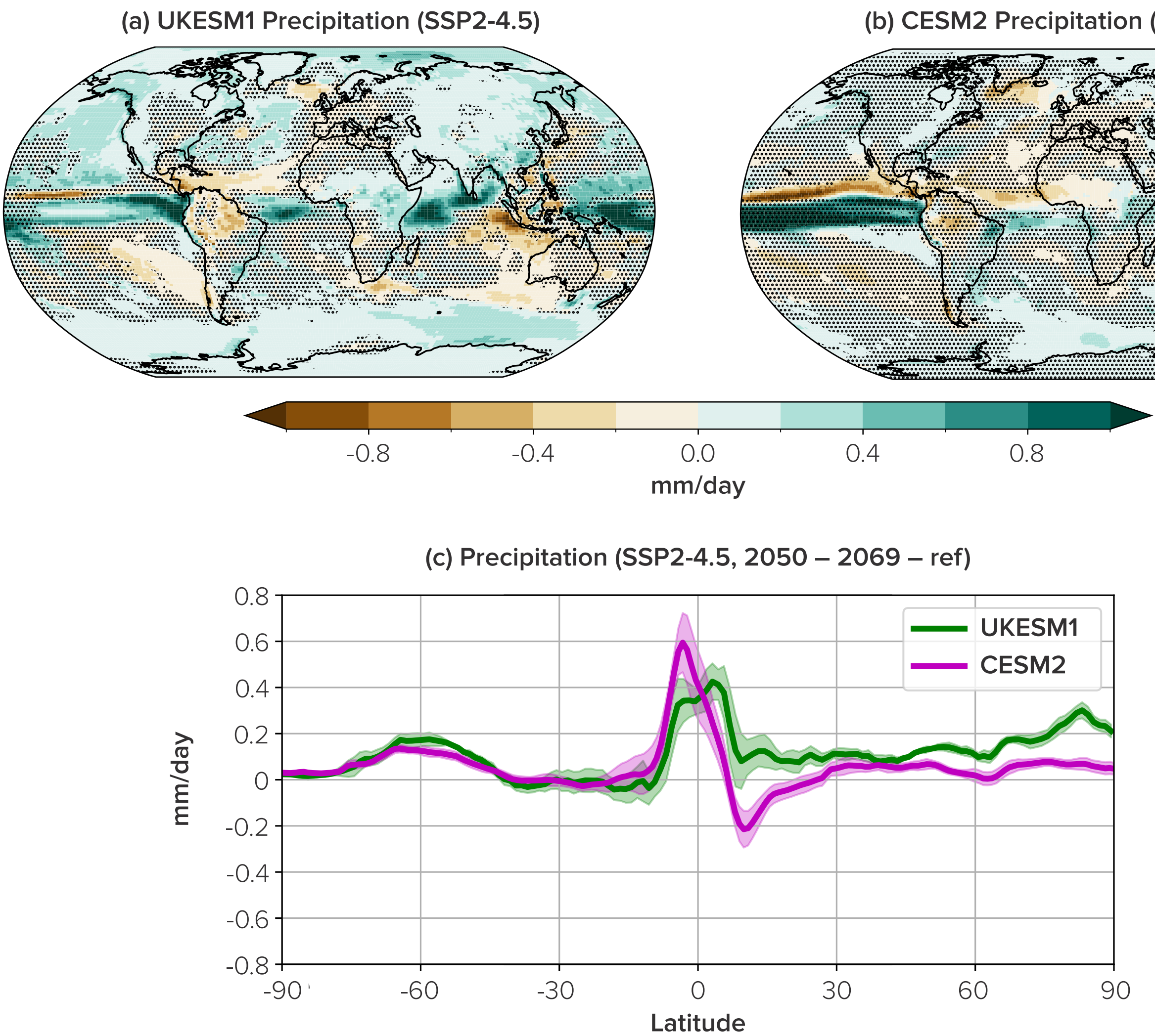
324 Jones *et al.* 2017 Impacts of hemispheric solar geoengineering on tropical cyclone frequency. *Nature Communications* **8**, 1382. See: https://doi.org/10.1038/s41467-017-01606-0 (accessed 1 October 2025).

325 *Op. cit*. 319.

FIGURE 12

Annual-mean precipitation change (in mm/day) in 2050 – 2069 for SSP2-4.5 (a – c) and ARISE-SAI-1.5 (d – f) for UKESM1 and CESM2 relative to each model's reference period (2020 – 2039 for CESM2 and 2014 – 2033 for UKESM1).

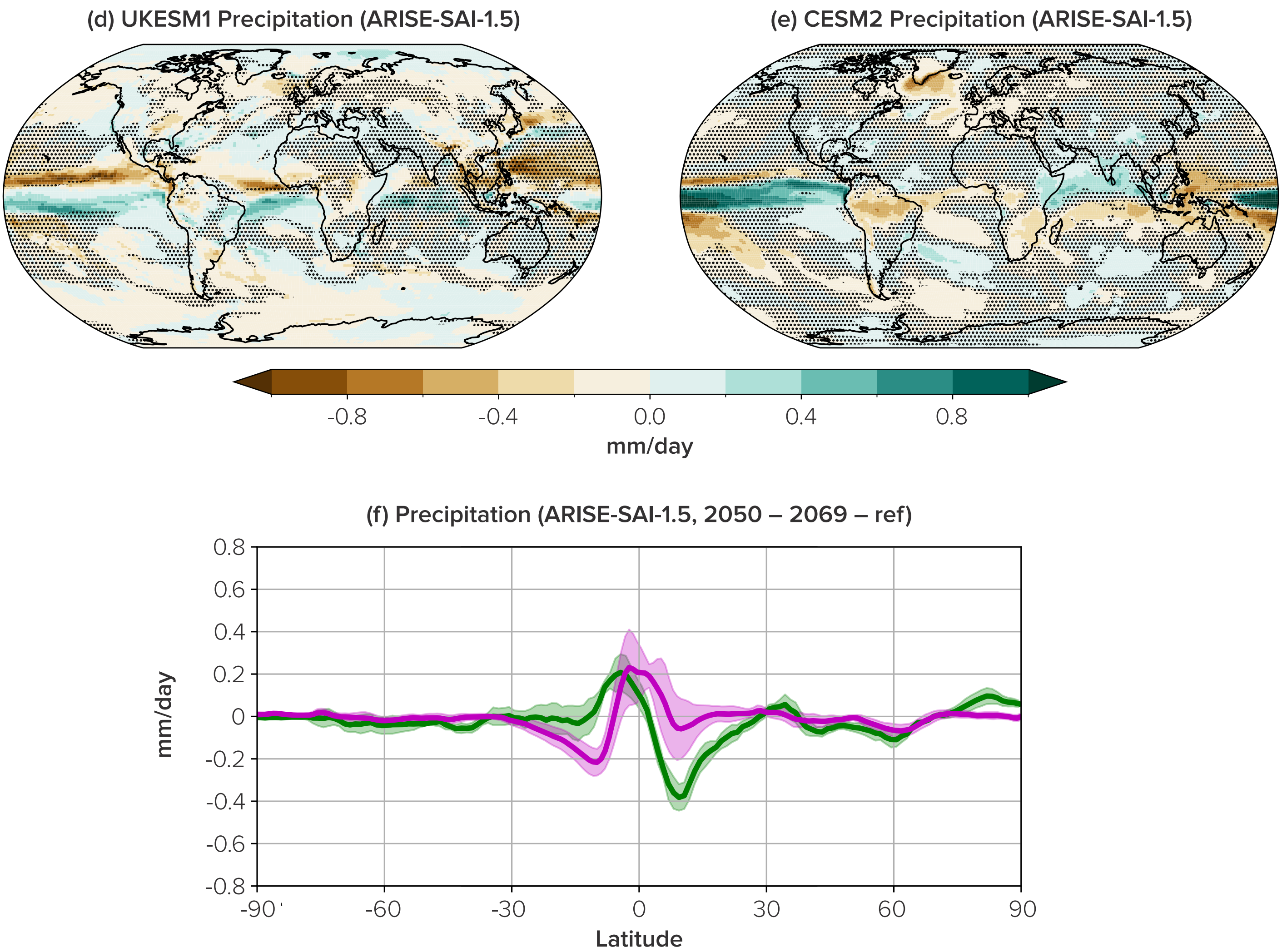
Shaded areas in the maps indicate where the difference is not statistically significant, as evaluated using a two-tailed t test with $p<0.05$ considering all ensemble members and 20 years as independent samples. Zonal-mean precipitation change is shown in panels c and f, the shaded area shows the standard deviation at each latitude point, and the thick lines show the ensemble mean.



Source: Model results are from the same set of simulations reported in Henry *et al.* (2023)[326].

326 *Op. cit.* 261.

FIGURE 12 (CONTINUED)



6.3 Stratospheric Ozone

Stratospheric ozone absorbs the sun's ultraviolet radiation, protecting humans, flora, and fauna from its harmful effects. The depletion of the stratospheric ozone layer was discovered in the early 1980s. The Montreal protocol[327], an international agreement to phase out ozone depleting substances (ODS), has led to the recovery of the stratospheric ozone layer, with full recovery expected by mid-century.

An injection of sulfur in the stratosphere (either through a volcanic eruption or SAI) would affect stratospheric ozone through two main pathways: First, the sulfate aerosols would act as surfaces further promoting reactions between ozone and ODSs of anthropogenic origin (such as halocarbons), and second the sulfate aerosol would heat the stratosphere thus changing stratospheric ozone chemistry and wind systems. The first pathway implies that, as anthropogenic ODS emissions are reduced, so too will the ozone-depleting reactions.

Modelling to date suggests a potential delay in the recovery of the Antarctic ozone hole if SAI were to be deployed[328]. However, the details of the location, amount, timing and material injected have a very significant effect on ozone impacts. For example, the injection location can significantly impact the spatial distribution of ozone changes[329]. It is worth noting that shortcomings in representations of stratospheric chemistry in ESMs limit our confidence in modelling results[330]. For a fuller discussion of impacts of SAI on ozone, see Haywood *et al*. (2022)[331].

Recently, it was demonstrated that scientifically uninformed MCB deployments can impact stratospheric ozone through inducing La Niña conditions, via an established mechanism for ENSO to influence stratospheric ozone concentrations[332]. It remains to be seen how strong these impacts are for different MCB strategies.

In summary, SAI may delay the recovery of the Antarctic ozone hole if it were to be deployed, and modelled deployments of MCB may impact stratospheric ozone through inducing La Niña conditions.

327 UN environment programme: About Montreal Protocol. See https://www.unep.org/ozonaction/who-we-are/about-montreal-protocol (accessed 11 September 2025)

328 *Op. cit*. 47.

329 *Op. cit*. 167.

330 *Op. cit*. 48.

331 *Op. cit*. 47.

332 Bednarz E M, Haywood J M, Visioni D, Butler A H, Jones A. 2025 How marine cloud brightening could also affect stratospheric ozone. Science Advances **11**, eadu4038. See: http://dx.doi.org/10.1126/sciadv.adu4038 (accessed 1 October 2025).

6.4 Modes of variability

'Modes of variability' refers to recurrent large-scale variations in the atmospheric circulation, which are important for variability in global temperature, regional weather patterns, and can influence climate links between geographically separated regions.

6.4.1 El Niño Southern Oscillation

The ENSO is the most important source of interannual climate variability. While the long-term trend in global temperatures is caused by human activities, year to year variations are dominated by ENSO. It manifests as changes in tropical Pacific sea surface temperatures, which switch from warm El Niño phases to cold La Niña phases every two to seven years. These changes affect the trade winds and have a large impact on global weather. It is, for example, one of the main drivers of interannual variability in Amazon basin rainfall which is suppressed during El Niño and enhanced during La Niña, and ENSO can also have large impacts on the Indian Summer Monsoon. There is no consensus on how the frequency and intensity of ENSO events will change with global warming even in high emissions scenarios[333], but there is emerging evidence that ENSO might be affected by SRM, and by MCB in particular.

An early climate model study showed no significant impact of SAI on ENSO[334], but a subsequent more detailed study showed that the latitude of injection has a noticeable impact on ENSO variability[335], consistent with the ENSO response to volcanic eruptions[336]. This indicates a significant knowledge gap.

Given that MCB produces more strongly localised cooling, any impact on ENSO very much depends on injection location. Deploying MCB over the eastern Pacific leads to a marked increase in La Niña conditions[337, 338] (see Section 6.1). It remains unclear how other MCB deployment strategies may impact ENSO.

6.4.3 North Atlantic Oscillation

The North Atlantic Oscillation (NAO) is a mode of internal variability characterised by fluctuations in sea level pressure over the North Atlantic ocean. This has important consequences on the climate of the British Isles and the Northern Hemisphere as a whole. On average, the surface pressure around Iceland is low and the pressure near the Azores is high. During a positive phase of the NAO, the difference in pressure between the two regions is higher than usual. This strengthens the jet stream and causes a northward shift of the Atlantic storm tracks and causes positive precipitation anomalies over northern Europe and negative precipitation anomalies over southern Europe during winter.

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333 *Op. cit*. 258.

334 Gabriel C J, Robock A. 2015 Stratospheric geoengineering impacts on El Niño/Southern Oscillation. *Atmospheric Chemistry and Physics* **15**, 11949–11966. See: https://doi.org/10.5194/acp-15-11949-2015 (accessed 1 October 2025).

335 *Op. cit*. 307.

336 Timmereck C, Olonscheck D, Ballinger A P, D'Agostino R, Fang S W, Schurer A, Hegerl G. 2024 Linearity of the climate response to increasingly strong tropical volcanic eruptions in a large ensemble framework. *Journal of Climate* **37**, 2455–2470. See: https://doi.org.10.1175/JCLI-D-23-0408.1 (accessed 1 October 2025).

337 *Op. cit*. 127.

338 Chen C C, Richter J H, Lee W R, MacMartin D G, Kravitz B. 2024 Rethinking the susceptibility-based strategy for marine cloud brightening climate intervention: experiment with CESM2 and its implications. *Geophysical Research Letters* **51**, e2024GL108860. See: https://doi.org/10.1029/2024GL108860 (accessed 1 October 2025).

The majority of exceptionally damaging northern Europe winter floods occur during a positive NAO phase[339], while droughts in Southern Europe are also associated with a positive NAO phase[340]. There is substantial model uncertainty in the NAO response to greenhouse gases[341], and climate models may underestimate the NAO response[342].

