

Solar radiation modification: Summary briefing

Introduction

The Paris Agreement to the United Nations Framework Convention on Climate Change (UNFCCC) aims to hold global-average surface temperatures to well below 2°C above pre-industrial levels and pursue efforts to limit warming to 1.5°C “recognising that this would significantly reduce the risks and impacts of climate change”¹.

The global-average surface temperature, averaged over the decade 2015 – 2024, is about 1.2°C above pre-industrial levels and the increase has been almost entirely attributed to human activity². It has been estimated that current policies implemented by Paris Agreement signatories, that aim to limit greenhouse gas (and particularly carbon dioxide (CO₂)) emissions, will almost certainly lead to a warming exceeding 2°C above pre-industrial by the year 2100, with a greater than one-third chance they will exceed 3°C³. Without further significant strengthening of mitigation actions, it appears unlikely that the Paris Agreement temperature goals will be met, which will also likely make the Agreement’s goal to increase “the ability to adapt to the adverse impacts of climate change” harder to achieve⁴.

This mismatch has led to increased attention on possible techniques for deliberate climate interventions with the aim of limiting warming and supplementing mitigation actions. One option, and the focus of this Briefing, is Solar Radiation Modification (SRM). Recent national UK funding by the Natural Environment Research Council (NERC) and the

Advanced Research and Invention Agency (ARIA) has put the UK at the forefront of SRM research^{5, 6}. SRM could mask the future warming caused by greenhouse gases by increasing the amount of sunlight reflected back into space, thus cooling the planet. It would not address the root causes of climate change associated with greenhouse gas emissions.

This document summarises the key points from the full policy briefing, *Solar radiation modification*. The policy briefing focuses on current understanding of climate science relevant to SRM, highlighting the many knowledge gaps. The briefing does not recommend whether or not further SRM research should be undertaken, but stands as a synthesis of research to date, highlighting key knowledge gaps, and presents general research governance principles that any research should follow.

Many other issues would need to be considered prior to any decision to implement SRM including engineering feasibility, costs, public perception, transparency, ethics, and inclusivity. Additionally, 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.

To view the policy briefing online and find out more about the Society’s work in this area, visit:
royalsociety.org/solar-radiation-modification

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1. The Paris Agreement. See <https://unfccc.int/process-and-meetings/the-paris-agreement> (accessed 15 September 2025).
 2. 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).
 3. 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).
 4. *Op. cit.* 1.
 5. 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).
 6. 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)
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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-coordinated⁷ 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 CO₂ concentrations would not be offset by SRM.
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.

7. 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.

Summary

Could SRM be considered a possible option in the future?

SRM must be viewed in the context of the current failure to mitigate climate change to the extent that the UNFCCC deems necessary.

- At some point in the future, policymakers may deem SRM to be the less bad of two bad options, in the sense that risks associated with its implementation might be regarded as lower than risks associated with not implementing it. At present, however, there are significant challenges in quantifying these relative risks.

If a decision was ever made to implement SRM, a globally coordinated strategy and international governance structure would be essential to both achieve global cooling and avoid potentially large undesirable regional climate effects.

- Research indicates that the deployment strategy would have large effects on the eventual climate outcome: if applied in an uncoordinated way, perhaps by a single party in one hemisphere of the planet, SRM could lead to large and potentially undesirable regional responses, in areas geographically distant from the initial area of deployment.
- International co-ordination and governance of any SRM deployment would be essential if risks of the most adverse consequences were to be ameliorated, and temperatures were to be reduced globally. Current understanding also indicates that, depending on the intended extent of SRM, a long-term commitment (many decades or even longer) would be required.

If it is ever deemed necessary, “SRM cannot be the main policy response to climate change and is, at best, a supplement to achieving sustained net-zero or net-negative CO₂ emission levels globally”^{8, 9}.

- Overall, the many uncertainties associated with the climate effects of SRM, and the fact that it could only mask the effects of increased greenhouse gas concentrations, lead us to reaffirm the view expressed in the IPCC’s Sixth Assessment Report (IPCC AR6).

What are the main proposed techniques for SRM and what is the basis for understanding their effects?

Several types of SRM have been proposed (see Figure 1). Two have received particular attention in the scientific literature: Stratospheric Aerosol Injection (SAI) and Marine Cloud Brightening (MCB).

