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World Climate Research Programme lighthouse activity: an assessment of major research gaps in solar radiation modification research

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It is increasingly evident that maintaining global warming at levels below those agreed in the legally binding international treaty on climate change. i.e., the Paris Agreement, is going to be extremely challenging using conventional mitigation techniques. While future scenarios of climate change frequently include extensive use of terrestrial and marine carbon dioxide removal in the second part of the 21st century, it is unproven that these techniques can be scaled-up to reach the scale required to significantly reduce concentrations of atmospheric carbon dioxide and significant uncertainties and detrimental side-effects exist. These issues have led to increasing interest in so-called “Solar Radiation Modification” whereby the global mean temperature of the Earth is reduced by either blocking a small fraction of sunlight from reaching it or by increasing the Earth’s albedo to reflect a small proportion of incident sunlight back out to space. Here we systematically identify key research gaps associated with the two most prominent Solar Radiation Modification techniques, i.e., Stratospheric Aerosol Injection (SAI) and Marine Cloud Brightening (MCB). We provide an assessment of the research gaps associated with other less prominent SRM techniques. We assert that transparency and inclusivity in SRM research is essential in providing objective and impartial research findings to each and every stakeholder in an equitable way.

KEYWORDS

SRM, geoengineering, stratospheric aerosol injection, marine cloud brightening, cirrus cloud thinning

1 Introduction

It is increasingly evident that limiting global warming since pre-industrial times to +1.5°C or + 2.0°C as agreed by the Paris COP21 are extremely challenging targets (e.g., Millar et al., 2017; Tollefson, 2018; IPCC, 2018, 2023). In response to the difficulties in abating anthropogenic greenhouse gas emissions and associated climate change through conventional mitigation and terrestrial and marine carbon dioxide removal (CDR) techniques, additional solar radiation modification (SRM) techniques have been suggested. These approaches are grounded in fundamental physics that determines the equilibrium temperature of the Earth, and are supported by observations from analogues such as periodic large volcanic eruptions which brighten the planet and cool the Earth.

The simplest model that represents the equilibrium temperature of the Earth’s surface temperature, T_{surf}, assumes that the amount of sunlight absorbed by the Earth/atmosphere system is balanced by the amount of terrestrial radiation emitted back to space (e.g., Coakley and Yang, 2014; Kravitz et al., 2018):

$$T_{surf} = \sqrt[4]{\frac{S_o(1-\alpha)}{2\sigma(2-\varepsilon)}} \tag{1}$$

where S_o is the solar constant in W m^{-2}, α is the planetary albedo (i.e., the ratio of the globally averaged reflected sunlight to the incident sunlight), ε is the effective emissivity of the atmosphere, and σ is the Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}). Substituting observed values of S_o = 1,365 W m^{-2}, α = 0.30 and ε = 0.8 yields a global mean T_{surf} of around 289 K, which is close to the observed global mean surface temperature.

The impact of increasing concentrations of greenhouse gases from anthropogenic activity is to increase the effective emissivity, ε, of the Earth's atmosphere thereby increasing T_{surf}. SRM proposals suggest reducing T_{surf} through either (i) reductions in S_o by blocking a small fraction of the sunlight reaching the Earth (e.g., through space mirrors) or (ii) increasing the planetary albedo, α, by deliberately brightening the Earth to increase the reflection of sunlight back to space. SRM therefore targets modulating solar radiation and is distinct from mitigation of GHG emissions and CDR methods that target terrestrial radiation by limiting the increase in ε to ameliorate global warming.

While many studies highlight that the primary method for combatting global warming should be through stringent emission reductions, augmented by techniques for removing carbon dioxide from the terrestrial and oceanic environments (Hurrell et al., 2024; Lawrence et al., 2025; Oschlies et al., 2024), a number of recent reports have supported research into SRM (e.g., NASEM, 2021; Haywood J. et al., 2022; Bala et al., 2023). Here we focus on how the World Climate Research Programme and its scientific community can address knowledge gaps that limit our understanding of the physics of SRM, its physical impacts and associated risks, with the aim of providing relevant information for decision makers. The two SRM techniques that have become the most prominent are those of Stratospheric Aerosol Injection (SAI) and Marine Cloud Brightening (MCB); these are addressed in some detail. Other techniques such as cirrus cloud thinning (CCT), which is frequently categorised as a SRM method although its primary impact is on ε, surface albedo modification, and space-based methods are also briefly discussed. Figure 1 provides a schematic diagram of how these different techniques interact with solar and terrestrial radiation.

As the first order impacts of all potential SRM techniques depend on the amount of cooling and how that cooling is delivered, we briefly describe some of the various SRM scenarios and strategies that have been examined in the literature. Subsequently, we examine SAI and MCB under the following broad headings: (i) ***Generation and delivery***; (ii) ***Process-level understanding*** of key processes, (iii) ***Scale required and deployment strategy*** to generate significant cooling, (iv) ***Large-scale circulation responses***, and (v) ***Impacts***. Other proposed SRM mechanisms are also briefly discussed. These categories are broadly similar to those put forward by Diamond et al. (2022). While socio-economic, political, governance, ethical and inclusivity

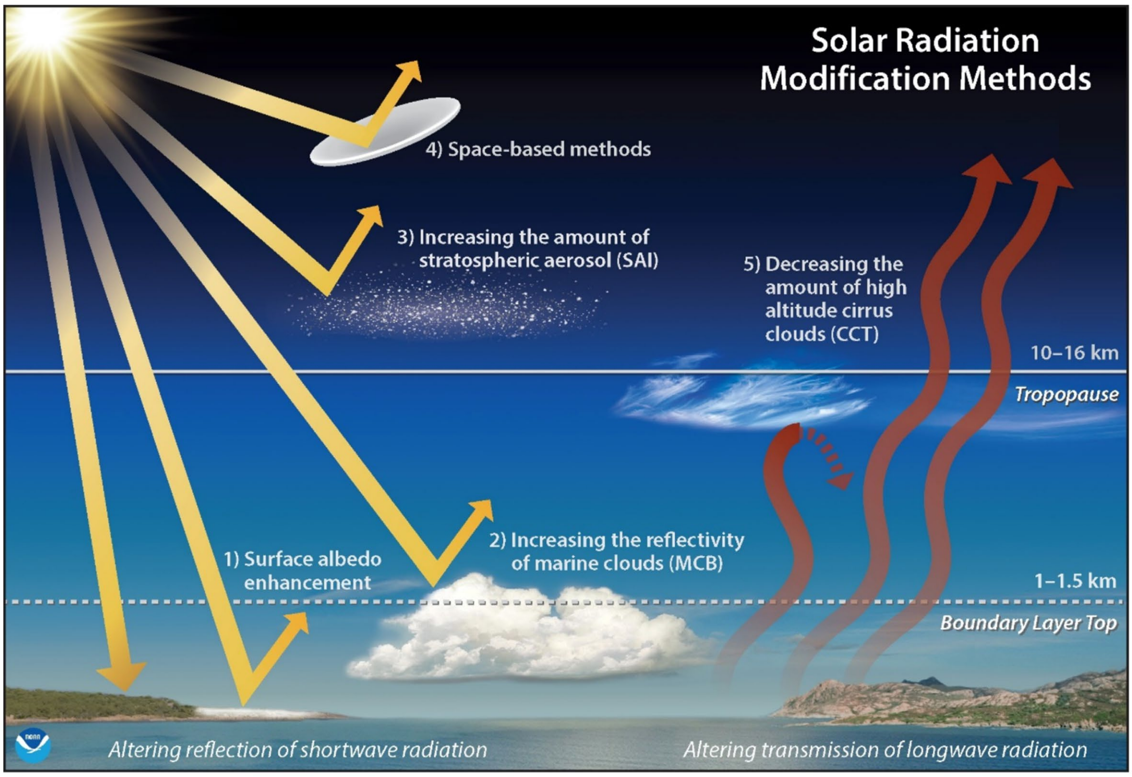

FIGURE 1
Schematic diagram showing the interaction of solar radiation (yellow arrows), and terrestrial radiation (wavy red arrows) with the various proposed SRM techniques. Image produced by Chelsea Thompson, NOAA.

considerations are extremely relevant for decision making on SRM research directions and any hypothetical deployment (e.g., Robock, 2008; Lawrence et al., 2018; Tilmes et al., 2024), they are only briefly discussed here.

2 Scenarios and strategies

The same models used in the IPCC (2023) synthesis report to evaluate climate change under various Shared Socioeconomic Pathway (SSP) scenarios have been used to evaluate SRM scenarios. The resulting climatic impacts depend strongly on the SRM ***scenario*** being considered, i.e., the amount of cooling (which depends upon the baseline SSP scenario and the target global mean temperature, see Figure 2), and the deployment ***strategy***, i.e., how, where, and when the cooling mechanism is deployed (Haywood J. et al., 2022).

SRM model simulations range from idealised experiments to more policy-relevant future ***scenarios***. The earliest Geoengineering Model Intercomparison Project (GeoMIP) multi-model simulations balanced the radiative forcing from an instantaneous quadrupling of carbon dioxide by a reduction in the solar constant, S_o, (GeoMIP experiment G1; Kravitz et al., 2013; Equation 1) to maximise signal/noise and to probe the uncertainties and differences between SRM and greenhouse gas-induced forcings. More policy-relevant simulations have since been performed and include simulations that follow a peak-shaving scenario, where SRM is applied for a limited amount of time until atmospheric GHG concentrations are sufficiently reduced (Tilmes et al., 2020), or reduced high-end (SSP5-8.5) global warming to moderate global warming levels (SSP2-4.5; GeoMIP experiment G6; Kravitz et al., 2015). G6 is consistent with the underlying socioeconomic development pathways of the high-tech, high-consumption storylines of the SSP5-8.5 scenarios (Riahi et al., 2017) but with SRM applied to bring the radiative forcing at the end of the century down from 8.5 W m^{-2} to 4.5 W m^{-2} by increasing the planetary albedo, α (Equation 1). As SSP5-8.5 is generally viewed as an implausible baseline given current climate commitments, other scenarios have been performed where the global mean temperatures from more moderate (SSP2-4.5) global warming emission scenarios are reduced to 1.5°C or 2°C above pre-industrial temperatures (Figure 2A; e.g. Jones et al., 2018; Richter et al., 2022; Henry et al., 2023) and are the subject of the next set of GeoMIP simulations (e.g., G6-SAI-1.5 K, Visioni et al., 2024). Vulnerable societies and ecosystems are sensitive not just to the absolute temperature and associated climate variables, but also to the rate of change (e.g., Trisos et al., 2018), so SRM could potentially be applied to limit the rate of warming (Figure 2B). One robust finding from GeoMIP is that if SRM is terminated abruptly for any reason, the climate will return to the non-SRM-mitigated state within a decade or two (the "termination effect" e.g., Jones et al., 2013). SRM should not be used as a substitute for emission reductions as any potential undesirable side-effects can be assumed to scale with the magnitude of the amount of SRM. Furthermore,