SAI can lead to a warming of the stratosphere through enhanced absorption of sunlight and infrared radiation at equatorial latitudes (see Chapter 4). This causes an increase in the equator-to-pole temperature gradient in the stratosphere, which strengthens the polar vortex and induces a positive NAO anomaly. A positive winter-time NAO anomaly would increase North Atlantic storm track activity impacting the Eurasian continent and lead to high-latitude warming over Europe and Asia. It would also lead to increases in winter precipitation in northern Europe and decreases in southern Europe[343].

This result was found in all six climate models analysed in Jones *et al*. (2022)[344] and is consistent with the response to equatorial volcanic eruptions[345] (see also Chapter 4 on the differences between pulse and sustained forcings). Results from two ESMs suggest that injecting the aerosols away from the equator (30 or 60° North and South) substantially reduces equatorial stratospheric warming[346, 347], thus reducing any NAO change or jet shift over the Atlantic[348]. Such results again show the dependence on the deployment strategy.

There is no direct research addressing how MCB might affect the NAO. However, as MCB would reduce local SSTs which play a key role in determining surface pressure, MCB could indirectly have an impact on the NAO, depending on which area is targeted. It is worth noting that the NAO exhibits considerable year-to-year and decadal natural variability[349], which makes it challenging to detect changes and attribute them to human causes; this will likely make it challenging to attribute NAO changes to SRM.

339 Zanardo S, Nicotina L, Hilberts A G J, Jewson S P. 2019 Modulation of economic losses from European floods by the North Atlantic Oscillation. *Geophysical Research Letters* **46**, 2631–2640. See: https://doi.org.10.1029/2019GL081956 (accessed 1 October 2025).

340 López-Moreno J I, Vicente-Serrano S M. 2008 Positive and negative phases of the wintertime North Atlantic Oscillation and drought occurrence over Europe: a multitemporal-scale approach. *Journal of Climate* **21**, 1220–1243. See: https://doi.org/10.1175/2007JCLI1739.1 (accessed 1 October 2025).

341 McKenna C M, Maycock A C. 2021 Sources of uncertainty in multimodel large ensemble projections of the winter North Atlantic Oscillation. *Geophysical Research Letters* **48**. See: https://doi.org/10.1029/2021GL093258 (accessed 1 October 2025).

342 Smith *et al.* 2025 Mitigation needed to avoid unprecedented multi-decadal North Atlantic Oscillation magnitude. *Nature Climate Change* **15**, 403–410. See: https://doi.org/10.1038/s41558-025-02277-2 (accessed 1 October 2025).

343 Jones *et al.* 2022. The impact of stratospheric aerosol intervention on the North Atlantic and quasi-biennial oscillations in the GeoMIP G6sulfur experiment. *Atmospheric Chemistry and Physics* **22**, 2999–3016. See: https://doi.org/10.5194/acp-22-2999-2022 (accessed 1 October 2025).

344 *Op. cit.* 343.

345 Shindell D T, Schmidt G A, Mann M E, Faluvegi G. 2004 Dynamic winter climate response to large tropical volcanic eruptions since 1600. *Journal of Geophysical Research* **109**. See: https://doi.org/10.1029/2003JD004151 (accessed 1 October 2025).

346 *Op. cit*. 307.

347 *Op. cit*. 48.

348 *Op. cit*. 227.

349 Olsen J, Anderson N J, Knudsen M F. 2012 Variability of the North Atlantic Oscillation over the past 5,200 years. *Nature Geoscience* **5**, 808–812. See: https://doi.org/10.1038/ngeo1589 (accessed 1 October 2025).

6.4.4 Quasi-Biennial Oscillation

The Quasi-Biennial Oscillation (QBO) refers to a natural oscillation of the winds in the equatorial stratosphere. These winds travel in a belt around the equator and switch between eastward and westward directions with a period of around 28 months (hence 'quasi-biennial'). The QBO influences the polar vortex, which in turn has impacts on surface weather, so the QBO is important for seasonal weather forecasting.

Tropical volcanic eruptions were shown to have an impact on the QBO through heating of the stratosphere[350] (Figure 7b), which has an impact on stratospheric winds. Similarly, model studies indicate that equatorial SAI could slow down the QBO and even lead to stalling into its eastward phase in some models[351]. Impacts on the QBO depend on the amount of heating in the equatorial stratosphere; as in studies of the NAO, models indicate that impacts can be ameliorated using subtropical injection strategies[352, 353, 354].

No direct research has addressed how MCB may affect the QBO, though it is known that there is a strong coupling between the surface climate and the stratosphere.

In summary, SAI injection could affect key modes of variability, including the ENSO, NAO and QBO, impacting global weather and climate patterns. These impacts are likely to be larger for equatorial SAI injections than for subtropical injection strategies. MCB deployments could have strong impacts on ENSO, but there is little direct research addressing how MCB might affect the NAO or QBO.

350 Brown F, Marshall L, Haynes P H, Garcia R R, Birner T, Schmidt A. 2023 On the magnitude and sensitivity of the quasi-biennial oscillation response to a tropical volcanic eruption. *Atmospheric Chemistry and Physics* **23**, 5335–5353. See: https://doi.org/10.5194/acp-23-5335-2023 (accessed 1 October 2025).

351 *Op. cit.* 343.

352 Franke H, Niemeier U, Visioni D. 2021 Differences in the quasi-biennial oscillation response to stratospheric aerosol modification depending on injection strategy and species. *Atmospheric Chemistry and Physics* **21**, 8615–8635. See: https://doi.org/10.5194/acp-21-8615-2021 (accessed 1 October 2025).

353 *Op. cit.* 307.

354 *Op. cit.* 48.

6.5 Atlantic Meridional Overturning Circulation

The Atlantic Meridional Overturning Circulation (AMOC) plays a major role in maintaining global climate by transporting heat polewards from the equator[355], and it exerts a significant influence on European climate. It also forms a key part of the ocean carbon sink[356]. According to the IPCC AR6 report, the strength of the AMOC is very likely to decline over the 21st century for all greenhouse gas emission scenarios. This decline is a consequence of decreasing density of the northern North Atlantic surface waters caused by increasing temperature and decreasing salinity. The decreasing salinity arises from increasing rainfall and the melting of the Greenland ice sheet.

There is medium confidence that the decline does not result in an abrupt collapse before 2100, which would be hard to reverse[357, 358]. Climate models demonstrate that a decline in AMOC strength can lead to widespread climate impacts: northern hemisphere cooling[359], changes in ENSO[360], hurricanes[361, 362], and ITCZ migration[363].

Recent studies have shown that SAI may mitigate part of this decline; however there remains significant uncertainty about both the strength and distribution of SAI required for effective mitigation[364], and the mechanism by which the AMOC is maintained[365].

355 Johns *et al*. 2011 Continuous, array-based estimates of the Atlantic Meridional Overturning Circulation at 26.5°N. *Journal of Climate* **24**, 2429–2445. See: https://doi.org/10.1175/2010JCLI3997.1 (accessed 1 October 2025).

356 Fontela M, García-Ibáñez M I, Hansell D A, Mercier H, Pérez F F. 2016 Dissolved organic carbon in the North Atlantic meridional overturning circulation. *Scientific Reports* **6**. See: https://doi.org/10.1038/srep26931 (accessed 1 October 2025).

357 Hawkins *et al*. 2011 Bistability of the Atlantic overturning circulation in a global climate model and links to ocean freshwater transport. *Geophysical Research Letters* **38**. See: https://doi.org/10.1029/2011GL047208 (accessed 1 October 2025).

358 Ditlevsen P, Ditlevsen S. 2023 Warning of a forthcoming collapse of the Atlantic meridional overturning circulation. *Nature Communications* **14**, 4254. See: https://doi.org/10.1038/s41467-023-39810-w (accessed 1 October 2025).

359 Vellinga M, Wood R A, Gregory J M. 2002 Processes Governing the Recovery of a Perturbed Thermohaline Circulation in HadCM3. *Journal of Climate* **15**, 764–780. See: https://doi.org/10.1175/1520-0442(2002)015<0764:PGTROA>2.0.CO;2 (accessed 1 October 2025).

360 Orihuela-Pinto *et al.* 2022 Reduced ENSO variability due to a collapsed Atlantic Meridional Overturning Circulation. *Journal of Climate* **35**, 5307–5320. See: https://doi.org/10.1175/JCLI-D-21-0293.1 (accessed 1 October 2025).

361 Yan X, Zhang R, Knutson TR. 2017 The role of Atlantic overturning circulation in the recent decline of Atlantic major hurricane frequency. *Nature Communications* **8**, 1795. See: https://doi.org/10.1038/s41467-017-01377-8 (accessed 1 October 2025).

362 Hallam S, Marsh R, Josey S A, Hyder P, Moat B, Hirschi J J M. 2019 Ocean precursors to the extreme Atlantic 2017 hurricane season. *Nature Communications* **10**, 896. See: https://doi.org/10.1038/s41467-019-08496-4 (accessed 1 October 2025).

363 Moreno-Chamarro E, Marshall J, Delworth T L. 2019 Linking ITCZ Migrations to the AMOC and North Atlantic/ Pacific SST Decadal Variability. *Journal of Climate* **33**, 893–905. See: https://doi.org/10.1175/JCLI-D-19-0258.1 (accessed 1 October 2025).

364 Fasullo J T, Richter J H. 2023 Dependence of strategic solar climate intervention on background scenario and model physics. *Atmospheric Chemistry and Physics* **23**, 163–182. See: https://doi.org/10.5194/acp-23-163-2023 (accessed 1 October 2025).

365 Muthers S, Raible C C, Rozanov E, Stocker T F. 2016 Response of the AMOC to reduced solar radiation – the modulating role of atmospheric chemistry. *Earth System Dynamics* **7**, 877–892. See: https://doi.org/10.5194/esd-7-877-2016 (accessed 1 October 2025).

Furthermore, the AMOC response to SAI has been shown to depend substantially on the location of injection[366]. The strength of the response is also model dependent, consistent with the wide range of AMOC strengths seen in different climate models[367].

The impact of MCB on the AMOC has not been researched extensively. Two studies using the same climate model suggest the extent to which the AMOC is restored is highly dependent on the location of injection[368, 369]. One can also expect that cooling the Arctic will be particularly effective in maintaining the AMOC in climate models.

In summary, SAI may mitigate part of the decline in the strength of AMOC due to climate change; however there remain significant uncertainties about both the strength and distribution of SAI required for effective mitigation, and the mechanism by which the AMOC is maintained. The impact of MCB on the AMOC has not been researched extensively.

6.6 Sea level rise

Global warming causes sea level rise through two primary mechanisms: thermal expansion (the volume of sea water expands as it warms) and the melting of land ice masses (mainly Greenland and Antarctica – see Section 7.4.3). Satellite records show that between 1993 and 2023, sea levels have risen by 111 mm and the rate of sea level rise has increased from 2.1 mm/year in 1993 to 4.5 mm/year in 2023[370]. This sea level rise occurs unevenly across the world's oceans. The timeframe over which these processes occur is a key climate risk: sea level rise will continue long after greenhouse gas emissions cease because deep ocean temperatures lag behind sea surface temperatures, and ice sheet melt responds to deep ocean temperatures. Moreover, there is large uncertainty around the future total sea level rise, which is primarily due to the uncertainties in how the large ice sheets will respond. If global temperature rise reaches 3°C by 2100, the projected global-mean sea level rise by 2100 is 0.61 (0.50 – 0.81) metres and the 2,000-year commitment is 4 to 10 metres[371].

366 Bednarz E M, Goddard P B, MacMartin D G, Visioni D, Bailey D, and Danabasoglu G 2025. Stratospheric aerosol injection could prevent future Atlantic Meridional Overturning Circulation decline, but injection location is key. *Earth's Future* **13**. See: https://doi.org/10.1029/2025EF005919 (accessed 1 October 2025).

367 Robson *et al.* 2022 The role of anthropogenic aerosol forcing in the 1850–1985 strengthening of the AMOC in CMIP6 historical simulations. *Journal of Climate* **35**, 3243–3263. See: https://doi.org/10.1175/JCLI-D-22-0124.1 (accessed 1 October 2025).

368 Hirasawa H, Hingmire D, Singh H, Rasch P J, Mitra P. 2023 Effect of regional marine cloud brightening interventions on climate tipping elements. *Geophysical Research Letters* **50**. See: https://doi.org/10.1029/2023GL104314 (accessed 1 October 2025).

369 Lee W R, Diamond M S, Irvine P, Reynolds J L, Visioni D. 2024 Informative risk analyses of radiative forcing geoengineering require proper counterfactuals. *Communications Earth and Environment* **5**, 748. See: https://doi.org/10.1038/s43247-024-01881-y (accessed 1 October 2025).

370 Hamlington *et al.* 2024 The rate of global sea level rise doubled during the past three decades. *Communications Earth and Environ*ment **5**, 601. See: https://doi.org/10.1038/s43247-024-01761-5 (accessed 1 October 2025).

371 Fox-Kemper *et al.* 2021 Ocean, Cryosphere and Sea Level Change. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. *Cambridge: Cambridge University Press,* 1211–1362. See: https://doi.org/10.1017/9781009157896.011 (accessed 1 October 2025).

The delayed response of sea level rise to emissions of greenhouse gases is a substantial challenge for climate adaptation and underscores the importance of understanding how SRM may mitigate future sea level rise. The efficacy of SRM in mitigating sea level rise is uncertain[372]. As it is effective at reducing ocean surface temperatures (Figure 5.1), it would reduce thermal expansion of the oceans[373] and surface melt of glaciers. Reconstructions of the surface mass balance of Greenland confirm a reduction in surface melt following the volcanic eruptions of El Chichón in 1982 and Pinatubo in 1991, which emitted significant amounts of aerosols into the stratosphere[374]. Despite these potential benefits, SRM is limited in its ability to prevent or reverse the melting of ice sheets on decadal timescales, as these depend on deep ocean temperatures which take longer to respond to SRM than surface waters. Additionally, SAI may cause shifts in surface winds around Antarctica and affect the upwelling of deep warm waters; however, this is very much dependent on the amount and location of injection[375].

Modelling studies of MCB with injection in tropical areas have been shown to produce strong La Niña conditions, which are associated with wind-induced increases in sea level rise in the western Pacific, above and beyond those in the global warming scenario that was mitigated. This underlines the importance of understanding these atmospheric circulation effects on sea level rise for MCB[376].