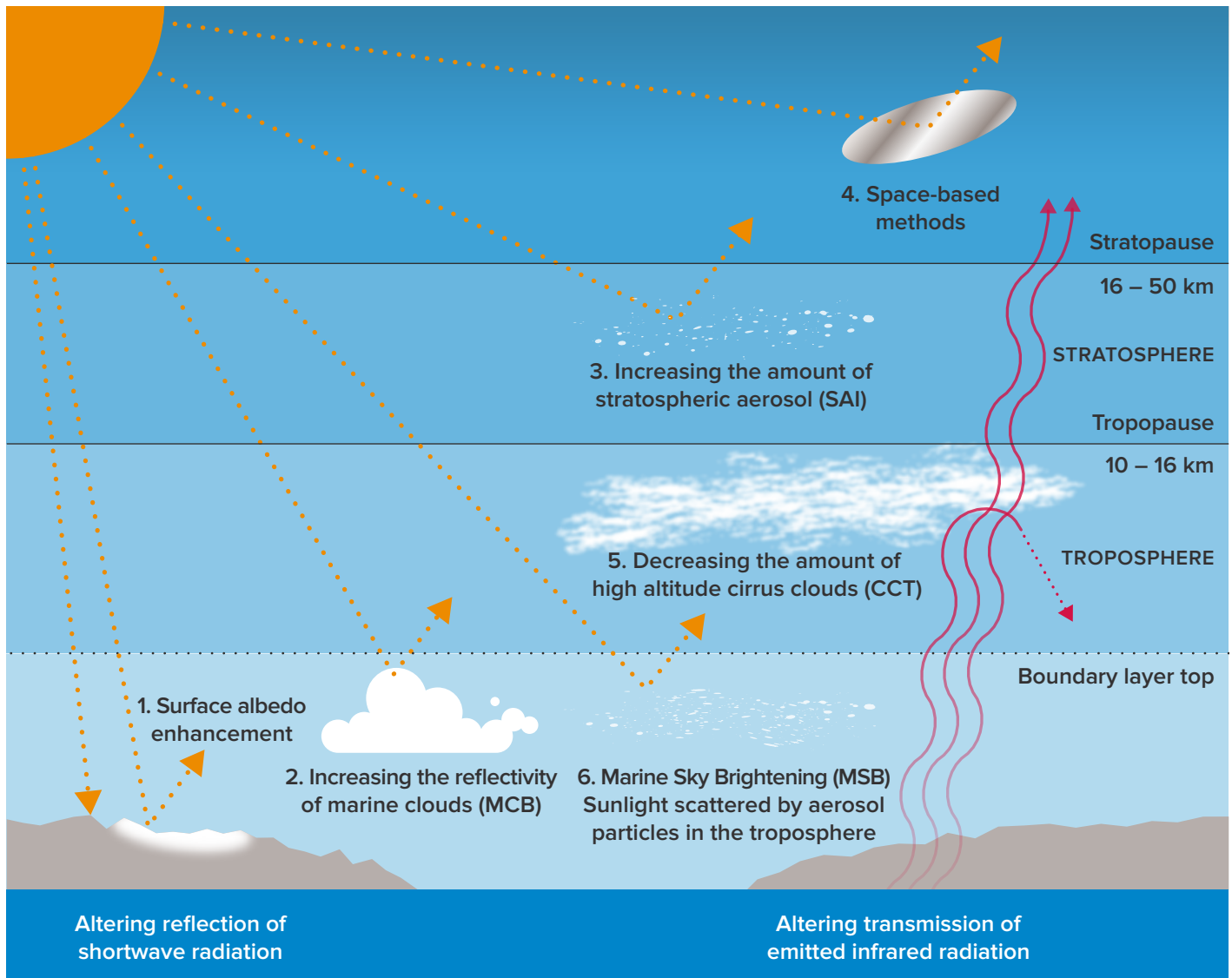
- SAI is a proposal to inject aerosol particles, or the gases that lead to aerosol formation, into the stratosphere to enhance the reflection of sunlight back into space, cooling the planet. Model simulations most commonly assume that sulfate aerosols would be used.
- MCB is a proposal to inject aerosol particles into low-altitude clouds, in specific ocean regions, leading to more reflection of sunlight. MCB model simulations usually assume that the aerosols are sea-salt particles generated by spraying seawater from near the ocean surface.
- Currently, SAI research is significantly more advanced than MCB research. The mechanism by which SAI influences climate is better understood, and scaling-up is considered technically feasible. Whilst the size of intervention needed to achieve a given cooling is uncertain, it is markedly less uncertain than MCB. The climate effects of both methods are less well understood than greenhouse-gas driven climate change.
- Other SRM techniques have been proposed, including marine sky brightening (MSB), cirrus cloud thinning and space mirrors, but these are considered to have lower levels of effectiveness to generate large-scale cooling, poorer understanding of the underlying physical mechanisms, and/or much higher technical barriers to deployment.