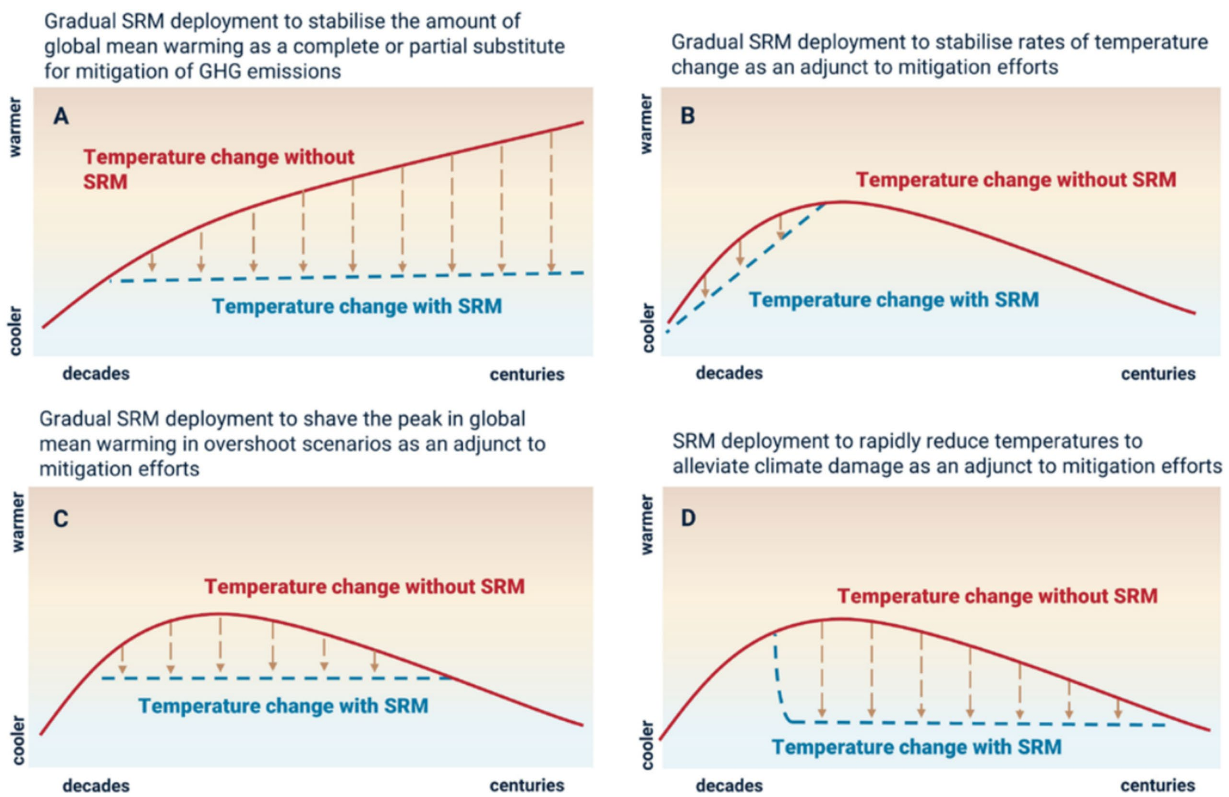

FIGURE 2
Schematic diagram showing some possible scenarios for SRM (from Bala et al., 2023). **(A)** maintaining a global mean target temperature under unabated GHG emissions, **(B)** reducing the rate of change of global-mean temperatures, **(C)** peak-shaving to maintain a global mean temperature while decarbonization is pursued, **(D)** delayed deployment peak-shaving with a temperature overshoot.

relying solely on SRM to counterbalance increased GHG concentrations would expose the planet to damaging termination effects. SRM should only be used in conjunction with conventional mitigation, emission reduction, and CDR policies. Peak-shaving scenarios (e.g., Figure 2C; Tilmes et al., 2020) minimise any potential termination effect, at least in the longer term.

SRM ***strategies*** rely on the deployment of one or several proposals for increasing α such as SAI (Section 3), MCB (Section 4) or other means (e.g., decreasing ε through CCT, Section 5). How such technologies are deployed (e.g., for SAI, the number of injection sites, the latitude, altitude and season of the injections, the emitted aerosol or gaseous precursor, etc.) is an integral part of the strategy as such parameters influence the climate forcing efficiency (i.e., the radiative forcing per unit SO_2 emitted) and the resulting residual climate change. Research has evolved in the last decade from assessing the efficacy of SRM to optimising its deployment to minimise any undesired residual climate effects. For instance, maintaining the global mean precipitation at its pre-industrial or present-day value might be preferable to maintaining the global mean temperature (e.g., Irvine et al., 2019). The latest SAI research tries to mitigate residual regional climate change by targeting not just global mean temperatures, but also inter-hemispheric and equator-pole gradients using control-feedback loops that automatically adjust the latitude and magnitude of injections (Section 3.3).

Generally, strategies have tended to focus on a single SRM technology and only a limited number of studies have examined combinations of different technologies (e.g., SAI and CCT, Cao et al., 2017; SAI and MCB, Boucher et al., 2017). At the time of writing, no studies have systematically investigated the combination of multiple SRM strategies combined with CDR in fully integrated policy-relevant scenarios. There is evidence from the increases in net primary productivity in coupled model simulations that SRM could be effective at sequestering carbon dioxide in the terrestrial biosphere as vegetation responds positively to high CO_2 and moderated global mean temperatures (e.g., Yang et al., 2020). SRM via SAI would also increase the diffuse fraction of sunlight which can increase photosynthesis and further draw down atmospheric CO_2 concentrations (e.g., Mercado et al., 2009). Therefore, SRM might be an effective CDR method. However, many uncertainties remain on the magnitude, saturation or even reversal of this effect with increasing SRM magnitude.

Major Research Gaps related to SRM scenarios and strategies include:

i) A lack of policy-relevant SRM scenarios. Only a limited number of policy-relevant SRM scenarios have been considered and only a fraction of those have been tested with multiple Earth System Models (ESMs), usually for a single SRM technique, leading to large uncertainties in the response of the physical climate and impacts.
ii) Insufficient evaluation of model robustness. Only a few models have run nominally identical scenarios including control-feedback loops and the results show a lack of inter-model consistency.
iii) Insufficient evaluation of control-feedback loops. Control-feedback loops have been limited to SAI where targets other than temperature have also been investigated; control-feedback loops for other technologies and strategies have not been documented.
iv) Insufficient evaluation of mixed climate intervention scenarios and strategies. Comprehensive investigations of the combined impacts of multiple SRM techniques (e.g., SAI and MCB) and the linearity of the climate responses have not been fully investigated, nor have the interactions between SRM, mitigation and CDR methods (e.g., impacts of SRM on renewable energy and CO_2 drawdown).

3 Stratospheric aerosol injection

The concept of SAI is inspired by naturally occurring large explosive volcanic eruptions that sporadically inject millions of tonnes of sulfur dioxide and other sulfur rich gases into the stratosphere, where it is oxidised to form sulfate aerosols in the form of liquid sulfuric acid (H_2SO_4) which reflect sunlight away from the planet increasing the planetary albedo, α (Equation 1). The sulfate aerosol size distribution evolves via nucleation, condensation, and coagulation (e.g., Kremser et al., 2016, Figure 3) before removal from the stratosphere via gravitational settling and stratosphere-troposphere exchange (e.g., Shapiro, 1980). Explosive volcanic eruptions result in a pulse-like increase followed by an exponential decay in stratospheric aerosol optical depth, leading to an increase in α and a reduction in observed near surface temperature (Equation 1). The eruptions of Pinatubo and Cerro Hudson in 1991 injected around 10–15 Tg SO_2 into the stratosphere (e.g., McCormick et al., 1995; Mills et al., 2017; Fisher et al., 2019), leading to a peak cooling of 0.3 to 0.5°C in mid-1992 (e.g., Soden et al., 2002).

Initial model simulations of SAI replicated the spread of aerosol into both hemispheres observed for tropical volcanic eruptions, by injecting aerosol into the tropical lower stratosphere to investigate the cooling efficiency (Robock et al., 2008). Subsequently, more detailed SAI scenarios and more complex injection strategies have been developed (e.g., Kravitz et al., 2016, 2017; Visioni et al., 2024).

3.1 Generation and delivery

Stratospheric injections from explosive volcanic eruptions are routinely incorporated in many global climate models used for future climate projections. Therefore, the majority of SAI studies model the emission of sulfur dioxide into the stratosphere, but on a continuous basis rather than the pulse-like injection characteristic of volcanic eruptions. Studies of the cooling potential of stratospheric sulfur dioxide suggests that the strongest radiative forcing occurs for emissions in the mid-stratosphere (21–24 km) (e.g., Jones et al., 2017; Marshall et al., 2019). Some exploration of other sulfur-based materials exists using direct aerosol injections of H_2SO_4 (Pierce et al., 2010; Vattioni et al., 2019; Janssens et al., 2020; Weisenstein et al., 2022) and carbonyl sulphide (COS, Quaglia et al., 2022), but the benefits in terms of resulting cooling efficiency depend on the details of the injection strategy and have been contested in the case of using COS (e.g., von Hobe et al., 2023). Materials other than sulfate aerosol have also been considered with the aim of reducing stratospheric heating or impacts on ozone (e.g., Ferraro et al., 2011; Jones et al., 2016; Dykema et al., 2016; Keith et al., 2016; Vattioni et al., 2023a).

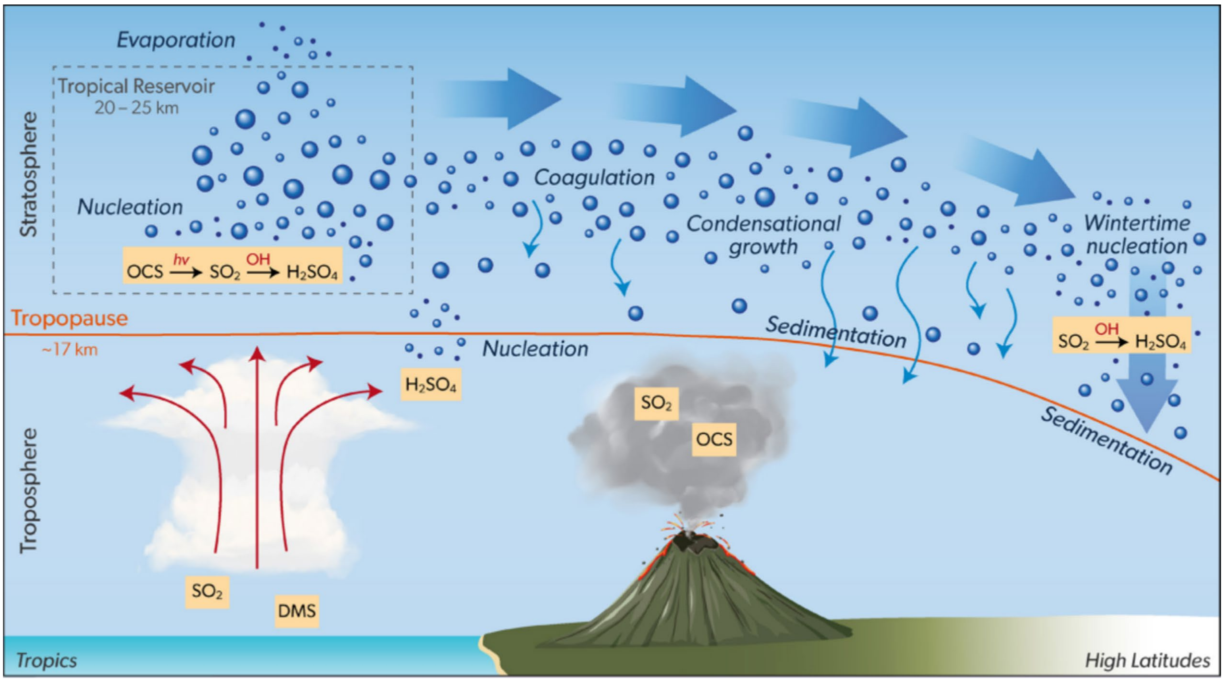

FIGURE 3
Showing the complexities of the sulfur cycle that are frequently included via parameterisation in earth system models. From Haywood and Tilmes (2023), adapted from Kremser et al. (2016).