In summary, while SRM could undoubtedly reduce sea level rise by reducing ocean heat uptake, the extent to which it can prevent the melting of ice sheets is still uncertain, and its effectiveness would depend on the details of deployment. MCB also brings risks from strong regional forcing and sea level pressure changes, which can impact the geographical pattern of sea level rise.

372 Irvine P J, Keith D W, Moore J. 2018 Brief communication: Understanding solar geoengineering's potential to limit sea level rise requires attention from cryosphere experts. *The Cryosphere* **12**, 2501–2513. See: https://doi.org/10.5194/tc-12-2501-2018 (accessed 1 October 2025).

373 Jones A C, Hawcroft M K, Haywood J M, Jones A, Guo X, Moore J C. 2018 Regional climate impacts of stabilizing global warming at 1.5 K using solar geoengineering. *Earth's Future* **6**, 230–251 See: https://doi.org/10.1002/2017EF000720 (accessed 1 October 2025).

374 Fettweis X. 2007 Reconstruction of the 1979–2006 Greenland ice sheet surface mass balance using the regional climate model MAR. *The Cryosphere* **1**, 21–40. See: https://doi.org/10.5194/tc-1-21-2007 (accessed 1 October 2025).

375 Goddard P B, Kravitz B, MacMartin D G, Visioni D, Bednarz E M, Lee W R. 2023 Stratospheric aerosol injection can reduce risks to Antarctic ice loss depending on injection location and amount. Journal of Geophysical Research: Atmospheres 128. See: https://doi.org/10.1029/2023JD039434 (accessed 1 October 2025).

376 *Op. cit*. 127.

BOX 3

UK climate impacts

By 2100, the UK is expected to be warmer, with hot summers being more common than they are today. While summers are likely to be drier overall, heavy summer rainfall events may be more intense. Winter precipitation is expected to increase. Sea level will rise around the UK, with greater increases in the south due to the movement of the land[377].

There is a lack of studies analysing SRM impacts on the UK specifically, as regional impact studies usually involve much higher spatial resolution simulations than the ~100 km resolution models used to explore the global impacts of SRM. However, many of the climate risks and impacts described within Chapter 6 are relevant to the UK:

- By masking greenhouse gas warming, SRM has the potential to reduce UK warming, and moderate the increase in the intensity and frequency of hot summer days.
- Changes in UK precipitation have thermodynamic (related to changes in temperature) and dynamic (related to changes in atmospheric circulation) components. Thermodynamic components (like the increase in intense summer precipitation) will likely be moderated by SRM, but the impact of SRM on regional circulation changes is uncertain and may increase certain risks for the UK.
- The response of the North Atlantic storm track to SRM is likely to be strategy and season dependent[378]. Equatorial SAI would force a positive phase of the North Atlantic Oscillation which would increase the risk of wintertime flooding in Northern Europe, including the UK[379]. However, many studies have found a general weakening of storm track activity under SAI[380, 381, 382]. While SAI can counteract enhancement in the frequency of extreme storms, it appears to be less effective at counteracting the northward displacement of the North Atlantic storm track seen in response to increasing greenhouse gases[383, 384].

377 Met Office. 2022 UK Climate Projections 2018: Headline Findings, Version 4.0. See https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18_headline_findings_v4_aug22.pdf) (accessed 15 September 2025)

378 *Op. Cit*. 320.

379 Jones A, Haywood J M, Jones A C, Tilmes S, Kravitz B, Robock 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**, 1287–1304. See: https://doi.org/10.5194/acp-21-1287-2021 (accessed 1 October 2025).

380 Richter *et al.* 2018 Stratospheric response in the first geoengineering simulation meeting multiple surface climate objectives. *Journal of Geophysical Research: Atmospheres* **123**, 5762–5782. See: https://doi.org/10.1029/2018JD028285 (accessed 1 October 2025).

381 *Op. cit*. 299.

382 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**. See: https://doi.org/10.1029/2020GL087348 (accessed 1 October 2025).

383 *Op. cit*. 373.

384 Op. *cit.* 299.

BOX 3 (CONTINUED)

- Global warming is expected to reduce and potentially shut down the AMOC which would have significant impacts on the UK, including significantly cooler winters and more extreme weather events, which would cause severe disruptions to UK agriculture[385]. In climate models, both SAI and MCB show promise in terms of reducing the decline in AMOC, though the location of the intervention matters.
- Sea level rise represents a key climate risk for the UK. SRM would undoubtedly reduce sea level rise by reducing ocean heat uptake and Greenland and Antarctic ice sheet melt. However, understanding the effectiveness and strategy dependence of using SRM to slow ice sheet melt, and potentially prevent abrupt changes in the ice sheets, is an important research gap.

385 *Op. cit.* 259.

What are the risks of SRM on components of the Earth System, relative to the risks of climate change without SRM?

7.1. Introduction

This chapter focuses on three Earth system components: the terrestrial biosphere, the marine biosphere, and the cryosphere. As detailed in Chapter 2, the modelled impacts of SRM upon these components depend both on the scenarios that are considered (ie the baseline temperature, and the degree of global cooling applied) and the strategy (ie how that cooling is achieved). We use the risk-risk analysis described in Chapter 1, ie the risks associated with climate change in a world where SRM abates some degree of global warming are weighed against the risks due to climate change in a world where SRM is not applied. Note that terrestrial and marine ecosystems are sensitive not just to absolute meteorological variables such as temperature and precipitation, but the rates of change of these and other such local environmental variables. As such they are vulnerable to rapid change which might be induced either by rapid climate change, too rapid a deployment of SRM, or too rapid a cessation of SRM, ie the termination effect[386, 387].

In general, there has been little research on impacts on ecosystems; many of the concerns raised in early studies[388] have still not been adequately addressed.

7.2 The Terrestrial Biosphere

The terrestrial biosphere is associated with, and underpinned by, the terrestrial carbon cycle, which shows much global variability as evidenced by the geographically diverse biomes across the planet. While there have been many studies of impacts upon the physical climate under SRM, such as changes in mean and extreme precipitation, far fewer have considered changes in the terrestrial carbon cycle and impacts on ecological systems and many research gaps remain[389, 390]. We consider net primary productivity (NPP) on a global average basis and in the few ecologically sensitive areas that have received attention before assessing impacts on crops and wildfires.

7.2.1 Global Net Primary Productivity

Carbon dioxide fertilisation and the impacts of diffuse radiation

NPP is the rate of carbon retained by vegetation and is the sum of the impacts of photosynthesis (which increases carbon uptake) and respiration (which decreases carbon uptake). NPP is therefore a key indicator of the health of the terrestrial biosphere and furthermore influences atmospheric CO_2 concentrations. NPP is influenced by photosynthetically active radiation (PAR; ie the incident sunlight at wavelengths used by plants for photosynthesis), CO_2 concentrations, temperature, precipitation, and soil moisture which is determined by evaporation and precipitation.

386 *Op. cit*. 268.

387 Hueholt D M, Barnes E A, Hurrell J W, Morrison A L. 2024 Speed of environmental change frames relative ecological risk in climate change and climate intervention scenarios. *Nature Communications,* **15**(1), 3332. See: https://doi.org/10.1038/s41467-024-47656-z (accessed 1 October 2025).

388 Russell L M, Rasch P J, Mace G M, Jackson R B, Shepherd J, Liss P, Morgan M G. 2012 Ecosystem impacts of geoengineering: a review for developing a science plan. *Ambio* **41**, 350–369. See: https://doi.org/10.1007/s13280-012-0258-5 (accessed 1 October 2025).

389 *Op. cit.* 268.

390 Zarnetske *et al.* 2021 Potential ecological impacts of climate intervention by reflecting sunlight to cool Earth. *Proceedings of the National Academy of Sciences* **118**. See: https://doi.org/10.1073/pnas.1921854118 (accessed 1 October 2025).

For SAI, climate modelling studies show that NPP would be significantly enhanced under SAI scenarios owing to the high CO_2 concentrations and reduced thermal stress, despite reduced sunlight conditions[391, 392]. Similarly, for MCB, studies have shown with the exception of the Nordeste and Amazonian regions of Brazil (see section 7.2.2.2), NPP responds positively to MCB owing to high CO_2 concentrations and reduced thermal stress[393]. On a global average basis, these two factors encourage photosynthesis and outweigh impacts of global mean precipitation changes and any reduction in photosynthetically active radiation at the surface[394]. One study, under idealised SRM with a single climate model, has challenged this finding suggesting that models with an active nitrogen cycle show a decrease in soil respiration with cooling, which decreases nitrogen availability[395]. The assessment of Arias *et al*. (2021) is that they find that SRM would lead to "enhancement of global land and ocean CO_2 sinks (medium confidence) and a slight reduction in atmospheric CO_2 concentration relative to unmitigated climate change".

At the surface, sunlight consists of a direct component consisting of photons that pass straight through the atmosphere, and a diffuse component consisting of photons that are scattered in all directions by atmospheric molecules, clouds, and aerosols. The impact of increasing aerosols through SAI would be to increase the diffuse component at the expense of the direct component. Rather counterintuitively, a greater fraction of diffuse sunlight enhances photosynthesis because fewer leaves are shaded from the sun; this more than compensates for the loss of total sunlight at the surface leading to an enhancement of global NPP[396]. Yang *et al* (2020)[397] suggests that SRM could be effective at sequestering CO_2 and might be viewed as an indirect method for CDR.

Only a few MCB studies diagnose changes in NPP[398, 399, 400] results again suggest that the cooling impact increases NPP, but to a lesser extent than for SAI because the areas of maximum cooling for MCB deployments are over ocean regions.

391 Bala G, Caldeira K, Mirin A, Wickett M, Delire C, Philips T J. 2006 Biogeophysical effects of CO_2 fertilization on global climate. *Tellus B: Chemical and Physical Meteorology* **58**, 620–627. See: https://doi.org/10.1111/j.1600-0889.2006.00210.x (accessed 1 October 2025).

392 Jones A, Haywood J M, Boucher O. 2010 A comparison of the climate impacts of geoengineering by stratospheric SO_2 injection and by brightening of marine stratocumulus cloud. *Atmospheric Science Letters* **12**, 176–183. See: https://doi.org/10.1002/asl.291 (accessed 1 October 2025).

393 *Op. cit.* 392.

394 Xia L, Robock A, Tilmes S, Neely III R R. 2016 Stratospheric sulfate geoengineering could enhance the terrestrial photosynthesis rate. *Atmospheric Chemistry and Physics* **16**, 1479–1489. See: https://doi.org/10.5194/acp-16-1479-2016 (accessed 1 October 2025).

395 Dagon K, Schrag D P. 2019 Quantifying the effects of solar geoengineering on vegetation. *Climate Change* **153**, 235–251. See: https://doi.org/10.1007/s10584-018-2342-y (accessed 1 October 2025).

396 Mercado *et al.* 2009 Impact of changes in diffuse radiation on the global land carbon sink. *Nature* **458**, 1014–1017. See: https://doi.org/10.1038/nature07949 (accessed 1 October 2025).

397 Yang *et al*. 2020 Assessing terrestrial biogeochemical feedbacks in a strategically geoengineered climate. Environmental Research Letters 15, 104043. See: https://doi.org/10.1088/1748-9326/abacf7 (accessed 1 October 2025).

398 *Op. cit*. 285.

399 *Op. cit*. 392.

400 *Op. cit*. 132.

The consistent results from modelling studies suggest that, on a global average basis, SRM will lead to an increase in NPP when compared to global warming scenarios without SRM.

Acid rain and sea salt deposition

As SAI is most frequently modelled using SO_2 which oxidises to sulfate aerosol in the stratosphere, it is logical to ask whether SAI could contribute to the well-known 'acid-rain' phenomena that can damage vegetation and aquatic ecosystems[401]. Similarly, sea salt has long been known to be detrimental to vegetation health and productivity[402].

Global modelling studies suggest that 1°C of SAI-induced cooling can be equated to approximately 8 – 16 Tg SO_2 yr^{-1} [403] (see Section 5.2). Anthropogenic sources of sulfur emitted into the atmosphere peaked at around 140 – 160 Tg SO_2 yr^{-1} in the 1980s[404]. This reduced steadily to around 100 Tg SO_2 yr^{-1} by the mid-2010s[405], and is projected to reduce further to approximately 50 – 70 Tg SO_2 yr^{-1} by 2060[406].

Thus the 8 – 16 Tg SO_2 yr^{-1} deposition associated with a 1°C cooling would be less than 10% of the peak that occurred in the 1980s or 11 – 26% relative to the future climate change scenarios.

The spatial distribution of the surface sulfur deposition from SAI would be much more homogeneous than those from anthropogenic emissions[407], leading to some increased deposition in pristine regions. These arguments suggest that, for a moderate SAI cooling of 1°C over the course of the 21st century, the impacts of sulfur-related SAI would not significantly affect ecosystems and NPP. Should deployments for significantly larger cooling be required at any stage, the impacts on acid-rain would need to be reassessed, particularly in relatively pristine regions.

The total amount of sea salt that is emitted into the atmosphere has been estimated to be about 10,000 Tg SS yr^{-1} of which around 4% is sufficiently small to undergo long-range transport[408].

401 Singh A, Agrawal M. 2008 Acid rain and its ecological consequences. *Journal of Environmental Biology* **29**, 15–24. (PMID: 18831326)

402 Neiman R. 1962 Some Effects of Sodium Chloride on Growth, Photosynthesis, and Respiration of Twelve Crop Plants. See https://www.jstor.org/stable/2473175 (accessed 15 September 2025).

403 *Op. cit*. 47.

404 Smith S J, Pitcher H, Wigley T M L. 2001 Global and regional anthropogenic sulfur dioxide emissions. *Global and Planetary Change* **29**, 99–119. See: https://doi.org/10.1016/S0921-8181(00)00057-6 (accessed 1 October 2025).

405 Zhong *et al*. 2020 Global sulfur dioxide emissions and the driving forces. *Environmental Science and Technology* 54, 6508–6517. See: https://doi.org/10.1021/acs.est.9b07696 (accessed 1 October 2025).

406 Szopa *et al.* 2021 Short Lived Climate Forcers. In *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press*, 33–144. See: https://doi.org/10.1017/9781009157896.002 (accessed 1 October 2025).