8. 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.

9. Patt *et al.* 2022 International cooperation. In: Shuklaet P R *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.

FIGURE 1

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



Adapted from WMO (2022)¹⁰.

10. 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).

The primary source of evidence for the climate impact of SRM comes from computer-based climate models, which are the same models used to project future climate change with the same inherent biases and uncertainties. As is the case with climate change in the absence of SRM, these models cannot yet reliably inform policy makers about regional impacts of SRM.

- The representation of small-scale aerosol and cloud-based physical and chemical processes important for SAI and MCB in global climate models is challenging, because these small scales are not explicitly represented. Consequently, their climate effect is less well understood than greenhouse-gas driven climate change. This substantially limits confidence in results from these models.
- Climate models are limited in how accurately they can simulate key circulation patterns, such as the Asian Summer Monsoon and recurrent large-scale natural variations in the atmospheric circulation, such as the North Atlantic Oscillation (NAO), El Niño – Southern Oscillation (ENSO) and their wider influence on regional and global weather. Consequently, there is a need for considerable improvement of modelling capabilities to improve confidence in predictions of regional impacts of climate change, both with and without the deployment of SRM, including the occurrence of extreme weather and climate events.

Observational analogues provide important evidence supporting the mechanisms behind SRM techniques and provide a test of the quality of representations of key processes within models.

- For SAI, the primary analogue is large explosive volcanic eruptions that cause a few years of global cooling. For MCB, the prime analogue is the effect of sulfur dioxide emissions from shipping and effusive volcanic eruptions on low-altitude clouds.
- There are key differences between these analogues and proposed SRM techniques. SAI would require a sustained enhancement of the stratospheric aerosol layer, in contrast to the short-lived (1 – 2 year) perturbation from individual volcanic eruptions, and the geographical pattern of climate response would likely differ significantly. For MCB, the capability to influence cloud properties in a controlled manner is beyond our current understanding.

What are the possible scenarios and strategies for deploying SRM?

The impact of any SRM implementation would depend upon the scenario of expected future greenhouse gas warming and decisions on the extent to which SRM is intended to mask that warming and other adverse impacts of climate change, and the strategy used to determine how, where, and when SRM is deployed.

- Maintaining the cooling effect of SRM aerosols would require regular replenishment to mask the climate effect of greenhouse-gas emissions. This is because SRM aerosols are much shorter lived in the atmosphere (days to a year or so) than gases most responsible for global warming (from a decade to centuries).
- If long-lived greenhouse gas emissions, and particularly those of CO₂, continued to stay net positive, the rate of SRM aerosol injections would need to increase over time, if the intention was to maintain global temperatures at a given target level.
- The duration of SRM deployments required to reduce global temperatures to a given target level would only be approximately known when any deployment starts. It would depend on future greenhouse gas mitigation measures and uncertain aspects of the climate system.
- An alternative emissions scenario is where greenhouse gas mitigation actions eventually halt and reverse global temperature rise but still do not prevent a period of overshoot of a desired target temperature, such as 1.5°C. SRM could be applied to reduce temperatures to that target for the duration of the overshoot, with the required amount of SRM declining as the mitigation actions take effect. This is referred to as ‘peak-shaving’. Even peak-shaving scenarios aimed at limiting global warming to 1.5°C might require deployments exceeding 100 years.

- If a deployment of SRM were halted, or significantly reduced, the climate would return to close to its non-SRM state in one to two decades. This is known as the termination effect. If the climate in the absence of the SRM masking would have been very different, as a result of continued greenhouse gas emissions, the termination effect would very likely have strong impacts on sensitive planetary systems that cannot adapt quickly. The rate at which the termination effect occurs could be mitigated to some extent by the gradual phase out of SRM.

What are the global and regional climate impacts of SRM?