However, physical and chemical properties, including details of coating with other aerosols in the stratosphere, are largely unknown (Dai et al., 2020; Vattioni et al., 2023a), owing to the scarcity of detailed laboratory studies at stratospheric conditions and the lack of suitable analogues (Haywood J. et al., 2022).

Modelling studies have shown that, for an appreciable cooling impact, SAI delivery systems need to be capable of delivering millions of tonnes of aerosols or their gaseous precursors to the stratosphere at altitudes of around 20 km each year (e.g., Robock et al., 2009). Currently, relatively few studies explore the feasibility and costs of an SAI delivery system (Robock et al., 2009; Smith and Wagner, 2018; Smith, 2020; Smith et al., 2022a; de Vries et al., 2020; Janssens et al., 2020). Such studies highlight the lack of feasibility for an immediate implementation but a relatively low cost and high feasibility for implementation in the next one to two decades compared to the costs of adaptation or other climate change mitigation measures. Costs are such that any deployment could feasibly be implemented by a number of governments or entities acting on their behalf. Studies also underscore the potential trade-offs between the benefits of higher injection altitudes and the complications of reaching those altitudes (Janssens et al., 2020; Smith et al., 2022b). Research into delivery mechanisms is contentious as it could be conceived as being the "slippery-slope" to deployment but the technical feasibility issues are critical in informing deployment scenarios for climate modelling purposes.

Analyses aimed at understanding the trade-offs and economic costs of any SAI deployment need to go beyond the simple expense of delivering the material. Preliminary efforts quantifying costs in an Integrated Assessment Modelling framework (IAMs, Moreno-Cruz et al., 2012; Belaia et al., 2021) found challenges in properly identifying a comprehensive damage function (i.e., the integration of an appropriate basket of metrics that best represent the detrimental impacts of climate change as a function of temperature). Such challenges included considering framing beyond temperature-dependent ones, monitoring costs, differentiating impacts depending on deployment strategies, regional trade-offs (Clark et al., 2023), residual impacts, risk of failure (Quaas et al., 2017), and potential compensation mechanisms between winners and losers. Such issues are not just confined to SRM research as there are similar concerns over CDR and conventional mitigation. Furthermore, as IAMs do not include a human-behaviour dimension, it might be hard to capture all the potential interactions between societies (Beckage et al., 2022), international politics and governance (Reynolds and Horton, 2020) over the full range of potential SAI deployment scenarios and strategies.

Major research gaps related to generation and delivery of SAI include:

i) The lack of quantification of technical barriers and costs. There is very limited work on understanding of technological limitations of different delivery systems.
ii) The lack of credible estimates for delivery timescales for deployment systems. Phase-in rates and start date depend on technology limitations and have not been evaluated.
iii) The lack of joined-up collaboration. There has been a general lack of collaboration between those working on delivery systems, on high-resolution atmospheric models, and on climate models.
iv) The lack a framework for evaluating financial risks. There is a dearth of work examining the costs of technological development and deployment versus the costs of climate change.

3.2 Process-level understanding

Many of the key aerosol processes, i.e., nucleation, condensation, and coagulation occur at a microphysical scale and therefore climate models need to represent the sub-grid scale processes via physical or statistical parameterisations. This can be done by representing the aerosol population in a variety of ways ranging from simple to complex. The simplest schemes transport aerosol mass and assume a fixed size distribution for the whole population; this method is computationally cheap relative to more sophisticated methods. More complex modal schemes assume that the aerosol size distribution can be represented by three or more overlapping log-normal distribution modes, and that an aerosol can evolve from one mode to another (e.g., Mann et al., 2010). The most detailed, and most computationally expensive sectional schemes do not assume any a-priori size distribution but represent aerosols of different sizes in multiple bins and allow particles to evolve between bins (e.g., Tilmes et al., 2023). Simulating aerosol size distributions with fidelity is of fundamental importance in aerosol-radiation interactions, owing to the sensitivity of reflection of sunlight to the radius of the particles; maximal impact occurs when the radius of the aerosols is similar to the wavelength of incident sunlight (Mie, 1908; Dykema et al., 2016). The surface area density of aerosol size distributions also influences heterogeneous chemical processes. Furthermore, aerosol sedimentation velocity and the lifetime of aerosol depend on the details of the aerosol size distribution. Only a few models exist with fully interactive stratospheric chemistry, 3-D atmospheric dynamics and aerosol microphysics (Kleinschmitt et al., 2017, 2018; Tilmes et al., 2022), and even the most advanced models struggle to reproduce aerosol size distributions after volcanic events (Quaglia et al., 2023). Process studies (Vattioni et al., 2023b) and observations of moderate volcanic eruptions (e.g., Wrana et al., 2023; Li et al., 2023) have shown strong inter-eruption dependency of the resulting stratospheric aerosol size distributions, with some unexpected decreases in the size of aerosols after some eruptions (Wrana et al., 2023). Lack of understanding of the processes and their inter-dependency result in significant uncertainties in the atmospheric burden for a specified injection rate (Weisenstein et al., 2022).

Further limitations when modelled aerosol size distributions are compared against those from volcanic eruptions arise from the pulse-like nature of the injection, while SAI simulations generally either maintain or increase emission rates over many years (e.g., Kravitz et al., 2013). Stratospheric burdens in many SAI simulations are therefore frequently many times larger than the well observed eruptions that have occurred in the satellite record. Theoretically, these enhanced burdens and continuous emission rates should lead to increases in aerosol sizes owing to enhanced condensation and coagulation rates (e.g., Niemeier and Timmreck, 2015), but supporting observational evidence is lacking. Additional limitations of using volcanic eruptions as natural analogues for SAI include the fact that other gaseous species (e.g., H_2S, HCl, Cl, Br, water vapour, e.g., Vömel et al., 2022) and other aerosols (e.g., ash, Kloss et al., 2021; Wells et al., 2023; sea salt, Colombier et al., 2023) are frequently co-emitted with SO_2 which influences the observed aerosol size distributions.

While satellite observations are very useful for observing the evolution of stratospheric SO_2 to sulfate aerosol at large spatial scales, retrieval limitations exist in accurately determining the evolution of aerosol size distributions. Furthermore, satellites can only provide limited information on the initial behaviour of injected plumes owing to saturation effects coupled with coarse temporal sampling, which frequently means that plumes are only observed once or twice a day. Limited outdoor experimentation and/or comprehensive laboratory studies under stratospheric conditions could potentially provide such information (Golja et al., 2021; Vattioni et al., 2023a) and could be extended to solid aerosols (such as diamond, TiO_2, calcite, or alumina) and account for their interaction with naturally occurring stratospheric aerosols (Dai et al., 2020).

Aerosol size distributions are intrinsically linked to ozone depletion as they provide a surface area on which heterogeneous halogen-induced chemical reactions occur. Absorption of solar and terrestrial radiation by stratospheric aerosols directly affects stratospheric temperatures, which can change stratospheric dynamics and influence the transport of ozone-rich air from the tropics towards polar regions (e.g., Haywood J. et al., 2022). Estimates of ozone depletion over Antarctica in spring (i.e., when the ozone hole is at its peak) could reach approximately 60 ± 20 DU for SAI deployments sufficient to achieve a 0.5°C global cooling over the period 2020–2040. Over the Arctic, the corresponding total column ozone depletion (in Dobson Units, DU) is uncertain, having been estimated as 13 DU ± 10 DU and 22 DU ± 21 DU by two models (Haywood J. et al., 2022). For reference, at the height of the ozone hole (around the year 2000), Antarctic and Arctic total column ozone decreased from unperturbed values of around 300 DU and 450 DU, respectively, to less than 150 DU and 375 DU, respectively. Some increases in total column ozone in mid-latitudes owing to changes in the dynamical transport occur, but these are very uncertain and very model dependent.

The net effect of SAI on stratospheric ozone depends on the availability of ozone-depleting substances present in the stratosphere for heterogeneous chemical reactions (e.g., Xia et al., 2017). Because ozone depleting substances have been effectively controlled by the Montreal Protocol (e.g., Laube et al., 2022), their concentrations are projected to decline in the future. Thus, SAI is modelled to have less impact on stratospheric ozone the later any deployment occurs (Tilmes et al., 2021; Tilmes et al., 2022; Haywood J. et al., 2022), but this area has not been well investigated owing to the limited number of SAI scenarios and strategies examined to date. Changes in ozone and aerosol concentrations ultimately affect the quantity and quality of surface radiation, especially at ultraviolet wavelengths.

Finally, SAI produces aerosols that are transferred into the troposphere through sedimentation and tropopause folds where they could act as either cloud condensation nuclei or ice nuclei. These impacts have been assessed in a few studies but have not been comprehensively investigated (Section 5.1).

Major Research Gaps related to the process-level understanding of SAI include:

i) The lack of model sophistication. Only a few models represent the complex gas-phase and heterogeneous chemistry processes, aerosol microphysics, and atmospheric dynamics of sulfate-based SAI with fidelity.
ii) The lack of consistency of GCM results. Some of the basic metrics such as the cooling per unit injection per year show a high degree of inter-model inconsistency.

iii) The limited number of models capable of modelling impacts on stratospheric ozone. This limitation couples with the limited parameter space in scenarios and strategies in limiting understanding of the impacts of SAI upon ozone.
iv) Lack of study of alternate particles to sulfates. The majority of GCM studies simply inject sulfur dioxide as a gaseous precursor of sulfate aerosols. There are very few laboratory experiments investigating alternate particles that can replicate stratospheric conditions and the mixing with naturally occurring aerosols.

3.3 Scale required and deployment strategies

Volcanic eruptions reveal that to achieve a long-lasting perturbation to aerosol optical depths and hence a considerable cooling of climate, aerosols or their gaseous precursors need to be injected at altitudes of around 20 km at the tropics, but lower altitudes at higher latitudes (e.g., Jones et al., 2017; Marshall et al., 2019). Pulse injections from large explosive volcanic eruptions in the tropics can result in aerosol plumes that spread into both hemispheres (e.g., Pinatubo in 1991; e.g. McCormick et al., 1995), into primarily the northern (El Chichon in 1982; Hofmann, 1987), or primarily the southern hemisphere (Agung in 1963; Rampino and Self, 1982) depending on the prevailing dynamical conditions within the stratosphere, and the altitude and latitude of the eruption.