407 Visioni D, Slessarev E, MacMartin D, Mahowald N M, Goodale C L, Xia L. 2020 What goes up must come down: impacts of deposition in a sulfate geoengineering scenario. *Environmental Research Letters* **15**, 094063. See: https://doi.org/10.1088/1748-9326/ab94eb (accessed 1 October 2025).

408 Gong S L, Barrie L A, Blanchet J P. 1997 Modeling sea salt aerosols in the atmosphere: 1. Model development. *Journal of Geophysical Research: Atmospheres* **102**(D3), 3805–3818. See: https://doi.org/10.1029/96JD02953 (accessed 1 October 2025).

MCB estimates of the amount of sea salt required to exert a global mean cooling of around 1°C from two models suggest emission fluxes of 7.5 to 50 Tg SS yr^{-1} [409] (see Section 5.2) which is insignificant compared to the total natural flux of sea salt. However, the modelled MCB emissions are 'tailored' towards small particles that provide an optimal cooling through aerosol-cloud-interactions, so they may be subject to greater long-range transport than natural sea salt and could potentially contribute to sea salt deposition over land areas which can have detrimental impacts on NPP[410]. Any deposition to land would be very dependent upon the deployment strategy with land masses close to the areas of deployment most significantly influenced.

A scale analysis of the impacts of sulfate deposition on acid rain suggests that this should not be a significant impact for moderate SAI-induced cooling. A similar scale analysis of MCB deposition suggests the impact of MCB deployments should not be significant for moderate MCB induced cooling.

7.2.2. Regional NPP

The Sahel

The Sahel is an area of sub-Saharan Africa with 400 million inhabitants that is particularly vulnerable to droughts associated with monsoon failures. There is well documented observational and model evidence (Chapters 4 and 6) that Sahelian rainfall is strongly influenced by temperature gradients across the Equator. Model simulations reveal that these gradients can be strongly influenced by SAI and MCB deployments that are not globally-coordinated. For example, Haywood *et al*. (2013)[411] showed a large-scale retreat of the northernmost extent of the ITCZ by around 500 km for their modelled SAI deployment of 5 Tg SO_2 yr^{-1} solely in the northern hemisphere. Areas of Niger, Mali, Burkina Faso, Senegal, Chad and the Sudan lost between 60 – 100% of NPP, which would likely make such areas uninhabitable. Simulations with a globally-coordinated, hemispherically-balanced strategy[412, 413] show significantly smaller impacts on Sahelian precipitation, which would induce lesser impacts on NPP.

Hemispherically asymmetric SAI deployment solely in the northern hemisphere could induce very damaging impacts on the Sahelian region. Globally-coordinated, hemispherically symmetric deployments of SAI and MCB appear to ameliorate these detrimental impacts.

409 *Op. cit*. 233.

410 Okon O G. 2019 Effect of salinity on physiological processes in plants. In: Giri B, Varma A (eds) Microorganisms in Saline Environments: Strategies and Functions. *Soil Biology* **56.** See: https://doi.org/10.1007/978-3-030-18975-4_10 (accessed 1 October 2025).

411 *Op. cit.* 179.

412 Alamou *et al*. 2022 Impact of stratospheric aerosol geoengineering on meteorological droughts in West Africa. *Atmosphere* **13**, 234. See: https://doi.org/10.3390/atmos13020234 (accessed 1 October 2025).

413 *Op. cit*. 315.

The Amazon rainforest

Parry *et al*. (2025)[414] suggest that NPP in the Amazon rainforest is projected to increase under SAI, suggesting a general increase in resilience when compared to future climate change simulations without SAI. For MCB applied to stratocumulus over the South East Atlantic (see Chapter 6), multiple models have shown a robust drying over the Amazon[415, 416, 417] which leads to a significant reduction in NPP over the Amazon and Nordeste of Brazil. These conclusions are supported by observed robust correlations between highly reflective clouds over the south-east Atlantic, the associated localised SST reduction, and rainfall over the Nordeste region of Brazil[418, 419]. Such responses have led to the examination of strategies that avoid MCB applications to the South-East Atlantic stratocumulus region[420].

The consistent multi-model response, and supporting statistical relationships between observations of reduced sea surface temperatures over the South East Atlantic and reduced precipitation over Nordeste of Brazil, suggest that MCB applied to South East Atlantic stratocumulus would detrimentally impact the Amazon.

7.2.3 Crops

National agricultural policies are typically optimised with respect to crop type, climate and soils, but imposition of heat stress reduces global yields. If SRM limits this additional heat stress, yields may rise and the present-day distribution of crops could be maintained or even enhanced relative to the present day owing to the CO_2 fertilisation effect[421]. The impact of SRM on crops has been investigated by Pongratz *et al* (2012)[422], who suggested that the cooling impact of SAI combined with the CO_2 fertilisation effect might lead to an increase in crop NPP.

414 Parry *et al.* 2025 Solar radiation modification is projected to increase land carbon storage and to protect the Amazon rainforest. *Submitted to Nature Communications.* See: https://doi.org/10.21203/rs.3.rs-4472495/v1 (accessed 1 October 2025).

415 *Op. cit.* 285.

416 *Op. cit*. 132.

417 *Op. cit*. 233.

418 Hastenrath S. 1990 Prediction of Northeast Brazil rainfall anomalies. *Journal of Climate* **3,** 893–904. See: https://doi.org/10.1175/1520-0442(1990)0032.0.CO;2 (accessed 1 October 2025).

419 Utida G *et al.* 2019 Tropical South Atlantic influence on northeastern Brazil precipitation and ITCZ displacement during the past 2,300 years. *Scientific Reports* **9**, 1698. See: https://doi.org/10.1038/s415 (accessed 1 October 2025).

420 *Op. cit*. 127.

421 Clark *et al.* 2023 Optimal climate intervention scenarios for crop production vary by nation. *Nature Food* **4**, 902–911. See: https://doi.org/10.1038/s43016-023-00853-3 (accessed 1 October 2025).

422 Pongratz J, Lobell DB, Cao L, Caldeira K. 2012 Crop yields in a geoengineered climate. *Nature Climate Change* **2**, 101–105. See: https://doi.org/10.1038/nclimate1373 (accessed 1 October 2025).

Fan *et al*. (2021)[423] suggest an increase in crop yield under SAI, but found little impact from changes in diffuse fraction, while Xia *et al* (2014)[424] indicate significant increases in maize production but negligible changes in rice in China from SAI. Grant *et al*. (2025)[425] suggest increases in India wheat production under SAI compared to unabated global warming. Proctor *et al*. (2018)[426] use empirical surface solar radiation network data subsequent to recent explosive volcanic eruptions, finding that the diffuse radiation effect for crops is negative rather than positive, which may be due to the very different nature of crop canopies compared to those in natural biomes.

When considered on a risk-risk basis, no significant decreases in global crop productivity under SRM are expected owing to increased CO_2 concentrations, reduction in heat stress, and reduction in extreme precipitation and drought events.

7.2.4 Wildfires

The increasingly frequent, larger, and more severe wildfires have been attributed to climate change[427, 428, 429]. Changes in wildfires are frequently assessed in climate models by using empirical metrics based on soil moisture, time since rain, temperature, relative humidity, and windspeed (eg the Forest Fire Danger Index)[430]. Under a risk-risk analysis, model studies show that the application of SAI reduces the risk of wildfires as evident in the reduction of fire risk indices across most areas of the globe[431, 432, 433]. Under SAI, the number of fire days classed as moderate to extreme risk are universally reduced over key areas that are prone to wildfires including the Amazon, southern Africa, Australia, the Mediterranean and North America.

423 Fan *et al.* 2021 Solar geoengineering can alleviate climate change pressures on crop yields. *Nature Food.* **2**, 373–381. See: https://doi.org/10.5194/esd-16-667-2025 (accessed 1 October 2025).

424 Xia *et al.* 2014 Solar radiation management impacts on agriculture in China: A case study in the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmosphere* **119**, 8695–8711. See: https://doi.org/10.1002/2013JD020630 (accessed 1 October 2025).

425 Grant N, Robock A, Xia L, Singh J, Clark B. 2025 Impacts on Indian agriculture due to stratospheric aerosol intervention using agroclimatic indices. *Earth's Future* **13**. See: https://doi.org/10.1029/2024EF005262 (accessed 1 October 2025).

426 Proctor J, Hsiang S, Burney J, Burke M, Schlenker W. 2018 Estimating global agricultural effects of geoengineering using volcanic eruptions. *Nature* **560**, 480–483. See: https://doi.org/10.1038/s41586-018-0417-3 (accessed 1 October 2025).

427 Abatzoglou J T, Williams A P, Barbero R. 2019 Global Emergence of Anthropogenic Climate Change in Fire Weather Indices. *Geophysical Research Letters* **46**, 326–336. See: https://doi.org/10.1029/2018GL080959 (accessed 1 October 2025).

428 United Nations Environment Programme. 2022 Spreading like Wildfire – The Rising Threat of Extraordinary Landscape Fires. A UNEP Rapid Response Assessment. *UNEP*. See http://www.un.org/Depts/ (accessed 15 September 2025).

429 Burton *et al.* 2024 Global burned area increasingly explained by climate change. *Nature Climate Change* **14**, 1186–1192. See: https://doi.org/10.1038/s41558-024-02140-w (accessed 1 October 2025).

430 McArthur AG. 1967 Fire behaviour in Eucalypt forests. Leaflet No 107. Canberra, Australia: Forest Research Institute, Forestry and Timber Bureau.

431 Burton C, Betts R A, Jones C D, 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* **45**, 3644–3652. See: https://doi.org/10.1002/2018GL077848 (accessed 1 October 2025).

432 Tang *et al.* 2023 Impact of solar geoengineering on wildfires in the 21st century in CESM2/WACCM6. *Atmospheric Chemistry and Physics* **23**, 5467–5486. See: https://doi.org/10.5194/acp-23-5467-2023 (accessed 1 October 2025).

433 Touma D, Hurrell J W, Tye M R, Dagon K. 2023 The Impact of Stratospheric Aerosol Injection on Extreme Fire Weather Risk. *Earth's Future* **11**, 984. See: https://doi.org/10.1029/2023EF003626 (accessed 1 October 2025).

Given that fire risk indices are strongly coupled to changes in extremes in temperature, precipitation, and drought, and that these extremes appear effectively ameliorated under SAI[434] these results appear in line with expectations. Studies that suggest that wildfires may increase under SAI assess their results against heavily mitigated emission scenarios and do not provide the appropriate counterfactuals for risk-risk framings[435] and have been heavily criticised[436]. There have been no studies assessing the impact of MCB on wildfires and results will undoubtedly depend on deployment strategies.

When considered on a risk-risk basis, it is likely that global wildfires would be reduced by SAI when compared to a warmer world.

7.3 The marine biosphere

The global ocean net primary productivity is modelled to decrease by around 9 ± 8% on average by the end of the 21st century under various future climate scenarios[437] owing to increased stratification and less vertical transport of nutrients from depth. The mitigation of ocean temperatures under SRM may preserve coral reefs[438, 439, 440] but it does not prevent the ongoing acidification of oceans due to increased CO_2 concentrations. The reduction of surface sunlight under SRM may redistribute ocean productivity in the water column[441] which may impact marine ecosystems where sunlight is the limiting factor on productivity[442].

434 Tye *et al*. 2022 Indices of extremes: geographic patterns of change in extremes and associated vegetation impacts under climate intervention. *Earth System Dynamics* **13**, 1233–1257. See: https://doi.org/10.5194/esd-13-1233-2022 (accessed 1 October 2025).

435 Müller *et al.* 2024 Radiative forcing geoengineering under high CO_2 levels leads to higher risk of Arctic wildfires and permafrost thaw than a targeted mitigation scenario. *Communications Earth and Environment* **5**, 180. See: https://doi.org/10.1038/s43247-024-01329-3 (accessed 1 October 2025).

436 *Op. cit.* 369.

437 Bopp *et al.* 2013 Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences* **10**, 6225–6245. See: https://doi.org/10.5194/bg-10-6225-2013 (accessed 1 October 2025).

438 Latham J, Kleypas J, Hauser R, Parkes B, Gadian A. 2013 Can marine cloud brightening reduce coral bleaching? *Atmospheric Science Letters* **14**, 214–219. See: https://doi.org/10.1002/asl2.442 (accessed 1 October 2025).

439 Kwiatkowski L, Cox P, Halloran PR, Mumby PJ, Wiltshire AJ. 2015 Coral bleaching under unconventional scenarios of climate warming and ocean acidification. *Nature Climate Change* **5**, 777–781. See: https://doi.org/10.1038/nclimate2655 (accessed 1 October 2025).

440 *Op. cit.* 116.

441 Hardman-Mountford N J, Polimene L, Hirata T, Brewin R J W, Aiken J. 2013 Impacts of light shading and nutrient enrichment geo-engineering approaches on the productivity of a stratified, oligotrophic ocean ecosystem. *Journal of The Royal Society Interface* **10**. See: https://doi.org/10.1098/rsif.2013.0701 (accessed 1 October 2025).

442 Partanen A, Keller D P, Korhonen H, Matthews HD. 2016 Impacts of sea spray geoengineering on ocean biogeochemistry. *Geophysical Research Letters* **43**, 7600–7608. See: https://doi.org/10.1002/2016GL070111 (accessed 1 October 2025).

However, the sign of net impacts on the marine carbon cycle remains unclear[443, 444, 445]. These upwelling areas are frequently targeted by MCB owing to the presence of ubiquitous marine stratocumulus. Applying MCB solely over such regions would likely induce La Niña-like conditions[446] which are generally associated with an increased flux of upwelling and nutrients and increased carbon sequestration by marine ecosystems and increased fish stocks. However, under a particular MCB scenario, La Niña conditions many times the strength of those of natural variability have been modelled[447] (see Chapter 6) and it is difficult to know how marine ecosystems would respond to such dramatic changes.

Some very limited manipulation of clouds over the Great Barrier Reef in Australia has been attempted using MCB sprayers with the aim of assessing the technology for protecting the coral from bleaching by oceanic heatwaves[448]. However, the complex chain of aerosol generation, aerosol cloud interaction, reduction in surface sunlight, sea surface temperatures, and coral bleaching and the cascade of uncertainties along the chain mean that impact assessment using such limited deployments is not yet possible.