There is robust evidence that a globally-coordinated deployment strategy for SRM would act to reduce global-mean and regional-mean surface temperatures and associated impacts, such as sea-level rise, wildfires and extreme precipitation. However, SRM is unlikely to counteract all regional effects of greenhouse gas induced climate change in some regions. There are key knowledge gaps in the understanding of complex climate interactions, at both global and regional levels. The possibility of undesirable regional-scale climate changes is an important concern.

- There is uncertainty in the rates of injection needed for SAI and MCB deployment. Recent estimates of the rate of injection required to achieve a given cooling via SAI differ by more than a factor of two. The difference in estimates of the required aerosol injection rate for MCB is larger, highlighting the uncertainty in climate model representations of complex interactions between aerosols and clouds.
- If SAI was intended to cause a sustained global-mean surface cooling of about 1°C, the amount of sulfur dioxide gas that would need to be injected every year would be roughly equivalent to that due to the largest single climatically significant volcanic eruption to have occurred in the last 140 years (the Mt Pinatubo eruption in 1991)^{11, 12}.

11. 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).

12. Guo S, Bluth G J S, Rose W I, Watson I M, Prata A J. 2004 Re-evaluation of SO₂ 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).

- SRM would not offset all aspects of climate change. Even if it masked the intended amount of globally-averaged warming, it would not perfectly offset the warming at regional (or country to continental) scales. Changes to other climate variables, such as precipitation, may not be balanced in the same way as surface temperature by SRM.

The regional climate responses to SRM would depend critically on how it is deployed.

- Evidence from climate model simulations indicates that some undesirable aspects of SRM (eg, changes in tropical rainfall patterns, Atlantic hurricanes and recurrent large-scale natural variations in stratospheric winds) can be expected with deployments at the equator or in one hemisphere. If deployed in an informed and globally-coordinated way, model simulations indicate that SRM could ameliorate many, but not all, of the adverse impacts of climate change.
- Undesirable regional-scale climate responses, such as substantial shifts in regional rainfall patterns, are likely to be significantly less for globally coordinated implementations of SAI than for MCB, because aerosols causing SAI would be spread more uniformly around the globe by winds. Since MCB can only be applied effectively in specific locations, rather than globally, simulations suggest strong regional climate responses.
- The current lack of confidence in predicting regional climate responses, with or without SRM, means that it is possible that SRM could exacerbate, rather than ameliorate, some regional effects of climate change.

- Stratospheric ozone would be affected by SAI. Aerosol particles enhance chemical reactions that lead to ozone depletion and also affect stratospheric winds that impact on ozone distribution. The magnitude of depletion due to SAI would depend on many factors including the abundance of ozone depleting gases, which are currently declining in response to international agreements.
- The Atlantic Meridional Overturning Circulation (AMOC) is very likely to decline this century should global temperatures continue to rise, leading to widespread climate impacts. Modelling studies indicate that by reducing warming and increasing salinity of North Atlantic surface waters, SAI may reduce part of this decline, but there are significant uncertainties about the strength and distribution of SAI required for effective amelioration. There has been little research on the effect of MCB on the AMOC.
- There has been little research on the effects of SRM on UK weather and climate. 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. The UK climate would also be expected to be influenced by any SRM-induced changes in the AMOC and in the NAO.

What are the potential effects of SRM on the wider Earth system?

In addition to the atmosphere and oceans, the Earth system includes terrestrial and marine biospheres and the cryosphere. Research into the impacts of SRM on these components is limited, but tentative conclusions can be drawn, assuming SRM is applied in a globally-coordinated way.