Recognising that differences in climate model results depend on the scenario, deployment strategy, process-level treatment of aerosol microphysics, and differences in the dynamical response of global climate models, GeoMIP was established (Kravitz et al., 2013) which aimed to standardise modelling efforts across multiple climate models. Much of the focus of GeoMIP has been on SAI, although early idealised GeoMIP simulations also included the impacts of idealised reductions in the solar constant and idealised MCB simulations. Within GeoMIP, multiple intercomparisons have been carried out by a range of climate models, also across different Coupled Model Intercomparison Project (CMIP) iterations, and almost 150 papers have been published based on its results (Visioni et al., 2023b). A further multi-model SAI experiment has been coordinated by the Community Climate Modelling Initiative (CCMI; Plummer et al., 2021).

Certain robust residual climate impacts were identified for deployment strategies that are limited to the equator, including an over-cooling of tropical regions and continued warming at polar regions when compared to a world warmed solely by greenhouse gases with the same global mean temperature. However, risk–risk analyses (i.e., the climate response of a global warming world to those of a world where SAI is used to abate climate warming) reveal that these regions are far less impacted than under global warming, and most associated regional climate extremes are mitigated under SAI (e.g., Curry et al., 2014; Jones et al., 2018).

To reduce any residual climate impacts, more recent studies proposed injection strategies that use multiple sulfur injection locations, to adjust the resulting aerosol latitudinal distribution and the resulting stratospheric aerosol optical depth (Kravitz et al., 2016, 2017; Tilmes et al., 2018; Visioni et al., 2023a; Henry et al., 2023). A control-feedback loop can be used to adjust the magnitude of emissions at multiple locations (Kravitz et al., 2016, 2017) to achieve a number of surface climate targets, with the intent of reducing residual impacts from climate change (Kravitz et al., 2019; Tilmes et al., 2018; Richter et al., 2022; Henry et al., 2023). These climate targets typically include global mean temperature, inter-hemispheric temperatures, and equator-pole temperature gradients. While nominally identical targets can be achieved, the resulting injection strategies (in terms of the latitudinal distribution and magnitude of injections) show considerable inter-model variation (Henry et al., 2023) and dependency on the modelled scenarios (Wells et al., 2024); the optimal latitudinal distribution for any SAI deployment in the real world is therefore unknown. Other studies include regional and global precipitation and sea-ice change targets (e.g., Lee et al., 2020) emphasising significant limitations as to how many climate targets can be controlled simultaneously.

The most comprehensive multi-model assessments of the efficacy of the radiative forcing, near-surface cooling, and injection rates required to cool the Earth by 1°C are summarised in Haywood J. et al. (2022) (Table 1).

The large uncertainties surrounding the metrics that are diagnosed by the different climate models are due to differences in model representations of stratospheric chemistry, transport, radiation and aerosol microphysical processes. However, the near surface cooling is broadly consistent with those subsequent to the eruption of Mount Pinatubo which injected a pulse of around 10–15 Tg SO_2 and cooled the planet by around 0.5°C.

Major Research Gaps related to SAI scale and deployment strategies include:

i) The large uncertainties in metrics associated with SAI. These limit assessments of the effectiveness of SAI as a climate intervention technique in reaching climate targets.
ii) The number of CMIP models that have engaged in GeoMIP simulations is relatively small. While numerous climate models participate in CMIP, only a small subsection of the models participate in multi-model assessments such as GeoMIP.
iii) The scenarios and strategies are limited. The parameter space investigated is small compared to that investigated in future climate change scenarios.
iv) The lack of coupling with technical feasibility. Climate model simulations do not generally account for the technical feasibility of injecting millions of tonnes of aerosols or their gaseous precursors at stratospheric altitudes.

TABLE 1 **Various metrics relating the radiative forcing and near surface cooling to emission rates and the injection rate required to cool the planet by 1°C (from Haywood J. et al., 2022).**

Metric	Range of values
Radiative forcing per million tonnes (Tg) of SO_2 injected per year	-0.04 to -0.10 W m^{-2}
Near surface cooling per million tonnes (Tg) of SO_2 injected per year	0.04 to 0.14°C
Injection rate to cool the planet by 1°C	8 and 16 Tg of SO_2 yr.$^{-1}$

3.4 Large-scale circulation response

SAI would affect surface climate patterns through two main pathways: (i) reducing sunlight, thereby cooling the surface and (ii) locally affecting temperatures in the stratosphere, thereby affecting stratospheric circulation (e.g., Visioni et al., 2021; Haywood J. et al., 2022). Furthermore, the sensitivity of global-mean precipitation per unit temperature change differs for GHGs and SAI; a unit warming from GHGs results in less increase in precipitation than the decrease in precipitation for a unit cooling from SAI (e.g., Irvine et al., 2019; Visioni et al., 2023a,b). This feature is well understood, having been investigated in a number of studies (Bala et al., 2008; Niemeier et al., 2013; Modak and Bala, 2014; Modak et al., 2016). Additionally, the spatial distributions of the warming from GHGs and the cooling from SAI differ. Thus, reflecting sunlight via SAI cannot perfectly cancel out the CO_2 warming signal, and while it would result in lower overall temperatures, it would not perfectly restore the climate. Multi-model simulations indicate that such residual warming patterns from SAI cooling would be minor compared to any large unabated warming signal from GHGs (e.g., Tilmes et al., 2018; Jones et al., 2018; Visioni et al., 2021).

SAI induces a large-scale reduction in precipitation and soil moisture (Tilmes et al., 2013; Cheng et al., 2019), that also is discernible in observations following the eruption of Pinatubo (Trenberth and Dai, 2007). Observations and model simulations suggest that precipitation patterns may be significantly affected in some regions under certain SAI scenarios and strategies (Haywood et al., 2013; Irvine et al., 2019; Jones et al., 2022). For instance, the location of the intertropical convergence zone (ITCZ), which regulates tropical precipitation, may be influenced depending on inter-hemispheric differences in cooling/warming, also affecting monsoonal precipitation (Oman et al., 2006; Haywood et al., 2013; Da-Allada et al., 2020; Krishnamohan and Bala, 2022). Other precipitation patterns may be affected under significant SAI deployments owing to changes in the position and strength of the storm tracks in mid-latitudes (e.g., Jones et al., 2021, 2022) that depend strongly upon the latitudinal dependence of the injection strategy that influence the equator-pole temperature gradients (e.g., Lutsko et al., 2020; Bednarz et al., 2023; Visioni et al., 2023b), or changes in circulation in tropical oceans (Pomalegni et al., 2022). These impacts stem from a combination of uneven cooling, changes in stratospheric circulation, and stratospheric-tropospheric coupling.

The Quasi-Biennial Oscillation, which is evident in observations as a reversal of equatorial stratospheric winds with a period of around 2 years has been shown to be strongly influenced or eradicated by the absorption of solar and terrestrial radiation by sulfate aerosols (e.g., Aquila et al., 2014; Jones et al., 2016; Jones et al., 2022; Haywood J. M. et al., 2022), but the consequences in terms of surface impacts have received little attention, and the impacts are lessened if SAI strategies avoid injecting at equatorial latitudes (e.g., Kravitz et al., 2019; Bednarz et al., 2023; Wells et al., 2024).

Major Research Gaps related to the large-scale circulation response to SAI include:

i) The lack of characterization of the stratospheric circulation. The representation of the stratospheric circulation differs significantly between models and in model-observational analysis.
ii) The lack of understanding of stratospheric circulation response to an imposed perturbation. Inter-model differences in dynamical response to an imposed aerosol perturbation are frequently very large.
iii) The representation of stratosphere-troposphere exchange differ between models. The lifetime and hence effectiveness of SAI as a climate intervention technique depend on the lifetime of the aerosol, which differs between models.
iv) The impacts on dynamics in the troposphere and ocean. Impacts on the surface climate via changes in the large-scale dynamical circulation which influence key features such as the monsoon circulation, the position of storm tracks, the ITCZ, AMOC, and ENSO need to be better understood.

3.5 Impacts

Together with an expanded climate modelling effort, there is a need to consider regional impacts far beyond average climatic variables. This includes ecosystems (managed and unmanaged land-based ecosystems and marine ones) that may be affected, for instance, by changes in climatic extremes, incoming solar radiation and sulfur deposition (Trisos et al., 2018; Zarnetske et al., 2021). Similarly, studies that explore the climate-health (Eastham et al., 2018; Carlson et al., 2022) and climate-food (Fan et al., 2021; Clark et al., 2023) nexus in the context of SRM are also fundamental to properly inform expected impacts for different populations, and for meaningful engagement with impacted communities. Currently, there is a paucity of such studies, which would require both increased involvement from the related ecology and epidemiology communities and a strengthening of the tools necessary for assessing impacts in these areas. This could be achieved by improving the dialogue between physical climate modellers and ecology and epidemiology specialists, by sharing data, and co-design of scenarios.

Major Research Gaps related to the impacts of SAI include:

i) Lack of understanding of ecosystem response. There is a general lack of studies on how single species and entire ecosystems respond to concurrent changes in CO_2 concentrations, temperature, precipitation and quality of light.
ii) Climate—biosphere interactions. The coupling between climate models and the biosphere is highly simplified and highly parameterised even in the most sophisticated Earth System models.
iii) Air-quality. The drivers of air quality and how they would respond to SAI has not been established.

4 Marine cloud brightening

The radiative forcing from increased concentrations of greenhouse gases could be counterbalanced by relatively modest increases in low marine cloud fraction or reflectivity (Slingo, 1990). The case for MCB benefits from long-standing satellite evidence of the observed brightening of clouds from the injection of aerosols or their precursors into pristine, unpolluted clouds (i.e., shiptracks; e.g., Conover, 1966), and on more substantial geographic injections from large effusive volcanic eruptions (e.g., McCoy and Hartmann, 2015; Malavelle et al., 2017; Chen et al., 2022; Chen Y. et al., 2024). The principle behind MCB is that aerosols (whether sea-salt, sulfate, or other chemical compositions) act as cloud condensation nuclei (CCN) upon which cloud droplets can form. As a result, polluted clouds typically contain a larger number of smaller cloud droplets leading to more reflective clouds, hence increasing the planetary albedo, α in Equation 1, and cooling the climate (Twomey, 1977). Theoretically, the formation of raindrops is inhibited by the presence of smaller cloud droplets thus leading to less rainout of cloud water from precipitation, leading to longer lived or more extensive clouds which again would further increase the planetary albedo (e.g., Albrecht, 1989; Haywood and Boucher, 2000; Bellouin et al., 2020).