SRM will not directly abate ocean acidification due to CO_2 increases, but there is little research that addresses the impacts of SRM on the marine biosphere, which makes drawing conclusions about impacts very difficult.

443 Keller D P, Feng E Y, Oschlies A. 2014 Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. *Nature Communications.* **5**, 3304. See: https://doi.org/10.1038/ncomms4304 (accessed 1 October 2025).

444 Lauvset S K, Tjiputra J, Muri H. 2017 Climate engineering and the ocean: effects on biogeochemistry and primary production. *Biogeosciences* **14**, 5675–5691. See: https://doi.org/10.5194/bg-14-5675-2017 (accessed 1 October 2025).

445 Tjiputra J F, Grini A, Lee H. 2015 Impact of idealized future stratospheric aerosol injection on the large-scale ocean and land carbon cycles. *Journal of Geophysical Research: Biogeosciences* **121**, 2–27. See: https://doi.org/10.1002/2015JG003045 (accessed 1 October 2025).

446 Chen C C, Richter J H, Lee W R, Tye M, MacMartin D G, Kravitz B. 2025 Climate impact of marine cloud brightening solar climate intervention under a susceptibility-based strategy simulated by CESM2. *Journal of Geophysical Research* **130**. See: https://doi.org/10.1029/2024GL108860 (accessed 1 October 2025).

447 *Op. cit*. 127.

448 *Op. cit.* 116.

7.4 The cryosphere

The cryosphere includes glaciers, sea-ice, ice sheets, snow, and permafrost. The most comprehensive review of the impacts of SRM on the cryosphere to date is provided by Duffey *et al*. (2023)[449]. Impacts on the cryosphere occur either remotely ie reduction in polar warming due to SRM applications at lower latitudes[450, 451, 452, 453, 454, 455], or through SRM applications that specifically target inducing a cooling at high latitudes [456, 457, 458, 459, 460, 461, 462, 463]. Cryosphere changes have a direct impact on sea level as discussed in Section 6.7.

7.4.1 Sea ice

If applied in sufficient quantities, there is little doubt that SRM would help to preserve sea ice[464, 465] as SRM would reduce the atmospheric and oceanic poleward energy transport leading to reduced polar heating. Equatorial SAI has long been known to lead to an overcooling of the tropical regions, with some continued residual polar warming[466] (see Chapter 6). Thus, equatorial injections of SAI prevent some, but not all sea-ice loss. These residual impacts can be minimised through deployments more focused on mid- and high latitudes[467].

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449 Duffey A, Irvine P, Tsamados M, Stroeve J. 2023 Solar geoengineering in the polar regions: A review. *Earth's Future* **11**. See: https://doi.org/10.1175/JCLI-D-12-00196.1 (accessed 1 October 2025).

450 *Op. cit*. 375.

451 Jiang *et al*. 2019 Stratospheric sulfate aerosol geoengineering could alter the high-latitude seasonal cycle. *Geophysical Research Letters* **46**, 14153–14163. See: https://doi.org/1029/2019GL085758 (accessed 1 October 2025).

452 *Op. cit*. 392.

453 *Op. cit*. 373.

454 *Op. cit*. 309.

455 Rasch P J, Latham J, Chen C C. 2009 Geoengineering by cloud seeding: influence on sea ice and climate system. *Environmental Research Letters* **4**, 045112. See: https://doi:10.1088/1748-9326/4/4/045112 (accessed 1 October 2025).

456 Caldeira K, Wood L. 2008 Global and Arctic climate engineering: numerical model studies. *Philosophical Transactions of the Royal Society A* **366**, 4039–4056. See: https://doi.org/10.1098/rsta.2008.0132 (accessed 1 October 2025).

457 Desch SJ *et al*. 2017 Arctic ice management. *Earth's Future* **5,** 107–127. See: https://doi.org/10.1002/2016EF000410 (accessed 1 October 2025).

458 *Op. cit*. 375.

459 *Op. cit*. 372.

460 *Op. cit.* 259.

461 MacCracken M C. 2016 The rationale for accelerating regionally focused climate intervention research. *Earth's Future* **4**, 649–657. See: https://doi.org/10.1002/2016EF000450 (accessed 1 October 2025).

462 Moore *et al*. 2014 Arctic sea ice and atmospheric circulation under the GeoMIP G1 scenario. *Journal of Geophysical Research: Atmospheres* **119**, 567-583. See: https://doi.org/10.1002/2013JD021060 (accessed 1 October 2025).

463 Tilmes S, Jahn A, Kay JE, Holland M, Lamarque J-F. 2014 Can regional climate engineering save the summer Arctic sea ice? *Geophysical Research Letters* **41**, 880–885. See: https://doi.org/10.1002/2013GL058731 (accessed 1 October 2025).

464 *Op. cit*. 392.

465 Jones *et al*. 2013 The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP) *Journal of Geophysical Research: Atmospheres*. **118**, 9743–9752. See: https://doi.org/10.1002/jgrd.50762 (accessed 1 October 2025).

466 *Op. cit*. 282.

467 *Op. cit*. 166.

Higher latitude SAI injections have been shown to preferentially protect sea-ice, but do not provide as efficient global cooling as lower latitude injections[468, 469]. These injection strategies typically inject at high latitudes in both hemispheres to avoid any shifts in the ITCZ caused by hemispherically imbalanced aerosol optical depth distributions. MCB deployment strategies using feedback controllers (see Section 5.3) to address multiple climate targets have only recently been developed, and show some promise in balancing global mean temperatures and sea-ice[470]. The modelling study of Villanueva *et al*. (2022)[471] showed that thinning of mixed phase clouds (ie those that contain both liquid water and ice) can lead to a significant cooling in polar regions which would support maintenance of sea-ice production. Interactions of sea-spray or other aerosols with mixed phase clouds are not understood.

At sufficient magnitude, SAI could combat sea-ice loss through reducing the energy transport of the atmosphere and oceanic circulations for low- and mid-latitude deployments, and through high latitude planetary albedo increase for high-latitude deployments. Modelled impacts of MCB are more uncertain, particularly for high latitude deployments where mixed phase clouds become a significant factor.

7.4.2 Permafrost

Permafrost thaw is a significant concern under global warming scenarios as it would release considerable carbon and methane into the atmosphere and impact freshwater ecology. Studies of the impact of large-scale SAI deployment[472, 473, 474, 475, 476] all suggest that permafrost loss can be reduced with SAI. Ji *et al*. (2025)[477] caution that although permafrost can be restored in overshoot scenarios, the carbon and methane that it locks-up cannot be recaptured in permafrost restoration.

468 *Op. cit*. 309.

469 Duffey A, Henry M, Smith W, Tsamados M, Irvine PJ. 2025 Low-altitude high-latitude stratospheric aerosol injection is feasible with existing aircraft. *Earth's Future* **13**. See: https://doi.org/10.1029/2024EF005567 (accessed 1 October 2025).

470 Lee W R, Chen C C, Richter J, MacMartin D G, Kravitz B. 2025 First simulations of feedback algorithm-regulated marine cloud brightening. *Geophysical Research Letters.* See: https://doi.org/10.1029/2024GL113728 (accessed 1 October 2025).

471 Villanueva D, Possner A, Neubauer D, Gasparini B, Lohmann U, Tesche M. 2022 Mixed-phase regime cloud thinning could help restore sea ice. *Environmental Research Letters* **17**, 114057. See: https://doi.org/10.1088/1748-9326/aca16d (accessed 1 October 2025).

472 Chen Y, Liu A, Moore J C. 2020 Mitigation of Arctic permafrost carbon loss through stratospheric aerosol geoengineering. *Nature Communications* **11**, 2430. See: https://doi.org/10.1038/s41467-020-16357-8 (accessed 1 October 2025).

473 Chen *et al.* 2023 Northern-high-latitude permafrost and terrestrial carbon response to two solar geoengineering scenarios. *Earth System Dynamics* **14**, 55–79. See: https://doi.org/10.5194/esd-14-55-2023 (accessed 1 October 2025).

474 Chen Y, Moore J C, Ji D. 2024 Simulated responses and feedbacks of permafrost carbon under future emissions pathways and idealized solar geoengineering scenarios. *Environmental Research Letters* **19**, 024050. See: https://doi.org/10.1088/1748-9326/ad2433 (accessed 1 October 2025).

475 Moore *et al*. 2024. Multi-modal Simulation of Solar Geoengineering Indicates Avoidable Destablization of the West Antarctic Ice Sheet, *Earth's Future* **12**. See: https://doi.org/10.1029/2024EF004424 (accessed 1 October 2025).

476 Lee *et al.* 2019 The response of permafrost and high-latitude ecosystems under large-scale stratospheric aerosol injection and its termination. *Earth's Future* **7**, 605-614. See: https://doi.org/10.1029/2018EF001146 (accessed 1 October 2025).

477 Ji D, Cui M, Chen Y, Dai Y. 2025 Permafrost response in northern high-latitude regions to 1.5°C warming and overshoot scenarios achieved via solar radiation modification. *Journal of Geophysical Research: Atmospheres* **130**. See: https://doi.org/10.1029/2024JD041772 (accessed 1 October 2025).

Müller *et al* (2024)[478] assess the impacts of permafrost thaw under SRM against a heavily mitigated emission strategy, which does not provide an adequate counterfactual[479].

From the limited number of studies available, it appears that permafrost loss may be ameliorated, but permafrost restoration cannot recover the carbon and methane stocks once thawed.

7.4.3 Glaciers and ice-sheets

While climate models may be able to give general information about the retreat of glaciers through downscaling temperature and precipitation to calculate the mass balance of precipitation and melt, glaciers are sub-grid scale and more detailed process modelling is required. At least ten mechanical intervention methods have been suggested[480, 481] but are outside the scope of this report. Modelling studies indicate that the threat of collapse of the West-Antarctic Ice Sheet can be ameliorated to some degree through SAI[482], but this depends strongly on the future climate scenario and injection strategy[483, 484].

We note again that SRM may have limited impacts in preventing the melting of ice sheets, as melting depends on deep ocean temperatures which are not as efficiently cooled by SRM as surface waters.

Understanding the timing of ice-sheet collapse is hindered by lack of observations near the grounding line and the fact that climate models (and many ice dynamics models) are incapable of realistically simulating critical processes such as calving, grounding and the influence of sub-glacial meltwater on ice flow. These issues are common to both greenhouse gas induced warming and SRM and make definitive statements difficult.

478 *Op. cit*. 435.

479 *Op. cit.* 369

480 Moore J C, Gladstone R, Zwinger T, Wolovick M. 2018 Geoengineer polar glaciers to slow sea-level rise. *Nature* **555**, 303–305. See: https://doi.org/10.1038/d41586-018-03036-4 (accessed 1 October 2025).

481 van Wijngaarden A, Moore J C, Alfthan B, Kurvits T, Kullerud L. 2024 A survey of interventions to actively conserve the frozen North. *Climate Change* **177**, Article 58. See: https://doi.org/10.1007/s10584-024-03705-6 (accessed 1 October 2025).

482 *Op. cit*. 475.

483 *Op. cit*. 375.

484 Sutter J, Jones A, Frölicher T L, Wirths C, Stocker T F. 2023 Climate intervention on a high-emissions pathway could delay but not prevent West Antarctic Ice Sheet demise. *Nature Climate Change* **13**, 951–960. See: https://doi.org/10.1038/s41558-023-01738-w (accessed 1 October 2025).

An overview of SRM governance – recent developments, governance principles, and practical challenges

In its 2009 report[485], the Royal Society stressed the governance and societal challenges that geoengineering (both SRM and CDR) would pose: "The acceptability of geoengineering will be determined as much by social, legal and political issues as by scientific and technical factors" and stressed that "There are serious and complex governance issues which need to be resolved if geoengineering is ever to become an acceptable method for moderating climate change".

In the years since, as research interest and the number of outdoor SRM field experiments has grown, questions of how to govern SRM research and development are increasingly pertinent. At the international level, governance discussions remain at an early stage, and few countries have commenced national discussions. In the absence of formal governance, SRM project teams and their funders have opted for different forms of self-governance, developing their own rules and procedures for small-scale field experiments. While the environmental risks posed by SRM field experiments to date have been extremely low, owing to the limited scale of any field experimentation, there are broader concerns about these efforts. Some groups have opposed field experiments, and several experiments have been cancelled.

Over the past 15 or more years, academics and civil society have provided detailed analysis of the governance challenges presented by SRM research and deployment. There have also been several proposals for governance principles for responsible research and development of SRM that are broadly in agreement[486]. With questions of SRM governance being now raised in international fora, eg the United Nations Environment Assembly (UNEA) and London Protocol, and regional fora, eg the European Commission, it is important to take stock of these rapidly evolving developments.

This chapter provides an overview of recent SRM governance efforts, focusing on research governance as this is where the bulk of these efforts has been focused. Broadly agreed governance principles are explained, as well as the challenges that project teams face in making these principles operational. The governance challenges that national and international policymakers face are also explored. While this chapter focuses on nearer-term governance issues, some of the longer-term governance issues that SRM presents, such as mitigation deterrence, are touched on here and in other chapters.

485 *Op. cit.* 16.

486 Brent K, Simon M, McDonald J. 2024 From informal to formal governance of solar radiation management. *Climate Policy* **0**, 1–18. See: https://doi.org/10.1080/14693062.2024.2430688 (accessed 1 October 2025).

8.1 International and domestic governance efforts

There are no binding international agreements that specifically govern SRM research or deployment, and attempts by treaty bodies to develop governance mechanisms for either or both types of activities have been limited[487]. The 1977 Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD) only prohibits the "hostile" use of environmental modification. There is potential for the ENMOD convention to be amended to provide more comprehensive SRM governance, but at present this prohibition would not apply to SRM intended to reduce climate harm[488]. In 2010, the Conference of the Parties to the Convention on Biological Diversity (CBD) passed a non-binding resolution calling for countries to prohibit activities that might negatively affect biodiversity until there is greater scientific justification, with the exception of small-scale research activities in controlled settings[489].

Parties to the London Protocol on marine pollution are currently considering further amendments to that treaty which could restrict certain ocean-based SRM proposals (eg, MCB)[490].