- Modelling studies suggest that, on a global basis, SRM would result in an increase in terrestrial net primary productivity (ie the amount of carbon retained by vegetation). This would be due to increased fertilisation effects from elevated CO₂ concentrations due to greenhouse gas emissions, combined with reduced temperature stress because of SRM. For similar reasons, no significant reduction in global crop productivity is expected, when comparing a world with and without SRM.
- An IPCC assessment suggests that SRM would “lead to the enhancement of global land and ocean CO₂ sinks and a slight reduction in atmospheric CO₂ concentration relative to unmitigated climate change”¹³.
- If SAI were implemented using sulfate aerosols, SAI could contribute to ‘acid-rain’. For applications of SAI intended to cause a cooling of about 1°C or less, little additional ecosystem damage due to acid rain is predicted when compared with other anthropogenic sources of sulfur. Similarly, sea-salt proposed for MCB is not predicted to cause a significant impact on vegetation health compared to natural deposition of sea-salt. These conclusions are based on limited research and would depend on the deployment strategy.
- Modelling studies indicate that it is likely that on average the frequency of global wildfires would be reduced by SRM compared to a warmer world without SRM.
- Increasing atmospheric concentrations of CO₂ are the major anthropogenic driver of acidification of the oceans which has adverse impacts on marine ecosystems. SRM would not abate damage due to this acidification. Little research has addressed the impacts of SRM on the marine biosphere, so few conclusions can be drawn. However, marine ecosystem damage due to rising ocean temperatures is likely to lessen due to SRM, compared to a warmer world without SRM.
- Low- and mid-latitude SAI deployments could combat polar sea-ice loss through global scale cooling, as could high latitude deployments that increase the reflection of sunlight (planetary albedo) in polar regions. The modelled impacts of MCB are much more uncertain, particularly for high-latitude deployments, because of differences in the characteristics of polar clouds.
- Sea-level rise due to the expansion of sea water and glacier melt is expected to be ameliorated by long-term SRM cooling. The effect of SRM on the contribution of ice sheets to sea-level rise is less well understood; it depends on both surface and deep ocean temperatures, which respond to SRM on different time scales.
- Understanding the impacts of SRM on the amelioration of ice-sheet collapse is hindered by the fact that modelling of ice sheets in Earth System Models is in its infancy.

13. *Op. cit.* 3.

What are the issues in monitoring any implementation of SRM?

If a decision was made to implement SRM, monitoring its effect would be essential and comes with many challenges.

- Monitoring of the effect of SRM on the planetary energy budget and climate change would require adequate observing systems to be in place prior to any deployment and be maintained afterwards.
- The aerosols resulting from SAI should be readily detectable within days. However, detection of the influence of SAI on the planetary energy budget would most likely take about a year, while the influence of MCB on that budget might take several years, because of the inherent natural variability in clouds.
- Depending on the scale of its implementation, confident detection of surface temperature change caused by SRM might take decades, because of both natural climate variability and changes in anthropogenic drivers of climate change.
- Detection time scales will be longer at regional scales compared to global scales, because natural climate variability is larger at regional scales.

If SRM were implemented, it would be challenging to assert how the climate would have changed in its absence.

- While models suggest that the frequency of many extreme climatic events (eg, heat waves and wildfires) could be reduced under SRM, extreme weather events would still occur. While there have been some advances in attributing individual extreme events to climate change, it remains difficult.

What are the wider issues associated with SRM research and proposed deployment?

Many other issues need to be considered for decision-making processes, and governance, regarding SRM implementation and for the conduct of SRM research.

- There remain open questions on the technology required to deploy SRM, at the scales and durations necessary to significantly affect climate.
- Even if these barriers, and those related to governance, can be overcome, it has been estimated elsewhere that timescales for development of equipment and infrastructure might be a decade or more.
- Small scale SRM field experiments have been planned or realised in several countries, which pose extremely low environmental risks owing to their limited scale, though there are broader concerns about these efforts. Some groups have opposed field experiments, and several experiments have been cancelled.
- There is broad agreement on the general principles that should govern SRM research and development. There remain open questions regarding how to operationalise SRM research governance principles. For example, while there is broad agreement that public and stakeholder engagement is important, the appropriate breadth, depth, mechanisms and scope of such engagement is not yet established.
- In the absence of formal governance arrangements, ad hoc approaches to research governance based on general principles have been applied for some SRM field experiments. For example, the UK-funded field experiments through ARIA will follow a set of governance principles overseen by an independent oversight committee.
- Beyond research governance, there is also a need to ensure that SRM research or potential deployment does not undermine emissions cuts, and that efforts are made to promote international cooperation around research and decisions around potential deployment.

- In the near term, governments will need to consider whether and how to apply the precautionary principle to SRM in the context of growing climate risks, and consider how to respond to calls for an international moratorium or a ban on large-scale SRM activities.
- If further research on SRM is funded, it should require objective, critical and transparent assessments of the merits and risks of SRM, relative to the risks of climate change, free from real or perceived vested interests.

Overall, the many uncertainties associated with the climate effect of SRM, and the fact that it could only mask, and not solve, the effects of increased greenhouse gas emissions, lead us to reaffirm the view expressed in IPCC AR6^{14, 15}: if it is ever decided that SRM is necessary, then it should not be the main policy response to climate change; it would, at best, be a supplement to actions to further mitigate greenhouse gas emissions.

14. *Op. cit.* 8.

15. *Op. cit.* 9.