Whether MCB could play a role in compensating for some of the global warming from increased greenhouse gases is shrouded with uncertainties surrounding aerosol-cloud interactions (ACI), regional aspects of the associated climate response, operational and technological feasibility and scalability. Quantifying the radiative forcing associated with ACI has remained elusive (e.g., Boucher et al., 2013; Bellouin et al., 2020; IPCC, 2023) because the scale of the processes governing ACI and their climate impacts range from the micrometre-scale (e.g., aerosol activation, growth, coalescence, precipitation; Figure 4), through metre-scales (e.g., turbulence, entrainment, detrainment), kilometre-scales (e.g., accurate resolving of clouds), and 1,000 kilometre-scales (e.g., feedback processes and dynamical responses). For the efficacy and feasibility of MCB to be assessed, operational and technological constraints and information gleaned from modest experiments need to be coupled with a comprehensive, multi-scale modelling strategy.

4.1 Generation and delivery

The most prominent proposed generation mechanism of additional CCN is by spraying sea water through modified nozzles of commercial sprayers used in agriculture or in industry for dust-suppression. However, commercial sprayers used in dust control generate droplets of typically ~100 micron size, which is an order of magnitude larger than cloud droplets and two orders of magnitude larger than the sea water droplet size required for the resultant aerosol to act as efficient CCN. Various techniques for spraying small droplets are summarised in Cooper et al. (2013) and Connolly et al. (2014). Alternate methods to sprays such as wet grinding in an organic solute, or cryochemical methods are available for making sea-salt aerosol of a suitable size (Zhilenko et al., 2016), but the scale required remains a formidable obstruction. Use of sea water also represents a challenge as the nozzles would need to be flushed very regularly to remove build-up of sea-salt and impurities. Owing to the location of low-lying marine clouds over open oceans, the most prominent proposed delivery system is via a dedicated large fleet of ships.

Commercial sprayers that are currently available operate at flow rates of up to around 100 litres per minute (lpm), equivalent to an injection of dry sea-salt aerosol (NaCl) of around 3.5 kg per minute which equates to around 1800 tonnes/year if run for 24 h per day for 365 days of the year. Production of sea-salt at an optimal mono-disperse size is a significant challenge owing to rapid coalescence (Cooper et al., 2013) leading to the presence of a small number of giant CCN (GCCN), which can initiate precipitation leading to the loss of cloud water and break up stratocumulus clouds (e.g., Feingold et al., 1999; Pringle et al., 2012; Jensen and Nugent, 2017; Dziekan et al., 2021; Hoffmann and Feingold, 2021). Evaporative cooling (Jenkins and Forster, 2013) can cause the plume to subside, preventing the generated aerosol from reaching cloud-base. The high flow rates of 100 lpm when producing sub-micron sea-salt aerosols also cannot currently be achieved using modified nozzles on commercially available sprayers where rates are typically a few litres per minute.

Global modelling studies suggest that there is considerable uncertainty in the optimal size of the generated sea-salt aerosol, meaning that the technologically challenging goals highlighted above are unclear. The majority of global climate model simulations of aerosol-cloud interactions rely on a Köhler-theory-based aerosol activation scheme (i.e., representation of the conversion of aerosol particles into cloud droplets) of Abdul-Razzak and Ghan (2000). However, limitations of this activation scheme have been highlighted particularly for the marine aerosols typically suggested for MCB. Nenes and Seinfeld (2003), Ming et al. (2006), and Morales Betancourt and Nenes (2014) have developed alternative activation schemes for global models, which have been implemented in some Earth System models. Climate model studies using these different

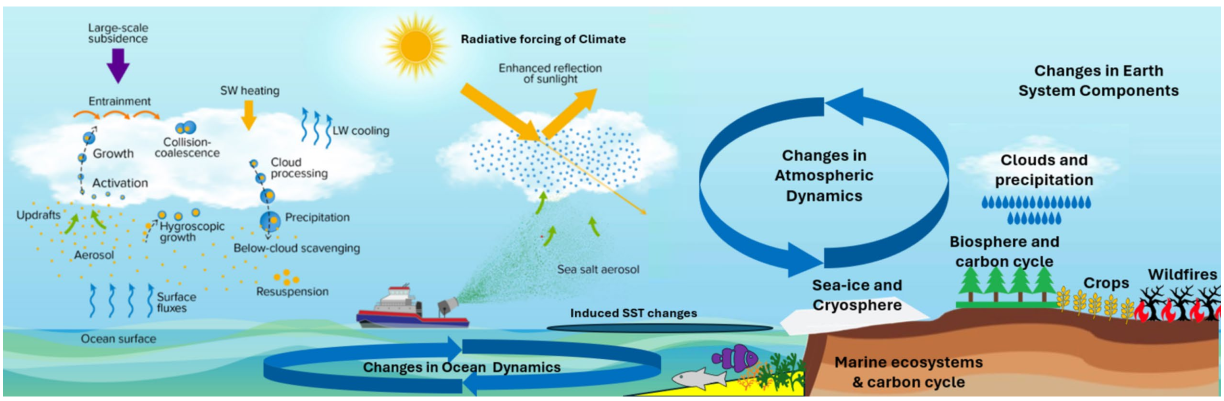

FIGURE 4
Schematic diagram of the processes that would be involved in proposed marine cloud brightening via the emission of sea-salt and the impacts on atmospheric dynamics and earth system components (adapted from Feingold et al., 2024).

activation schemes suggest that injection of aerosols generally increases CDNC, but reductions can occur if even a small number of giant aerosols (>250 nm dry radius) are injected into clouds with low cloud-base updraft velocities (Pringle et al., 2012). More recent systematic investigations have shown that cloud droplet number concentrations strongly depend on the size of the sea-salt aerosol injected into clouds. The climate model study by Haywood et al. (2023) suggested that sea-salt aerosols with a dry radius of around 90 nm were most effective at increasing cloud droplet number concentrations when using the Abdul-Razzak and Ghan (2000) activation scheme. However, process-level modelling studies (e.g., Connolly et al., 2014; Wood, 2021) suggest aerosols of 15–50 nm dry radius appear optimal. Thus, on a global mean basis, there are considerable uncertainties that propagate through the choice of activation scheme and the optimum size distribution for sea-salt aerosol that impact the relationship between mass of sea-salt emitted and the resulting cloud droplet number concentration. These uncertainties will be even greater on a regional or cloud-regime basis.

While the issues noted above undoubtedly present serious challenges, other aspects may enhance the efficiency of delivery. Continuous operation is unlikely to provide the most effective delivery as marine stratocumulus clouds typically thin during the day when exposed to sunlight and thicken overnight in the absence of solar heating. High resolution modelling studies have probed the impacts of injecting aerosols into different cloud-precipitation regimes (Wang et al., 2011) including injections at different times of day (Jenkins et al., 2013; Prabhakaran et al., 2024). These studies are consistent in suggesting that results appear strongly dependent upon whether the baseline clouds are precipitating or non-precipitating and reveal that weakly precipitating unpolluted clouds seeded in the morning exert the strongest radiative forcing through either reduction in loss of LWP (Jenkins et al., 2013) or enhanced cloud fraction (Wang et al., 2011; Prabhakaran et al., 2024). Thus, optimal strategies might focus on delivery in the morning in areas of weakly precipitating clouds. Further efficiencies could be envisaged through the injection of aerosol higher in the marine boundary layer where losses through deposition to the surface are reduced. However, neither high-resolution nor GCM simulations have robustly quantified these impacts.

Major Research Gaps related to MCB generation and delivery include:

i) The lack of consistency between aerosol activation schemes. Different schemes give different results and they may be pushed beyond their design limits in modelling extensive MCB deployments.
ii) The paucity of high-resolution studies. Only a few high-resolution modelling studies of MCB exist and they have not been used to confront global climate model simulations.
iii) The lack of traceability from process-global scales. Aerosol-cloud-interaction studies have been performed using multi-scale approaches for large-scale effusive eruptions, but not for MCB.
iv) Technical limitations. Practical technological limitations examining the impact of emission rate, altitude, and particle size distribution on cloud microphysical and macrophysical properties for a range of meteorological conditions have not been performed.
v) Experimental evidence from limited deployments. It is currently unknown whether technical limitations of generation of an optimum aerosol size distribution is possible at the scale needed to induce a significant cooling.

4.2 Process-level understanding

The impact of emissions of sulfate aerosols from sulfur-rich marine fuels on ship-tracks has received considerable attention for some time (e.g., Capaldo et al., 1999; Lauer et al., 2007; Eyring et al., 2010; Partanen et al., 2012; Christensen et al., 2022). Ship-tracks and larger-scale volcanic eruptions provide plentiful evidence of reductions in cloud droplet effective radius (e.g., Toll et al., 2017, 2019; Christensen et al., 2022) when aerosol concentrations are enhanced. While assessing the fidelity of GCM responses from individual ship-tracks is difficult (e.g., Glassmeier et al., 2021), larger scale perturbations from effusive volcanic eruptions or in larger scale shipping lanes (Diamond et al., 2020) provide more relevant comparisons. Simulations of the reduction in cloud droplet effective radius by multiple models of the large-scale effusive eruption of Holuhran (Malavelle et al., 2017; Jordan et al., 2024) reveal that GCM scale models are able to capture the magnitude and the spatial distribution of the aerosol-induced perturbation to the cloud effective radius. Generally, the mean from the models performs better than the individual models, a feature that has been noted in several studies for other climate model variables (e.g., Gleckler et al., 2008). However, evidence of cloud liquid water changes under polluted conditions are inconsistent, with observational studies frequently diagnosing weak cloud liquid water decreases (e.g., Malavelle et al., 2017; Gryspeerdt et al., 2019; Toll et al., 2017, 2019). While some global climate models replicate this weak impact on cloud liquid water with reasonable fidelity, others do not (e.g., Malavelle et al., 2017).

There is new observational evidence from effusive volcanic eruptions (e.g., Chen et al., 2022) and ship-tracks (Manshausen et al., 2022) that the cloud-fraction response to increased concentrations is more significant than previously diagnosed. The response of cloud fraction to increases in aerosol concentrations appears weaker in GCMs than in observations. Further evidence that the local cloud adjustments do not significantly offset the expected microphysical brightening of clouds comes from the reduction in sulfur content in marine fuel from 3.5 to 0.5% in 2020. This follows International Maritime Organisation (IMO) regulations designed to reduce pollution and provides a natural experiment to examine aerosol-cloud interactions over remote ocean regions. Yuan et al. (2022) report an almost 50% reduction in visible ship-track occurrence contributing a radiative forcing estimated to be as strong as approximately +0.3 W m^{-2} although March et al. (2021) point out that some reductions in ship-track occurrence may be due to the concomitant reductions in shipping owing to the impacts of Covid-19. Watson-Parris et al. (2022) account for Covid-19 reductions and find a 25% reduction in ship-tracks for an estimated 80% reduction in sulfur emissions indicating that even in remote shipping lanes, pristine conditions are not always present. Diamond (2023) estimate a radiative forcing due to adoption of IMO regulations of around 1Wm^{-2} in major shipping corridors suggesting that the global estimates from climate models of approximately +0.1Wm^{-2} (+0.07 to +0.15Wm^{-2}, Gettelman et al., 2024) appear reasonable. Climate model studies that assess the impacts of the IMO shipping regulations on global mean temperatures (e.g., Jordan and Henry, 2024; Gettelman et al., 2024) suggest that IMO regulations will have brought forward global warming by 3–4 years, but definitive attribution is difficult owing to rapid changes in anthropogenic aerosol emissions, particularly in Asia, and owing to the concurrent El Nino.