The governance of SRM has also been raised twice at the UNEA. In 2019, Switzerland alongside several other countries unsuccessfully proposed a resolution calling for an assessment of the current state of knowledge of SRM and carbon dioxide removal technologies[491]. At the February 2024 UNEA-6 meeting, a new proposal was put forward to conduct a scientific assessment of SRM. The proposal did not reach consensus, with significant disagreements between the parties over the introductory text, framing and scope of such an assessment[492]. Some countries also proposed a more restrictive 'non-use agreement', echoing an academic campaign which seeks to prohibit outdoor experimentation and public funding for SRM research, in addition to deployment[493].

487 Reynolds J L. 2017 An economic analysis of liability and compensation for harm from large-scale solar climate engineering field research. In: Mathis K, Huber BR (eds) *Environmental Law and Economics*. Switzerland, Springer International Publishing. See: https://doi.org/10.1007/978-3-319-50932-7_20 (accessed 1 October 2025).

488 McGee J, Brent K, McDonald J, Heyward C. 2020 International governance of solar radiation management: does the ENMOD convention deserve a closer look? *Carbon and Climate Law Review* **14**, 294–305. See: https://www.jstor.org/stable/27076703 (accessed 1 October 2025).

489 McGee J, Brent K, Burns W. 2018 Geoengineering the oceans: an emerging frontier in international climate change governance. *Australian Journal of Maritime and Ocean Affairs* **10**, 67–80. See: https://doi.org/10.1080/18366503.2017.1400899 (accessed 1 October 2025).

490 International Governance of mCDR: Small Steps Forward, but Much More Work to do. See https://blogs.law.columbia.edu/climatechange/2025/01/09/international-governance-of-mcdr-small-steps-forward-but-much-more-work-to-do/ (accessed 15 September 2025).

491 Jinnah S, Nicholson S. 2019 The hidden politics of climate engineering. *Nature Geoscience* **12**, 876–879. See: https://doi.org/10.1038/s41561-019-0483-7 (accessed 1 October 2025).

492 McLaren D, Corry O. 2025 Solar geoengineering research faces geopolitical deadlock. *Science* **387**, 28–30. See: https://doi.org/10.1126/science.adr9237 (accessed 1 October 2025).

493 Biermann *et al.* 2021 Solar Geoengineering: The case for an international non-use agreement. *WIREs Climate Change* **13**, e754. See: https://doi.org/10.1002/wee.754 (accessed 1 October 2025).

In September 2023, the Climate Overshoot Commission, composed of high-level former government ministers from around the world, recommended implementing a moratorium on SRM deployment and large-scale experiments with a risk of significant transboundary harm[494]. In December 2024, the European Commission received recommendations from their chief scientific advisors including a call to impose an EU-wide moratorium on SRM deployment and large-scale field experiments and to push for an international moratorium[495]. Both groups also recommended expanded research and that small-scale field experiments should be permitted.

At a domestic level, nation states are yet to implement SRM-specific regulation or oversight. However, legislation that would ban SRM, weather control and atmospheric releases of chemicals has been passed in four US states and proposed in 30 more and at the federal level[496]. The previous administration in Mexico also announced an intention to ban SRM activities[497], including research, in 2023 following small-scale releases in its territory conducted by Make Sunsets, a US company.

8.2 Voluntary research governance principles

Independent from activities in international and domestic fora are efforts by academics and various organisations to develop voluntary governance principles for SRM research. The first set of principles was led by academics at the University of Oxford in 2009 and published in a report to the UK House of Commons Science and Technology Committee[498]. There has since been a proliferation of similar sets of principles, most recently by the American Geophysical Union[499]. While each set of principles has been authored by different groups, with different audiences in mind (eg, researchers, domestic and/or international policymakers), there is a considerable degree of similarity, making it possible for researchers to distill shared principles. Here, we summarise the findings of a recent review of these governance principles by Brent *et al*. (2024)[500]; see Figure 13 for an overview.

Although voluntary in nature, these principles represent shared expectations regarding: (1) the objectives of SRM governance; (2) the timing and form of SRM governance; and (3) the types of operational and procedural rules needed to promote responsible SRM research.

494 Climate Overshoot Commission. 2023 Reducing the Risks of Climate Overshoot. See https://www.overshootcommission.org/_files/ugd/0c3b70_bab3b3c1cd394745b387a594c9a68e2b.pdf (accessed 15 September 2025).

495 *Op. cit*. 23.

496 SRM360 2025, US proposals to ban solar geoengineering. See https://srm360.org/us-bans/ (accessed 1 October 2025).

497 Temple J. 2023 What Mexico's planned geoengineering restrictions mean for the future of the field. MIT Technology Review. January 20 2023. See https://www.technologyreview.com/2023/01/20/1067146/what-mexicos-planned-geoengineering-restrictions-mean-for-the-future-of-the-field/ (accessed 15 September 2025).

498 Rayner S, Redgwell C, Savulescu J, Pidgeon N, Kruger T. 2009 Memorandum on draft principles for the conduct of geoengineering research. House of Commons Science and Technology Committee enquiry into The Regulation of Geoengineering. See http://www.schrogl.com/03ClimateGeo/DOKUMENTE/102_HOUSE_OF_COMMONS_MEMO_REGULATION_GEOENGINEERING_2009.pdf (accessed 15 September 2025).

499 AGU Global Initiatives. 2024 Ethical Framework for Climate Intervention. See https://www.agu.org/ethicalframeworkprinciples (accessed 15 September 2025).

500 *Op. cit*. 486.

Brent *et al*. (2024)[501] conclude that there is general agreement among these sets of principles that SRM governance should:

- aim to promote responsible research, minimising risks while also realising potential climate benefits,
- avoid detracting from efforts to reduce greenhouse gas emissions,
- be consistent with existing legal rules and principles of environmental and intergenerational justice.

There is also strong support for developing 'adaptive' governance mechanisms that can evolve in the light of changing scientific knowledge and community attitudes[502, 503]. One idea is to establish thresholds for either proceeding with projects (sometimes known as 'stage gates') or for terminating projects (sometimes known as 'exit ramps')[504]. Another is to impose a moratoria or temporary ban on larger-scale SRM activities while allowing smaller-scale field experiments and other research to proceed (see Section 8.5).

These sets of principles also propose norms to manage risks, promote research integrity and engage the public.

- **Risk management**
  Common recommendations include developing impact assessment, risk management and monitoring protocols. Some proposals recommend adopting a precautionary approach (though how to apply this in the context of climate risks is unclear, see below). Most recommend liability or insurance mechanisms to respond to harm that might occur as a result[505, 506].
- **Research integrity**
  There is general agreement that research should be conducted transparently, involving interdisciplinary expertise, with results subject to rigorous peer review. Most sets of principles also recommend that commercial interests should be avoided if they are likely to detract from the credibility of research.
- **Public Engagement**
  All sets of principles advocate for public engagement processes, with some also voicing additional support for engagement with vulnerable communities and First Nations People, as well as access to dispute resolution mechanisms. Given the potentially global nature of SAI, voluntary sets of principles also emphasise the need for international cooperation, such as the coordination of research programmes, and the development of SRM governance.

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501 *Op. cit.* 486.

502 Payne CR, Shwom R, Heaton S. 2015 Public Participation and Norm Formation for Risky Technology: Adaptive Governance of Solar-Radiation Management. *Climate Law* **5**, 210-251. See: https://doi.org/10.1163/18786561-00504005 (accessed 1 October 2025).

503 Simon M. 2024 Learning from weather modification law for the governance of regional solar radiation management. Singapore: Springer Nature. See: https://doi.org/10.1007/978-981-97-1904-4 (accessed 1 October 2025).

504 Diamond *et al.* 2022 To assess marine cloud brightening's technical feasibility, we need to know what to study – and when to stop. *Proceedings of the National Academy of Sciences of the United States of America* **119**. See: https://doi.org/10.1073/pnas.2118379119 (accessed 1 October 2025).

505 Horton J B, Lefale P, Keith D. 2021 Parametric Insurance for Solar Geoengineering: Insights from the Pacific Catastrophe Risk Assessment and Financing Initiative. *Global Policy* **12**, 97–107. See: https://doi.org/10.1111/1758-5899.12864 (accessed 1 October 2025).

506 Reynolds J L. 2019 Solar geoengineering to reduce climate change: A review of governance proposals. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* **475**, 2229. See: https://doi.org/10.1098/rspa.2019.0255 (accessed 1 October 2025).

FIGURE 13

Summarising research governance principles.

1 GOVERNANCE OBJECTIVES

- Enable responsible research
- Promote climate benefits
- Minimise risks
- Avoid mitigation deterrence
- Congruence with law
- Environmental justice

2 TIMING AND FORM OF GOVERNANCE

- Early governance of research
- Incremental and adaptive governance
- Place temporary limits on activities

3 PROCEDURAL AND OPERATIONAL PRINCIPLES

Manage risk and uncertainty

- Risk assessment, management and minimisation
- Monitoring and review
- Precautionary approach
- Mechanisms to respond to damage

Promote research quality and credibility

- Transparency
- Peer review of research
- Interdisciplinarity
- Prevent negative commercial interests

Public engagement

- Participation processes
- Engagement with vulnerable groups
- Engagement with First Nations groups and rightsholders
- Dispute resolution
- International cooperation

Source: Based on (Brent *et al.*, 2024)[507].

507 *Op. cit.* 486.

8.3 Overview of SRM field experiments

Several small-scale SRM field experiments have been planned over recent years, some of which were conducted, while others were cancelled. Table 1 presents a list of all publicly disclosed SRM field experiments to date; there may be others that have yet to be disclosed. As mentioned in Chapter 1, further field experiments are also planned, eg, those funded by the UK's ARIA research programme. Field experiments can contribute to better understanding of key processes in the climate system and improve model representations of SRM approaches. It is worth noting that field experiments that perturb atmospheric composition are not unique to SRM research, and there are many such experiments in environmental science, such as Free-Air Carbon dioxide Enrichment (FACE) experiments[508]. However, as SRM research moves outdoors, there has been heightened controversy and concern.

To date, small-scale SRM field experiments appear to pose negligible environmental impacts, in themselves, given the relatively tiny releases of material into the environment compared to those from natural or non-deliberate anthropogenic practices. For example, experiments could involve releasing kilograms of SO_2 for SAI as compared to the Tg released by volcanic eruptions.

The motivations and objectives for these field experiments differ considerably, which complicates efforts to govern such activities by their intent. Most, but not all, of the SRM field experiments listed in Table 1 were explicitly motivated by a desire to advance the scientific understanding of SRM or to develop the engineering capability to test or deploy SRM. However, some, such as E-PEACE and CloudLab were motivated by understanding aerosol-cloud processes for their own sake but also had implications for understanding SRM interventions.

Researchers are largely based at academic institutions with some involvement from the government and private sector. Funders similarly vary, with a mix of philanthropic and government funding, though commercial actors are also working in this space.

508 Ainsworth E A, Long S P. 2021 30 years of free-air carbon dioxide enrichment (FACE): What have we learned about future crop productivity and its potential for adaptation?. *Global Change Biology* **27**, 27–49. See: https://doi.org/10.1111/gcb.15375 (accessed 1 October 2025).

TABLE 1

Overview of publicly disclosed SRM field experiments.

Project	Description
Russian aerosol experiments (2008 – 2010)	**Completed** A series of experiments in Russia observed the effects of tropospheric aerosol layers generated by smoke generators on sunlight reaching the surface[509].
SPICE (2010 – 2012)	**Cancelled** A proposed engineering test of a tethered balloon deployment method for SAI, subject to additional governance by funder and cancelled after intellectual property conflict of interest discovered as well as some Non-Governmental Organisation (NGO) opposition[510].
E-PEACE (2011)	**Completed** The Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE) was a ship-borne experiment to evaluate the cloud response to the introduction of aerosol particles from a smoke generator[511].
SCoPEx (2015 – 2024)	**Cancelled** A proposed SAI experiment involving a propelled balloon platform to release a few kg of aerosols in the stratosphere to better understand their dispersion and chemistry. Pushback from some NGOs as well as public engagement issues in Sweden, where the platform was being tested, contributed to the team canceling the project in March 2024[512].
Great Barrier Reef Restoration and Adaptation Program (RRAP)[513] (2020 – Present)	**Ongoing** This project has tested ship-borne sea salt spraying devices to evaluate the potential of marine cloud brightening to protect the Great Barrier Reef. The first experiment was conducted in March 2020, and further work is ongoing[514, 515].

509 Izrael *et al.* 2009 Field experiment on studying solar radiation passing through aerosol layers. *Russian Meteorology and Hydrology* **34**, 265–273. See: https://doi.org/10.3103/s106837390905001x (accessed 1 October 2025).

510 Cressey D. 2012 Geoengineering experiment cancelled amid patent row. *Nature*. See: https://doi.org/10.1038/nature.2012.10645 (accessed 1 October 2025).

511 Russell *et al*. 2013 Eastern Pacific Emitted Aerosol Cloud Experiment. Bulletin of the American Meteorological Society 94, 709–729. See: https://doi.org/10.1175/BAMS-D-12-00015.1 (accessed 1 October 2025).

512 Jinnah *et al*. 2024 Do small outdoor geoengineering experiments require governance? *Science* **385**, 600–603. See: https://doi.org/10.1126/science.adn2853 (accessed 1 October 2025).

513 Reef Restoration and Adaptation Program: Cooling and Shading. See https://gbrrestoration.org/program/cooling-and-shading/ (accessed 15 September 2025).

514 Foster R, Shumway N, Harrison D, Fidelman P. 2025 Governing marine cloud brightening for ecosystem conservation under a warming climate. *Earth System Governance* **23**, 100240. See: https://doi.org/10.1016/j.esg.2025.100240 (accessed 1 October 2025).

515 *Op. cit.* 116.

TABLE 1 (CONTINUED)

Project	Description
SATAN (2022)	**Completed** The Stratospheric Aerosol Transport and Nucleation (SATAN) project conducted a demonstration of the controlled release of 400 grams of SO_2 into the stratosphere via a balloon system launched from Southeast England[516]. There do not appear to be peer reviewed outputs from this work.
CLOUDLAB (2022 – Present)	**Ongoing** A field experiment to investigate the effect of cloud seeding on mixed phase clouds conducted in Switzerland. This research aims to understand fundamental cloud properties, but also provides insights into mixed phase cloud thinning, an SRM proposal that is in its infancy[517].
University of Washington Experiment (2024)	**Cancelled/Delayed** An MCB experiment that sprayed salt aerosols to assess if they could be sprayed at the correct size. The experiment was launched publicly in April 2024 and stopped after the City of Alameda council raised concerns in June 2024[518]. The research team has indicated they are looking for other sites.
Advanced Research and Invention Agency (ARIA)	**Planned** Five projects will undertake outdoor experiments. These experiments will only proceed if ARIA's governance requirements, ensuring safety, ethical conduct, environmental responsibility, and community engagement, are met[519]. These will explore: the efficacy of rethickening Arctic sea ice, the effects of seawater spray on cloud reflectivity, the effects of electric charge on cloud reflectivity, and the ageing of mineral dusts in the stratosphere (though none of these materials will be released into the atmosphere). Project lengths vary from 15 months to over three years.