Taken together, these results suggest that there is a significant aerosol-induced microphysical brightening of clouds (Twomey, 1991) that appears to be enhanced by increases in cloud cover. However, evidence of any enhancement (or abatement) in cloud liquid water path appears contradictory, which means that the conventional sequential chain of interactions highlighted by Haywood and Boucher (2000) may be incorrect.

Major Research Gaps related to MCB process-level understanding include:

i) Lack of representation of key microphysical processes. Aerosol activation, cloud updraft, entrainment, and turbulence are all sub-gridscale in GCMs and are therefore heavily parameterised.
ii) Lack of process-level validation of aerosol-cloud-interactions in GCMs. While the Twomey effect appears reasonably well represented, cloud adjustments remain poorly validated.
iii) Lack of process-level understanding across a range of cloud-regimes. Many modelling studies have focussed on relatively homogeneous stratocumulus decks, but observations suggest that ACI operate in many other cloud regimes.
iv) Understanding large-scale changes in aerosols. The cloud changes and temperature responses to IMO-shipping regulation changes and large-scale effusive volcanic eruptions show some consistency, but also much uncertainty.

4.3 Scale required and deployment strategies

The most efficient clouds to target with MCB are low-lying, unpolluted stratocumulus clouds which exert a cooling of climate as they strongly increase the local albedo (see Equation 1), have little compensating impact on terrestrial radiation (e.g., Slingo, 1990) and are susceptible to MCB injections as evident from ship-tracks. Satellite-based relationships of cloud susceptibility have been derived (e.g., Quaas et al., 2009; Quaas et al., 2008), but have been questioned owing to the lack of sensitivity of satellite retrievals at low aerosol concentrations (Ghan et al., 2016; Ma et al., 2018).

Early climate modelling studies of the potential impacts of MCB (e.g., Rasch et al., 2009; Jones et al., 2009) simply increased the reflectance of low-lying marine stratocumulus clouds by setting cloud droplet number concentration (CDNC) to an asymptotic maximum that was informed by aircraft observations (e.g., Martin et al., 1994; Jones et al., 2001). These early studies were subsequently improved upon by more explicit modelling through the injection of sea-salt aerosol (Jones and Haywood, 2012; Partanen et al., 2012). For example, Jones and Haywood (2012) explicitly modelled sea-salt injection rates dependent on wind speed according to Korhonen et al. (2010) and targeted the most susceptible 10% of cloudy areas. Owing to difficulties in distinguishing the climatic response from the differences due to the specific climate intervention scenario or strategy, coordinated GeoMIP simulations were performed (e.g., Alterskjaer et al., 2013; Kravitz et al., 2013; Ahlm et al., 2017; Stjern et al., 2018).

The earliest GeoMIP study relevant to MCB was the G3-SSCE experiment (Alterskjaer et al., 2013) where the top-of-atmosphere radiative forcing was maintained at 2020 levels in a scenario with rising greenhouse-gas concentrations. The three participating models treated sea-salt with different degrees of complexity ranging from fully prognostic sea-salt and CDNC, through using a climatology of sea-salt concentrations and diagnostic CDNC, to prescribed sea-salt and CDNC. The results show very different cloud responses and susceptibilities, but common findings include a suppression of latent heat flux and precipitation over the low-latitude oceans, and shifts in the hydrological cycle associated with an enhanced Walker circulation. This change to the Walker circulation appears confined to MCB strategies as simulations of the same global mean cooling scenario with either SAI or space mirrors reveal little impact (Niemeier et al., 2013). Subsequently, a simpler GeoMIP experiment was defined (G4cdnc; Kravitz et al., 2013) where a 50% increase in the CDNC of low marine clouds was imposed over the oceans on a global basis; the simplicity of this experimental design meant that nine climate models were able to participate (Stjern et al., 2018) and confirmed strengthening of the Walker circulation for MCB deployment. A more complex GeoMIP experiment called G4sea-salt (Kravitz et al., 2013) was performed by three models that could all explicitly represent sea-salt injection into the marine boundary layer at latitudes between 30°S-30°N; this experiment highlighted that the aerosol direct effect could contribute a significant fraction of the modelled cooling through so-called "Marine Sky Brightening" (MSB, Ahlm et al., 2017; Jones and Haywood, 2012). The finding that MSB could be an effective method is corroborated by recent work that modelled sea-salt emissions targeting brightening of the susceptible stratocumulus clouds of the eastern Pacific (Haywood et al., 2023).

Rasch et al. (2024) analyse the results from UKESM1, E3SM, and CESM2 climate models and suggest a protocol for MCB-style simulations where injections are confined to specific oceanic regions. However, the findings suggest a great degree of variability in the radiative forcing per unit sea-salt injection, with values of around −13, −23, and −140 mW Tg^{-1} yr. for UKESM1, E3SM, and CESM2 accordingly. This factor of ten discrepancy translates to a large uncertainty in the temperature response per unit sea-salt injection; according to simulations with the UKESM1 earth system model (Haywood et al., 2023), the maximum cooling efficiency for sea-salt emissions is around −20 mK Tg^{-1} yr. Simulations with the CESM2 model using the same Abdul-Razzak and Ghan (2000) activation scheme suggest a maximum cooling efficiency of around −200 mK Tg^{-1} yr. (Rasch et al., 2024). Jones and Haywood (2012) diagnosed an MCB-induced cooling of 0.54 K if the most susceptible 10% of marine clouds were targeted using a seeding size distribution similar to that of naturally occurring sea-salt, while Haywood et al. (2023) suggest an MCB-induced cooling of up to 1 K might be achievable for their specific deployment strategy targeting the eastern Pacific with MSB-induced cooling being responsible for coolings exceeding this. The MSB efficiency derived in the UKESM1 model is about 4 times smaller than for MCB at around −4 mK Tg^{-1} yr. (Haywood et al., 2023).

Marine cloud brightening could conceivably be used, not to target the global mean temperature, but to ameliorate some of the symptoms of global warming. For example, Latham et al. (2014) suggest that

MCB strategies could target maintenance of the Arctic sea-ice. Latham et al. (2014) propose that this could be achieved not through the general cooling of the Earth's climate to reduce the flow of energy from the tropics to the poles in the atmospheric and oceanic circulations, but through a targeted high latitude MCB deployment. While this strategy is undoubtedly complicated by the presence of ice clouds (Kravitz et al., 2014), observational evidence from a large-scale effusive volcanic eruption in Iceland (e.g., McCoy and Hartmann, 2015; Malavelle et al., 2017; Chen et al., 2022) show a definitive decrease in the cloud droplet effective radius over vast swathes of the northern Atlantic, and machine learning algorithms have diagnosed an aerosol-induced increase in cloud fraction over northern latitudes (Chen et al., 2022). Climate model studies (Zoëga et al., 2024) show a more complex Arctic temperature response to this effusive eruption with a high latitude cooling during the summer when insolation levels are high, but a high latitude warming in winter owing to the limited insolation combined with an enhanced trapping of outgoing terrestrial radiation from increased cloud cover and cloud optical depth.

Observations of cumulus-dominated regions have also been shown to be sensitive to increased aerosol concentrations via large-scale effusive eruptions on Hawaii (e.g., Eguchi et al., 2011; Mace and Abernathy, 2016; Malavelle et al., 2017; Chen Y. et al., 2024) indicating that cloud regimes dominated by clouds other than stratocumulus are also susceptible to increased concentrations of aerosols suggesting that MCB could potentially be effective on a more global basis or in targeting local cooling. This observational evidence combined with the finding that marine sky brightening could potentially contribute a significant cooling suggests that marine environments of sufficient scale exist for an appreciable cooling through the emission of sea-salt into the boundary layer. A further area of investigation is whether MCB strategies could conceivably be used to induce a localised cooling over ecologically sensitive regions such as over the Great Barrier Reef off the east coast of Australia (Harrison, 2024). Indeed, vessels equipped with state-of-the-art spray technologies have recently been deployed in this area in a limited scientific outdoor investigation of the feasibility of this technique.

The magnitude of the deployment needed to determine a particular level of cooling is currently unknown. However, given that a recent state-of-the-art climate model study (Haywood et al., 2023) suggested that around 50 million tonnes of optimally-tuned dry sea-salt would need to be injected into optimally selected susceptible clouds to cool the climate by 1°C gives some idea of the current challenges in scaling up the technology for MCB. Around 27,000 sprayers working at 100 lpm, 24 h a day for 365 days per year producing optimally sized aerosols, deployed to optimally susceptible clouds would be required.

Major Research Gaps related to MCB scale and deployment strategies include:

i) Only very idealised MCB deployments have been simulated. Deployment strategies that target susceptible clouds in a more intelligent and progressive manner within GCMs are required.
ii) The role of Marine Sky Brightening (MSB). There have been very few studies of the effects of MSB, and none have been dedicated to using optimum size distributions and spraying scenarios to maximise their efficiency.
iii) Multi-model studies that target ameliorating the impacts of global warming using more regional deployment strategies such as protecting sea-ice, ecologically sensitive regions such as coral reefs, or cooling specific regions such as the Mediterranean do not yet exist.

4.4 Large-scale circulation response

Rasch et al. (2024) showed that the pattern of inter-model responses in temperature and precipitation to perturbing specific geographical regions using the same effective radiative forcing is remarkably similar. This result suggests that common responses exist between climate models and presents a pathway for designing deployment strategies that minimise any detrimental residual climate responses.

Modelling studies have targeted specific susceptible cloud regions (Rasch et al., 2009; Jones et al., 2009; Jones and Haywood, 2012; Partanen et al., 2012; Alterskjaer et al., 2013; Kravitz et al., 2013; Ahlm et al., 2017; Stjern et al., 2018; Hirasawa et al., 2023; Haywood et al., 2023). An aerosol lifetime of a few days to a few weeks is typical within the troposphere meaning that the cooling associated with MCB deployments that target specific regional areas is frequently localised and very inhomogeneous. If globally significant cooling is to be achieved, very much stronger localised cooling is frequently evident in the region of deployment.

Impact assessments of MCB are sparse compared to those of SAI. Should MCB be applied over the South East Atlantic region, then detrimental responses to such regionalised applications of MCB have been noted (e.g., Jones et al., 2009; Jones and Haywood, 2012; Hirasawa et al., 2023) with reductions in precipitation over the Nordeste and Amazonian regions of Brazil, a response that appears robust across models (Rasch et al., 2024). Idealised simulations (Jones et al., 2009) and explicit sea-salt injection simulations (Jones and Haywood, 2012) yield similar responses, suggesting that sea-surface temperature (SST) changes are the primary driver of changes in the Walker circulation that influence precipitation. 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 (e.g., Hastenrath, 1990; Utida et al., 2019).

Detrimental regional impacts are much reduced should deployments be applied at much larger scales. For example, the three models that applied MCB over the region 30^0N-30^0S did not find significant reductions in precipitation compared to GHG-induced impacts over any land areas (Alterskjaer et al., 2013). The multi-model simulations of Ahlm et al. (2017) and Stjern et al. (2018) show a significant, and potentially beneficial, increase in precipitation over countries surrounding the Mediterranean Sea and over Australia. The similarity of these results appears to be due to the similarity in the large-scale forcing patterns that are applied in each study.

The detrimental impact of MCB over the South East Atlantic on precipitation over South America has led some studies to focus solely on susceptible clouds over the east Pacific (Haywood et al., 2023). Depending on quantity of sea-salt emitted, this deployment strategy has the potential to induce undesirable side-effects caused by a La Niña-like response many times stronger than natural variability. The impacts of the subtropical gyre ocean circulations are highlighted as playing a key role in redistributing the MCB-induced SST anomalies. Evidence for a La Niña-like climate response produced by this and similar injection strategies (more cooling in the eastern compared to the western Pacific), is also found in Rasch et al. (2009), Jones and Haywood (2012), Hill and Ming (2012), Hirasawa et al. (2023), and Chen C. C. et al. (2024). Detrimental impacts from a permanent strong La Niña-like response include shifts in tropical and extratropical precipitation and are likely to exert other far-reaching impacts. For example, Haywood et al. (2023) show that sea-level rise over the low-lying islands of the south Pacific under their deployment scenario and strategy is greater than in the unmitigated greenhouse-gas warming scenario. Hirasawa et al. (2023) suggest that the strong increase in precipitation over Australasia that was also found in Haywood et al. (2023) originates from forcing the southeast Pacific and that, of the three regions investigated in their study, this region produces the strongest global cooling response.

Even though the number of studies is quite limited, it is clear that strong regional forcing patterns have the potential to induce strong regional responses. The more uniform forcing patterns deployed in some modelling studies, and in SAI deployments, suggests a more uniform global response.

Major Research Gaps related to large-scale circulation response to MCB include:

i) Model dynamical responses of regional cooling and associated inter-model consistency need to be thoroughly investigated using a suitable risk–risk framework.
ii) The role of the oceans. How oceans redistribute thermal anomalies associated with the strong localised cooling of MCB has not been rigorously investigated.
iii) The additivity of regional MCB deployments needs investigating to examine whether the overall response of targeting many areas is similar to that obtained by summing the response from each individual area.

4.5 Impacts

The impacts of MCB on terrestrial ecosystems are intrinsically linked to the impacts on large scale dynamics which influence precipitation, temperature, and net primary productivity and are therefore not differentiated in Section 4.4. However, the impacts of MCB on marine ecosystems are almost entirely absent in the scientific literature. The lack of certainty in the effectiveness of MCB couples with the lack of a specific deployment scenario, lack of a specific deployment strategy, and uncertainties in subsequent large-scale dynamical impacts in the atmosphere and ocean resulting in too large a parameter space to comprehensively assess this issue.

If MCB were deployed, it is likely that there may be both local and remote impacts on marine ecosystems. These impacts will depend strongly on the deployment scenario and strategy. It is likely that local impacts would include those induced by reduced downwelling solar radiation at the surface, strong local reductions in SST, and changes in surface winds and oceanic currents. As many studies have indicated a La Niña-like response following the preferential targeting of susceptible clouds of the eastern Pacific, impacts might be expected to follow those evident in naturally occurring La Niña events. Positive impact on the fishing industry of western South America owing to oceanic upwelling at the west of the Pacific bringing nutrient-rich waters to the surface might be expected. However, such an assumption is dangerous as permanent La Niña conditions some five times greater than that of naturally occurring La Niñas could occur under a deployment that reduces the global mean temperature from that of SSP5-8.5 to that of SSP2-4.5 (Haywood et al., 2023). This unprecedented state would very likely bring unintended and unpredictable consequences and could potentially lead to large-scale marine ecosystem impacts.

Major Research Gaps related to impacts of MCB include:

i) A lack of engagement with the marine biology/ecological community. As MCB scenarios and strategies are still relatively under-developed, there has been little engagement between the physical scientists engaged with GCM modelling and the marine biology/ecological community.
ii) A lack of engagement with the community engaged in modelling the productivity of regional fisheries. A model intercomparison project (endorsed under CMIP) already exists that could be exploited in this regard (Fish-MIP, Tittensor et al., 2018), but MCB scenarios and strategies need further development.

5 Other proposed SRM techniques

In addition to SAI and MCB, a wide range of other SRM strategies have been proposed. Here, we discuss research needs associated with a subset of these, where there is sufficient scientific literature available for identification of key knowledge gaps. We distinguish between (i) strategies that aim to modify cloud or tropospheric aerosol composition and (ii) surface-based strategies that primarily aim to increase surface albedo. Both methods increase the planetary albdeo α (Equation 1), either through increasing the reflectivity of the atmosphere, or through increasing the reflectivity on the surface. All strategies discussed here tend to target smaller geographic areas than SAI and large-scale MCB, and are sometimes specifically tailored for the preservation of certain climate variables (Arctic sea ice coverage or Greenland ice mass, for instance). Notably, SRM is also a misnomer for some of the strategies under (i), as they do not aim to increase α, but rather target longwave radiation by reducing effective emissivity ε (Equation 1). By doing so, they can potentially more directly compensate for the increased ε following increases in greenhouse gas concentrations, but as will become evident, large uncertainties remain at present. For simplicity we continue to use the term SRM, despite the inconsistency noted above. In the following, we assess the limited literature available for the three types of "other" SRM strategies, i.e., (i) Cirrus Cloud Thinning (CCT), (ii) mixed-phase cloud thinning (MCT), and (iii) surface albedo modification and discuss research needs associated with them that have been identified to date.

As discussed in Section 4, aerosol-cloud interactions form the foundation for MCB, in which an increase in CCN induces brighter and potentially longer-lived and more extensive liquid clouds. Similarly, aerosol-cloud interactions also form the foundation for two other SRM strategies, targeting high-latitude ice (cirrus) and mixed-phase clouds. As for MCB, cloud modification through injection of aerosols into air masses that will subsequently take part in cloud formation is the objective for both CCT and MCT. But differently from MCB, in CCT and MCT, the aerosols to be injected are ice-nucleating particles (INPs) rather than CCN. In both cases, the purpose of such INP injections is cloud thinning, which would allow more emission of longwave infrared radiation to space and thus lead to cooling. By targeting regions and seasons with limited incoming solar radiation, accompanying cloud albedo reductions would have minimal compensating warming effect. However, the mechanisms by which cloud thinning can be achieved for CCT and MCT are somewhat different.

For CCT, the injection of INPs can allow ice crystals to form at a lower supersaturation than would be required for the numerous solution droplets in the upper troposphere to freeze spontaneously. Microphysically, this means that fewer cirrus clouds will form through *homogeneous ice nucleation*, and more will form through *heterogeneous ice nucleation* (i.e., with the aid of INPs). This in turn results in cirrus clouds that consist of fewer and larger ice crystals with higher fall speeds, such that they are more rapidly removed by sedimentation.

For MCT, the injection of INPs allows for ice formation in high-latitude mixed-phase clouds that would otherwise mainly consist of supercooled liquid droplets. Again, hydrometeor size differences, in this case between the numerous and small liquid droplets and the much fewer and larger ice crystals, lead to cloud optical thinning and increased precipitation in response to INP seeding.

For surface albedo modification, the underlying mechanism is more straightforward, namely to increase the surface reflectivity (albedo). However, this albedo increase can be achieved through a wide range of surface modifications, including crop modifications, painting rooftops and other surfaces in urban areas white, or generating microbubbles in the ocean surface.

5.1 Cirrus cloud thinning and mixed-phase cloud thinning

SRM through CCT was first proposed by Mitchell and Finnegan (2009), and has since been investigated in several global modelling experiments (e.g., Storelvmo et al., 2013; Muri et al., 2014; Gasparini and Lohmann, 2016). These modelling experiments have differed widely in approach, with the simplest ones merely increasing ice crystal fall speed in order to mimic the result of actual INP injection (e.g., Muri et al., 2014; Kristjánsson et al., 2015; Jackson et al., 2016). These studies have consistently found the proposed cooling through increased LW infrared emission to space to occur. Despite being highly idealised, they allowed for investigations of the climate response to a proxy for actual INP injection. The validity of using such a proxy for studies of CCT climate response has been tested and confirmed (Gasparini et al., 2017). Consistent findings across these types of studies were (i) considerable SW compensation for the desired LW cooling effect, which makes CCT most effective under large solar zenith angle conditions, (ii) an enhancement of the hydrological cycle compared to a pre-industrial control climate when CO_2 warming is cancelled by CCT (for mechanism, see Kristjánsson et al., 2015), and thus potential to avoid the suppression of precipitation found in comparable multi-model SRM studies targeting incoming solar radiation, and (iii) amplified cooling of the Arctic, more closely mirroring the geographic patterns of greenhouse gas induced warming than equatorial injections of SAI, which tend to lead to undercooling of polar regions. A GeoMIP experiment ("G7cirrus") is currently being carried out in order to explore these effects more deeply based on a consistent set of experiments across multiple models (Kravitz et al., 2015).

However, an underlying assumption in the above studies is that INP injection does in fact have the intended outcome of producing larger ice crystals with higher fall speeds. Global modelling studies that have attempted to explicitly simulate the cirrus microphysical changes induced by INP increases have found a number of challenges to this assumption. These include (i) large uncertainty about what proportion of present-day cirrus clouds form through homogeneous nucleation (a prerequisite for CCT to work; Storelvmo and Herger, 2014), (ii) the risk of under-seeding or overseeding (Storelvmo et al., 2013), and (iii) the possibility of inducing cirrus formation under certain conditions that would otherwise not be conducive to cirrus formation (Gasparini and Lohmann, 2016). These are all factors that could either lead to negligible net impact on cirrus clouds and thus no cooling effect, or worse, lead to the opposite of the desired effect.

Despite these potential pitfalls, coordinated experiments with two global climate models that had displayed large differences in previous CCT studies owing to different scenarios and strategies led to several robust conclusions: (i) CCT, when optimised in terms of seeding amounts, could according to these experiments lead to a global ERF between -1.8 and -0.8 Wm^{-2}, which in these two models equates to offsetting between 30 and 70% of the warming from CO_2 increases experienced to date and (ii) CCT could potentially reduce estimated climate damages caused by the CO_2 increase experienced since pre-industrial by between 50 and 85% (Gasparini et al., 2020). These simulations assumed extensive intervention in the form of globally uniform cirrus seeding. However, to optimise cooling, CCT should in fact not be globally uniform, but rather target high-latitude cirrus clouds in the winter hemisphere only (Storelvmo and Herger, 2014; Liu and Shi, 2018). The fact that all explicit simulations of INP injections have so far been carried out with only two GCMs (ECHAM-HAM and CESM) is concerning, as one model consistently finds a relatively weak or negligible CCT forcing (e.g., Tully et al., 2022; Gasparini et al., 2020), while the other generally reports CCT to be a potent SRM method (e.g., Storelvmo and Herger, 2014; Shi et al., 2024). Coordinated multi-model CCT experiments of explicit INP injection are urgently needed to fully assess the feasibility of CCT.