516 Temple J. 2023 Researchers launched a solar geoengineering test flight in the UK last fall. 1 March 2023. See https://www.technologyreview.com/2023/03/01/1069283/researchers-launched-a-solar-geoengineering-test-flight-in-the-uk-last-fall/ (accessed 15 September 2025).

517 Henneberger *et al.* 2023 Seeding of Supercooled Low Stratus Clouds with a UAV to Study Microphysical Ice Processes: An Introduction to the CLOUDLAB Project. *Bulletin of the American Meteorological Society.* See: https://doi.org/10.1175/BAMS-D-22-0178.1 (accessed 1 October 2025).

518 Begert B. 2024 California city votes to block solar geoengineering experiment. April 5 2024. See https://www.eenews.net/articles/california-city-votes-to-block-solar-geoengineering-experiment/ (accessed 15 September 2025).

519 Advanced Research and Invention Agency: Exploring Climate Cooling. See https://www.aria.org.uk/opportunity-spaces/future-proofing-our-climate-and-weather/exploring-climate-cooling (accessed 15 September 2025).

8.4 Research governance challenges for project teams and institutions

In the absence of formal SRM governance mechanisms (aside from regulations generally applicable to research activities), some project teams and institutions have developed ad-hoc standards and processes. These range from establishing independent oversight or advisory bodies to researchers and private funders self-governing their activities. This inconsistency between these approaches and the lack of accountability mechanisms may detract from the perceived legitimacy of research programmes[520].

Existing research programmes underscore the challenge of putting the following voluntary SRM governance principles into practice:

- **Transparency**
  Transparency in funding and data are common practice for responsible research in emerging fields. Almost all versions of SRM governance principles highlight transparency as a necessary aspect of oversight, yet practice varies widely between projects[521]. A related concern is the extent to which projects disclose funding sources and potential conflicts of interest. The revelation of an undisclosed conflict of interest regarding intellectual property was reported to be a key contributing factor in the cancellation of field experiments in the SPICE project[522].
- **Research integrity**
  SRM research supported through government funding typically undergoes rigorous scientific merit review processes. Private actors, however, may not be subject to this level of scientific oversight.
- **Public engagement**
  Public engagement encompasses methods used by researchers, funding organisations, and decision-making bodies to inform, gather input from, understand, and empower the public and stakeholders. What constitutes meaningful public engagement, who should be engaged for field experiments, and what is sufficient for different research proposals are amongst the most debated aspects of research governance in SRM. Making principles operational for public engagement can be both challenging and potentially contentious. Even when engagement is built into a research program, social licence cannot be guaranteed. For example, while SCoPEX had plans for engagement, vocal opposition from Indigenous communities arose which led the Swedish hosts of the experiment to cancel a planned launch.

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520 *Op. cit.* 512.

521 Talati S, Buck H J, Kravitz B. 2025 How to address solar geoengineering's transparency problem. *Proceedings of the National Academy of Sciences* **122**. See: https://doi.org/10.1073/pnas.2419587122 (accessed 1 October 2025).

522 *Op. cit.* 510.

8.5 International governance challenges

There are several near- and mid-term governance challenges that national and/or international policymakers face prior to any deployment of SRM. These include:

- **Mitigation deterrence**
  Limiting the potential for research and development of SRM to undermine efforts to cut emissions, ie, to avoid mitigation deterrence (also known as 'moral hazard'). This is a complex issue that dovetails with broader climate policy[523, 524]. As a starting point, it is important to develop a more nuanced understanding of the extent and nature of this risk[525, 526].

- **The precautionary principle**
  Considering the application of the precautionary principle to SRM research governance. This is a widely accepted principle of environmental governance, generally understood to mean that scientific uncertainty should not be used as a basis to avoid taking steps to prevent significant harm. How this principle should be interpreted in relation to SRM is unclear, given that SRM is intended to address risks associated with climate change[527, 528]. However, Davies and Vinders (2025)[529] conclude that it does suggest a procedural requirement to conduct a comprehensive review of the evidence before decision-making on SRM policy.

- **Balanced assessments**
  Conducting a balanced assessment of SRM. SRM is highly contentious and even deciding whether and how to assess the possibility has proven challenging, with calls for such an assessment at the UNEA falling through twice (see Section 8.1). A balanced assessment of SRM would need to weigh the physical risks of SRM against the risks of climate change that it might help reduce, but it would also need to consider the broader socio-political and geopolitical risks associated with SRM and climate change[530].

- **International cooperation**
  Promoting international cooperation. This includes international collaboration on research programmes, eg, the World Climate Research Programme's lighthouse activity on SRM, and scientific assessments, eg, through the IPCC or as a stand-alone report through UNEA or the UN Convention on Biological Diversity (UNCBD). Ensuring that developing countries have sufficient resources and expertise to contribute to international assessments, research programs, and governance discussions is another important consideration[531].

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523 McLaren D. 2016 Mitigation deterrence and the "moral hazard" of solar radiation management. *Earth's Future* **4**, 596–602. See: https://doi.org/10.1002/2016EF000445 (accessed 1 October 2025).

524 *Op. cit.* 506.

525 *Op. cit.* 523.

526 Tsipiras K, Grant W J. 2022 What do we mean when we talk about the moral hazard of geoengineering? *Environmental Law Review* **24**, 27–44. See: https://doi.org/10.1177/14614529211069839 (accessed 1 October 2025).

527 *Op. cit.* 486.

528 *Op. cit.* 506.

529 Davies G, Vinders J. 2025 Geoengineering, the Precautionary Principle, and the Search For Climate Safety. *European Journal of Risk Regulation,* 1–12. See: https://doi.org/10.1017/err.2025.14 (accessed 1 October 2025).

530 Brent, K. 2023 Solar Geoengineering and the Challenge of Governing Multiple Risks in the Anthropocene. *The Routledge Handbook of Law and the Anthropocene.* See: https://doi.org/10.4324/9781003185360-39 (accessed 1 October 2025).

531 Winickoff D E, Flegal J A, Asrat A. 2015 Engaging the Global South on climate engineering research. *Nature Climate Change* **5**, 627–634. See: https://doi.org/10.1038/nclimate2632 (accessed 1 October 2025).

As the scale of field activities increases, policymakers and international organisations will need to contend with potential geopolitical and security risks, especially in the absence of widely agreed rules of international law[532, 533].

- **A potential moratorium**
  Assessing the suitability and potential parameters of a moratorium. As mentioned above, adopting a temporary ban on certain SRM activities has been suggested as an interim governance measure (see also McLaren and Corry 2025[534]). Most recently, the European Commission's Group of Chief Scientific Advisors recommended a moratorium on large-scale SRM activities[535]. Key challenges in instituting a moratorium would include clearly defining prohibited activities, including any scale or threshold-based parameters, establishing the conditions for terminating the moratoria, and the process for making any such determinations[536]. One suggestion is to include time limits as it can be challenging to lift a moratorium without them, even if uncertainties are sufficiently reduced and adequate governance mechanisms established[537].

If SRM were ever deployed at climate-altering scales, there are several additional governance considerations that would need to be addressed. Given space constraints and the more pressing nature of nearer-term governance challenges, here we raise some of these issues briefly and in the form of questions:

- What could be done to discourage or constrain unilateral deployment and promote multilateral, inclusive decision-making on SRM deployment?
- How could SRM be responsibly integrated into climate policy plans, and what could it mean for emissions cut targets and other climate policies?
- How could claims of harm resulting from SRM deployment be evaluated and remedied, given the uncertainties in attributing regional climate trends?
- What steps could be taken to build trust and reduce the risks of conflict over the potential deployment of SRM?
- How could the long-term stability of SRM deployment be ensured to limit the risk of termination effects, ie, a potential rapid warming, if it were interrupted (see Section 5.4)?

532 Corry O, McLaren D, Kornbech N. 2024 Scientific models versus power politics: How security expertise reframes solar geoengineering. *Review of International Studies*, 1-20. See: https://doi.org/10.1017/S0260210524000482 (accessed 1 October 2025).

533 Lockyer A, Symons J. 2019 The national security implications of solar geoengineering: An Australian perspective. *Australian Journal of International Affairs* **73**, 485–503. See: https://doi.org/10.1080/10357718.2019.1662768 (accessed 1 October 2025).

534 McLaren D, Corry O. 2025 Solar geoengineering research faces geopolitical deadlock. *Science* **387**, 28–30. See: https://doi.org/10.1126/science.adr9237 (accessed 1 October 2025).

535 *Op. cit.* 23

536 Herzog M, Parson E, Ted A. 2016 Moratoria for Global Governance and Contested Technology: The Case of Climate Engineering (SSRN Scholarly Paper No. 2763378). Social Science Research Network. See: https://doi.org/10.2139/ssrn.2763378 (accessed 1 October 2025).

537 Bodansky D. 2013 The who, what, and wherefore of geoengineering governance. *Climatic Change* **121**, 539–551. See: https://doi.org/10.1007/s10584-013-0759-7 (accessed 1 October 2025).

8.6 Governance conclusions

SRM governance is a complex, evolving, and often sensitive topic, and the issues raised by research and potential implementation are distinct. It is important to recognise that this chapter gives only a brief introduction, providing a snapshot of the current state of play of SRM governance in both the literature and in practice, and focusing on nearer-term governance challenges associated with research. SRM governance activity is underpinned by more than 15 years of governance research and guidance, providing detailed, interdisciplinary perspectives on the challenges SRM presents. Moreover, there is now a collection of common governance principles that provide a strong foundation for developing formal mechanisms across multiple scales. Efforts by research teams to develop self-governance for SRM projects provide early lessons for how principles can be made operational in practice. However, these efforts also highlight the limits of ad-hoc governance approaches, and the relationship between governance (or lack thereof) and public trust concerning these proposed technologies.

As the scale of SRM research and technology development activities grows, shifting from informal to formal governance arrangements could help to ensure this is managed responsibly. International fora, such as international organisations and treaty bodies, could play an important role in SRM governance, but the potential role of national, sub-national and institutional governance should not be underestimated. For example, institutional rules, research ethics processes, and domestic law could all play a crucial role in governing SRM research[538, 539]. As a starting point, SRM governance could be elevated onto domestic policy agendas, with responsibility for monitoring this issue and developing policies towards it clearly allocated to relevant departments and organisations.

538 *Op. cit.* 486.

539 McDonald J, Simon M. 2023 Ethics requirements for environmental research. *Australasian Journal of Environmental Management* **30**, 148–169. See: https://doi.org/10.1080/14486563.2023.2217152 (accessed 1 October 2025).

Conclusions

Currently implemented policies on greenhouse gas emissions are projected to lead to a peak global-mean warming this century of about 3.1°C (relative to pre-industrial levels). Such a warming would have high to very high risks of potential adverse consequences and be a breach of the UNFCCC Paris Agreement 1.5°C warming target.

Scientific evidence assessed in this Briefing indicates that, with high confidence, Solar Radiation Modification, if it was ever deemed necessary, could be used to mask global-mean warming due to greenhouse gases; the intended extent of that masking would be a policy choice. Many impacts of climate change associated with global-mean temperature rise (including sea-level rise, wildfires and extreme precipitation) would be expected, on average, to be reduced in a world with lower temperatures.

The most-researched methods for SRM (stratospheric aerosol injection (SAI) and marine cloud brightening (MCB)) utilise atmospheric aerosol particles to reflect a portion of incoming sunlight back to space; the climate effects of SAI have been subject to significantly more research and are currently better understood than MCB.

Understanding of SRM's climate effects is mostly based on research using climate models, supported, to an extent, by understanding of observed real-world analogues to SAI and MCB. This research indicates that the extent of masking of global-mean surface temperature by SRM would not fully carry over to regional temperature change or other climate variables, such as precipitation and regional circulation patterns.

The strategy by which SRM is implemented is modelled to have large effects on the eventual climate outcome. At one extreme, it might be applied in a globally-coordinated and scientifically-informed way to reduce some undesirable regional impacts. At another extreme it might be applied in an uncoordinated way, perhaps by a single party, that could lead to large regional climate responses. This indicates that international governance of any SRM deployment would be essential if risks of adverse consequences were to be reduced.

Aerosols that cause SRM's cooling effect are much shorter-lived in the atmosphere than gases most responsible for global warming. Hence, regular injections would be necessary to maintain the cooling effect. Depending on the intended extent of masking, and the success or otherwise to mitigate the greenhouse gas emissions, this implies that a long-term commitment to SRM could be necessary. Should injections be abruptly halted or significantly reduced in extent (unless it was for a short period – a few months to a year), there would be a termination effect where the climate would return to its state without SRM in about a decade. If temperatures would have continued to rise significantly without SRM, this termination effect would have strong impacts on sensitive planetary systems that cannot adapt quickly, such as natural ecosystems.

Much progress has been made in understanding the climate impact of SRM in recent years, but many knowledge gaps have been identified and explored, many of which are also relevant more generally to understanding the climate impact of human activity. These gaps include:

- Uncertainties in the quantity of aerosol required to cause a given cooling. This is associated (a) with limitations in the ability of the current generation of climate models to represent small scale-processes associated with aerosols and clouds – this in itself is limited by incomplete understanding of those small-scale processes and by insufficient observations to test and improve that understanding; and (b) with a more fundamental uncertainty in the sensitivity of global-mean temperatures to changing concentrations of (for example) greenhouse gases and aerosols.

- Uncertainties in the representation of regional responses (for example in temperature and rainfall, including local extremes) to climate change. These uncertainties arise from long-standing model biases in large-scale circulation patterns and recurrent variations in these patterns, and difficulties in representing small scale features and processes in models with relatively coarse spatial resolution. There is little confidence in the ability of current models to predict how some circulation patterns will change as climate changes (with or without SRM). Because of this, it cannot be ruled out that SRM could, in some locations, exacerbate the impacts of climate change
- Monitoring of the climate effects of SRM at both global and regional scales. An adequate and sustained global climate observing system, and robust techniques to detect and attribute the effects of any deployment, would be needed. Because of the natural variability of climate, which is more marked at regional scales, confident detection of the impact of SRM on surface temperatures might take decades. It is also important to maintain continuity in current global observational capacity to monitor ongoing global change and to provide essential data to test and improve climate models.
- Uncertainties in the possible wider effects of SRM on the wider Earth System, including stratospheric ozone, ocean circulation, the cryosphere and natural and managed terrestrial and marine ecosystems.

If greenhouse gas emissions continue to rise, or do not fall rapidly enough to avoid prolonged adverse consequences of climate change, at some point in the future policymakers may decide that the risks associated with SRM deployment are smaller than those associated with climate change without SRM.

The many uncertainties associated with the climate effect of SRM deployment, and the fact that it would only partially mask the climate effects of increased greenhouse gas concentrations for the duration of its deployment, lead us to reaffirm the view expressed in the IPCC's Sixth Assessment Report: if it is decided that the risks associated with climate change need to be reduced, then SRM should not be the main policy response to climate change; it would, at best, be a supplement to action to further mitigate greenhouse gas emissions.

Many other important issues beyond climate science would need to be considered prior to any decision to deploy SRM. These include governance, engineering feasibility, economic costs, public perception, transparency, ethics and inclusivity. This indicates that a thorough and inclusive multidisciplinary assessment of all aspects of SRM would be necessary, under the auspices of an appropriate international body.

ANNEX A

Expert evaluation of proposed SRM methods

50 experts were contacted in March 2025, of which 22 replies were received and collated. The experts were selected as having at least one of the following: a significant contribution to publications in GeoMIP, author on the UNEP (2023) report, lead authors of Chapter 6 of the 2026 WMO Ozone Assessment, and scientific attendees of the University of Washington Marine Cloud Brightening Workshop (April 2025).

Each participant was asked to make an objective assessment as follows, "Based on the ability of the various techniques in providing a 1°C cooling please provide your expert judgement (1 = lowest, 6 = highest) on the following":

- Effectiveness in achieving a 1°C cooling
- Technical barriers
- Level of Scientific Understanding (a composite LOSU combining LOSU of effectiveness, technical barriers, and risks)

Figure 4 shows the results.

The evaluation was led by Josh Smith and James Haywood (University of Exeter)

Participants were also asked to make an objective assessment of risks (potential for adverse consequences) of each technique, but following concern about its interpretation from peer reviewers, it was not used here.

ANNEX B

Future pathways

The 'Shared Socioeconomic Pathways' (SSPs)[540, 541] are narratives for five possible futures, focusing on the social and economic factors that drive fossil fuel use. These socio-economic scenarios are used to derive emissions scenarios, which form the basis of climate projections. The SSPs were used extensively in IPCC AR6.

The SSPs encompass different challenges for mitigation and adaptation: sustainable development (SSP1), middle-of-the-road development (SSP2), regional rivalry (SSP3), inequality (SSP4), and fossil-fuelled development (SSP5). SSP1 policies focus on well-being, clean energy technologies, and the preservation of the natural environment. Conversely, SSP3 includes heavy reliance on fossil fuels and an increased use of coal, while nationalism drives policy so that focus is placed on regional and local issues rather than on global issues.

Within an SSP there can be multiple emission scenarios, driven by different assumptions about mitigation, which lead to different levels of radiative forcing and global mean temperature rise. The SSPs have some alignment with the 'Representative Concentration Pathways' (RCPs), which featured in IPCC AR5. The RCPs described different emission pathways to reach a range of radiative forcing in 2100 (2.6, 4.5, 6.0, and 8.5 W m^{-2}), but did not include socioeconomic narratives. The radiative forcing in each SSP is denoted by a second set of numbers, eg SSP1-1.9 and SSP1-2.6, which have a radiative forcing of 1.9 and 2.6 W m^{-2} by 2100, respectively.

SSP1-1.9 is in line with Paris Agreement targets, while SSP2-4.5 is the closest representation of the trajectory arising from currently implemented policies. The majority of SRM experiments use SSP2-4.5 or RCP4.5, as their baseline. SSP1-1.9 and SSP1-2.6 both rely on carbon dioxide removal (CDR – ie, technologies or practices that achieve long-term removal of CO_2 from the atmosphere) to stay below 2°C above pre-industrial temperatures by 2100. IPCC (2023)[542] therefore regards deployment of CDR as 'unavoidable' if net-zero is to be achieved. However, there are many concerns as to whether it can be deployed at the necessary scale, and about the social and environmental risks of doing so[543].

540 Riahi *et al*. 2017 The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* **42**, 153–168. See: https://doi.org/10.1016/j.gloenvcha.2016.05.009 (accessed 1 October 2025).

541 Chen *et al.* 2021 Framing, context and methods. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press, Cambridge,* United Kingdom and New York, NY, USA.147–286. See: https://doi.org/10.1017/9781009157896.003 (accessed 1 October 2025).

542 IPCC. 2023 AR6 Synthesis Report: Climate Change 2023. See https://www.ipcc.ch/report/ar6/syr/ (accessed 15 September 2025).

543 *Op. cit.* 17.

Changes in global temperature tend to follow changes in radiative forcing, leading to the smooth curves seen in Figure 14. The risks of climate change increase with each degree of warming (IPCC 2023)[544], but not all aspects of the climate system change in the same steady way as global temperature. In some cases, a climate 'tipping point' may be reached, triggering sudden and potentially irreversible changes in certain components of the climate system.

Some tipping points could be passed at levels of global warming seen in the SSP2-4.5 and SSP3-7.0 pathways, triggering, for example, Amazon Rainforest dieback, an abrupt thaw of boreal permafrost, or the collapse of the West Antarctic Ice Sheet[545]. While some of these impacts will be realised decades after the tipping point is crossed, others will occur on centennial timescales. Some discussion of SRM focuses on avoiding such dramatic changes in the climate system, and whether SRM can be used to restore the system after key thresholds are crossed.

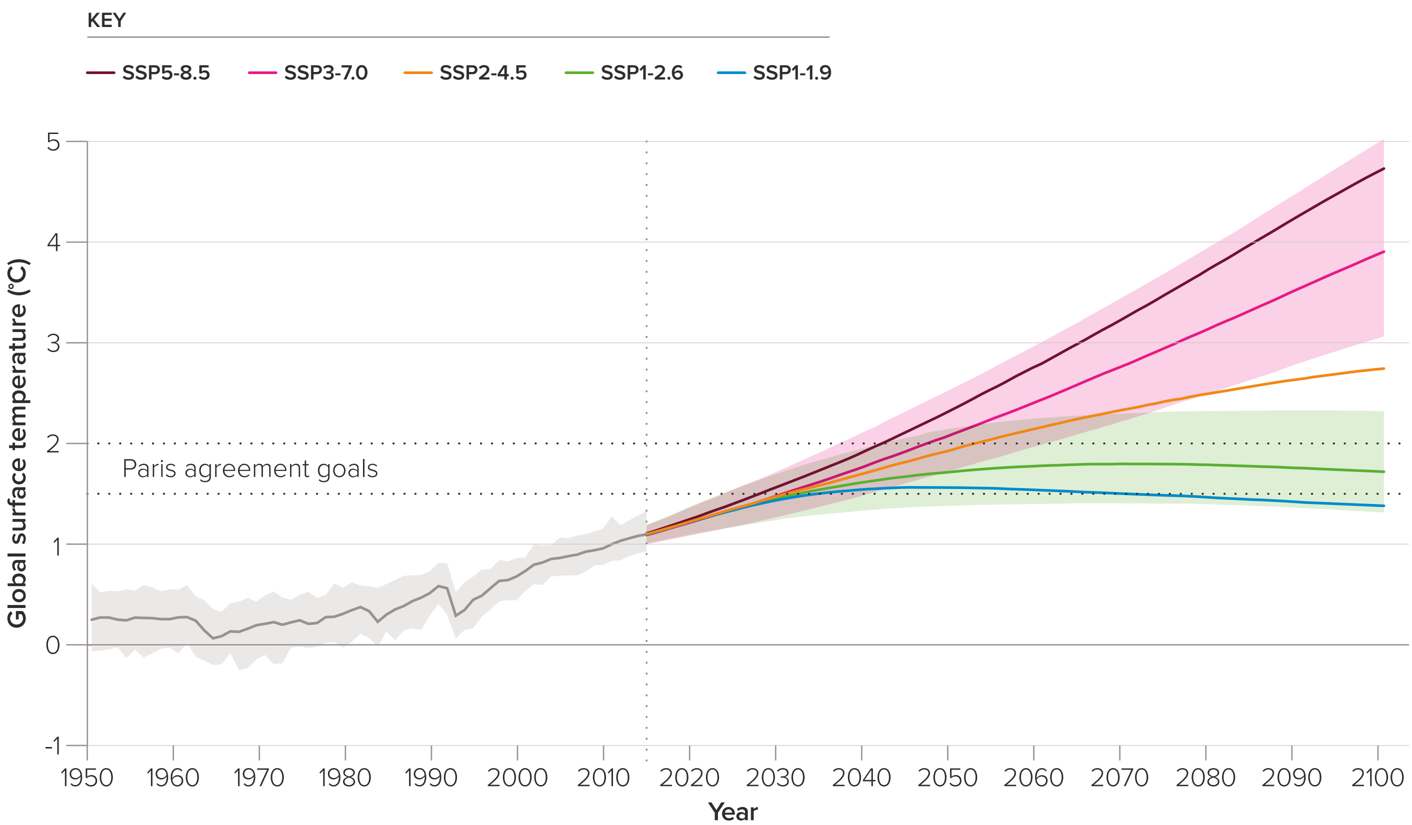
544 *Op. cit.* 542.

545 Deutloff J, Held H, Lenton T M 2025 High probability of triggering climate tipping points under current policies modestly amplified by Amazon dieback and permafrost thaw, *Earth System Dynamics* **16,** 565–583. See: https://doi.org/10.5194/esd-16-565-2025 (accessed 1 October 2025).

FIGURE 14

Global surface temperature change in °C relative to 1850 – 1900.

Observed temperature changes to 2015 are shown by the black line and different coloured lines show smoothed predicted temperature changes associated with five SSP scenarios. 'Very likely' ranges are shown for the observations and for the low and high GHG emissions scenarios (SSP1-2.6 and SSP3-7.0). Dashed horizontal lines indicate the 1.5°C and 2°C goals.



Source: Adapted from IPCC (2023)[546].

546 *Op. cit.* 542.

ANNEX C

Acknowledgements

Working group

The members of the Working Group involved in this report are listed below. Members acted in an individual and not a representative capacity and declared any conflicts of interest, of which relevant conflicts are highlighted below. Members contributed to the project based on their own expertise and good judgement.

Chair	
Professor Keith Shine FRS	Regius Professor of Meteorology and Climate Science, University of Reading

Members	
Professor David Beerling FRS	Director of the Leverhulme Centre for Climate change mitigation and Sorby Professor of Natural Sciences, University of Sheffield
Professor Ken Carslaw FRS	School of Earth and Environment, University of Leeds. Co-Chief Editor of Atmospheric Chemistry and Physics
Professor Jim Haywood	Professor of Atmospheric Science, University of Exeter and the UK Met Office (until April 2025)
Dr Matthew Henry	Senior Research Fellow, Department of Mathematics and Physics, University of Exeter
Dr Pete Irvine	Research Assistant Professor, Geophysical Sciences, University of Chicago. Editorial Director, SRM360
Professor Amanda Maycock	Professor of Climate Dynamics, University of Leeds
Professor Tim Palmer FRS	Royal Society Research Professor Emeritus in Climate Physics, University of Oxford, and Senior Fellow, the Oxford Martin Institute
Professor Sheila Rowan FRS	Physical Secretary of the Royal Society and Director of the Institute for Gravitational Research, University of Glasgow
Professor Anja Schmidt	Head of Earth System Modelling at DLR and Professor of Climate Modelling, LMU Munich
Professor Laura Wilcox	Professor of Aerosol-Climate Interactions, University of Reading

Contributing authors

Contributing authors	
Dr Kerryn Brent	Research Scientist, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Hobart, Australia.
Dr Dan Hodson	Postdoctoral Research Scientist, NCAS/ Department of Meteorology, University of Reading
Dr Shuchi Telati	Founder and Executive Director, the Alliance for Just Deliberation on Solar Geoengineering

Reviewers

This report has been reviewed by experts before being approved by the Council of the Royal Society. Reviewers were not asked to endorse the conclusions or recommendations of the report, but to act as independent referees of its technical content and presentation. Reviewers acted in a personal and not a representative capacity. The Royal Society gratefully acknowledges the contribution of the reviewers.

Reviewers	
Professor John Burrows FRS	Emeritus Professor of the Physics of the Ocean and Atmosphere and Director of the Institutes of Environmental Physics and Remote Sensing at the University of Bremen, Germany
Professor Piers Forster	Professor of Physical Climate Change and founding Director of the Priestley Centre for Climate Futures, University of Leeds. Chair of the independent Oversight Committee of ARIA's Climate Cooling Programme
Professor Gabi Hegerl FRS	Professor of Climate System Science, School of GeoSciences, University of Edinburgh
Professor Gideon Henderson FRS	Professor of Earth Sciences, University of Oxford
Professor John Pyle FRS	Emeritus Professor, Yusuf Hamied Department of Chemistry, University of Cambridge
Professor John Shepherd FRS	Emeritus Professor of Earth System Science, University of Southampton, National Oceanography Centre Southampton.
Professor Ted Shepherd FRS	Grantham Professor of Climate Science, University of Reading
Professor Julia Slingo FRS	Independent expert

Royal Society staff

Royal Society staff	
Mia Kett	Senior Policy Adviser – Climate Change
Madeleine Quirk	Programme Coordinator – People and Planet
Luke Reynolds	Head of Policy – People and Planet
Jamie Rishworth	Policy Adviser – Climate Change

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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For further information
The Royal Society
6 – 9 Carlton House Terrace
London SW1Y 5AG

T +44 20 7451 2500
E science.policy@royalsociety.org
W royalsociety.org

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9 781782 528036

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