Cirrus clouds may also inadvertently be affected by SAI (Visioni et al., 2020), mainly through temperature changes due to the sulfate aerosol heating affecting temperature and relative humidity in the upper troposphere, but also in this respect uncertainties remain large. In a global modelling study, Kuebbeler et al. (2012) also found cirrus thinning in response to SAI due to warming and stabilisation of the upper troposphere. This thinning contributed 60% to the overall cooling due to SAI. A study explicitly considering the injection of calcite into the stratosphere (see Section 3.2) likewise found significant but poorly constrained cirrus responses to the stratospheric aerosol injection (Cziczo et al., 2019).

Compared to CCT, far less research has been conducted on MCT so far. However, from the limited studies available, it appears that some of the concerns associated with CCT are not applicable for MCT. That being said, MCT may have its own problems and pitfalls that have yet to be identified because so few studies have been conducted. The first study to investigate MCT, a regional cloud-resolving modelling experiment initially designed to investigate Arctic CCT, was an accidental one (Gruber et al., 2019). The study conducted high-resolution regional modelling of the Arctic, and was among the first to actually simulate the injection of aerosols acting as INPs in the Arctic upper troposphere (as opposed to assuming some background concentration of seeding INPs), and therefore could also simulate the response of the lower-altitude Arctic mixed-phase clouds as the injected particles sedimented down through the troposphere. The unintended effect on Arctic mixed-phase clouds amounted to between 4 and 5% reduction of their cloud cover in these simulations, and was as expected accompanied by strong additional LW infrared cooling.

The only study to date that intentionally targeted MCT was conducted by Villanueva et al. (2022). In a global climate model, they injected INPs (or in some experiments increased droplet freezing rates) in high-latitude mixed-phase clouds, and found significant high-latitude cooling given the right timing and INP dosage (approximately −1 K over the Arctic Ocean, and −0.6 K over the Southern Ocean). The cooling was accompanied by a recovery of annual mean Antarctic and Arctic sea ice, but with a very uneven seasonal distribution exhibiting a strong winter recovery partly compensated by spring/summer rebound, most likely associated with increased poleward heat transport. The study found no risk of overseeding (in contrast to CCT), but also limited scalability, as MCT is spatially and temporally limited to winter hemisphere high-latitude mixed-phase clouds. As these findings all rely on a single modelling study, the above conclusions cannot yet be considered robust.

Based on recent research, it now appears likely that a clear separation of CCT and MCT is not possible in practice. Seeding of the upper troposphere with the intention of targeting cirrus would almost certainly also impact mixed-phase clouds at lower altitudes. Likewise, but to a lesser extent, some of the seeding material that would be intended for low/mid-level mixed-phase clouds would likely make it to higher levels in the atmosphere and impact cirrus. There is also the possibility of SAI-related solid particles such as calcite acting as INP when re-entering the troposphere through tropopause folds (Cziczo et al., 2019).

While there are significant unknowns related to the optimal seeding material and strategy as well as associated environmental impacts for CCT and MCT, addressing these is premature until more fundamental research gaps related to cirrus and mixed-phase cloud thinning have been addressed.

Major Research Gaps related to CCT and MCT include:

i) Susceptibility: It is not clear whether a sufficient number of cirrus and mixed-phase clouds are susceptible to seeding in regions and seasons that would yield significant cooling.
ii) Scalability: The bounds on the effective radiative forcing and associated cooling that could be achieved by CCT, MCT, or a combination of the two, is highly uncertain.
iii) Interdependency: It is not clear whether MCT and CCT are inextricably linked, such that one cannot occur without the other.

5.2 Surface albedo modification

SRM approaches that aim to modify surface albedo can be divided into land-based and ocean-based surface albedo modifications. The former have been studied more extensively to date, primarily with the use of global climate models. For example, Irvine et al. (2011) implemented three types of land surface albedo modification, targeting urban, desert and cropland areas. The global coverage of these areas at the time amounted to an estimated 0.56, 1.8 and 3.1%, respectively. For all three regions, surface albedo enhancement at the upper end of the realistic ranges led to only minor effects on global temperature, but did result in regional cooling, albeit with strong seasonality. In all three cases, and especially for the desert region, the albedo enhancement resulted in a significant reduction in rainfall over land.

Despite the issues identified above, it has been argued that regional surface albedo modification should be considered more prominently as part of regional climate adaptation and mitigation efforts (Seneviratne et al., 2018). This argument is rooted in the finding that surface albedo modifications in agricultural and densely populated areas could significantly alleviate hot extremes in these regions. Furthermore, it is argued that regional surface albedo modification may potentially avoid some of the issues identified in SAI or large-scale MCB. A GeoMIP test bed experiment (Kravitz et al., 2019) systematically exploring land surface albedo modification has been proposed for potential adoption by GeoMIP as an official core experiment (named "Land-GeoMIP"), and could reveal whether the findings of Seneviratne et al. (2018) are robust across multiple models.

Ocean surface albedo enhancement, which could be achieved through the generation of foams or microbubbles in the ocean surface, has been explored for example for Arctic Ocean surface areas in global modelling experiments, as a means to avoid sea ice melt and associated surface-albedo feedback mechanisms (Mengis et al., 2016). In a set of experiments with different emission scenarios for greenhouse gases and other climate forcers, the ocean albedo was set to 0.8 (the approximate albedo of sea ice) whenever sea ice cover dropped below 50% in model grid cells poleward of 70°N. While sea ice trends or permafrost thaw could not be reversed in any of these experiments, sea ice loss was delayed by between 25 and 60 years depending on the scenario considered, and permafrost thaw was likewise significantly delayed. Kravitz et al. (2018) performed analysis of idealised multi-model simulations performed under GeoMIP whereby ocean albedo was increased to balance an instantaneous quadrupling of carbon dioxide concentrations and compared the results to similar simulations that reduced the solar constant. Many similarities were noted in the comparison including residual warming over polar regions.

Targeting lower latitudes instead, Gabriel et al. (2017) conducted a similar experiment, but modified the surface albedo of the major subtropical ocean gyres in the Southern Hemisphere. The hemispheric asymmetry was deliberate owing to the potential desirability of a shift in the rain-bearing ITCZ to enhance precipitation over sub-Saharan Africa (e.g., Haywood et al., 2013). The ocean gyres specifically were selected because they are largely cloud free, thus increasing the efficacy of the surface albedo enhancement, and because they have low wind speeds, weak currents and limited biological productivity. In simulations following the RCP6.0 emission pathway (Meinshausen et al., 2011), the surface albedo of the SH ocean gyres were set to 0.15 (from an unperturbed value of around 0.06), and the associated climate response was evaluated. The albedo enhancement led to a global cooling of approximately 0.6 K, accompanied by increased precipitation over tropical land areas, many of which are at present under severe water scarcity threats. The experiment, referred to as "G4foam," was a so-called GeoMIP test bed experiment proposed for potential adoption by GeoMIP as an official core experiment, but has so far only been conducted by a single model, and no formal experiment protocol has been developed to further this approach. Major hurdles associated with the viability of ocean surface albedo modification exist at present, for example regarding the feasibility of creating a stable, highly reflective layer of microbubbles at the ocean surface, and largely unexplored but likely significant effects on ocean circulation and marine biology and chemistry.

Major Research Gaps related to surface albedo modification include:

i) Land-based surface albedo modification: the effective radiative forcing and/or cooling that could be achieved through albedo modifications of the land surface is poorly constrained, and robust features of the associated climate have yet to be identified.
ii) Ocean-based surface albedo modification: Stable perturbations to ocean albedo may not be technically achievable, and assessments of the consequences for the marine environment are lacking.

6 Discussion and concluding remarks

This article has summarised the current research gaps in SRM with a detailed analysis of the SAI and MCB technologies that are currently the most prominent potential SRM techniques discussed in the scientific literature. Some of the less prominent methods of SRM (e.g., CCT, MCT and land albedo modification) are also briefly discussed, but the research in these areas is recognised as being quite embryonic in nature, which precludes a detailed analysis of research gaps. It is recognised that the research agenda in the SRM area is rapidly expanding, so it is not inconceivable that these less prominent technologies or other methods might move more to the forefront of research in the future.

The focus of this work has been on the research gaps in SAI and MCB via technical and scientific aspects such as generation and delivery, process-level understanding, scaling issues, large scale circulation responses and impacts. Both SAI and MCB approaches need to be thoroughly assessed to work towards scientific progress within an interdisciplinary framework to inform decision makers and the public (Diamond et al., 2022; Tilmes et al., 2024). In the opinion of the authors, the support of international organisations such as WCRP that have a duty of responsibility to all of its member nations need to support research into the research gaps that are outlined here, and acknowledge and discuss associated issues of diversity, equality and inclusivity (Hurrell et al., 2024).

Most countries in the Global South are vulnerable to climate change despite their low historical greenhouse gas emissions (Trisos et al., 2022). Similarly, the risk from climate intervention such as SRM would have regional impacts, likely felt more significantly by the most vulnerable countries, hence there is an ethical imperative for them to be at the forefront of SRM research, discussion and evaluation (e.g., Horton and Keith, 2016; Rahman et al., 2018). Global South (GS) communities add value to these discussions as they have different value systems to those of the western world, where most SRM research has originated, and bring different perspectives on climate change impacts, ecosystems, loss and damage and adaptation/mitigation (Bala and Gupta, 2019). Indeed, surveys of the GS suggest that while SRM technologies are viewed more favorably in terms of potential benefits they also express greater concerns that climate-intervention technologies could undermine climate-mitigation efforts, and that SRM could promote an unequal distribution of risks between poor and rich countries (Baum et al., 2024).

In the opinion of the authors, international organisations such as the WCRP can provide an objective and transparent approach, free from any real or perceived vested interests, and facilitate comprehensive assessments of the benefits and risks of proposed CDR and SRM approaches, and synthesising these results. The authors recognise the moral and ethical complexities of SRM research and recommend a globally inclusive, transparent, and equitable scientific endeavour undertaken by a global research community that includes the GS and Global North (GN), as both are key stakeholders.

Bala et al. (2023) acknowledge "…unresolved issues around equity, ethics and consent" and support "significantly more scientific research into the potential impacts of SRM technologies on low- and middle-income countries, which are on the frontlines of climate change," "to establish a robust, equitable and rigorous trans-disciplinary scientific review process to reduce uncertainties associated with SRM and better inform decision-making." Historically, most CI research has emerged from global north research institutions largely because most funding for CI research has derived from GN funders. The SRM research agenda has therefore been set by GN researchers, and impacts have frequently been interpreted through a GN lens (e.g., Dove et al., 2021). Hence there have been a number of analyses with a global north focus on climate impacts perspectives of climate. It is well understood that global north driven research cannot adequately address the research concerns of the global south, reinforces inequitable power relationships and asymmetries in knowledge, expertise and technical capacity, does not foster a two-way learning process and does not build relationships on which sustained research can be conducted (Steynor et al., 2020; Vincent et al., 2020).

Many barriers to inclusivity in SRM research are faced by GS researchers including access to funding (Overland et al., 2022), infrastructure (Meque et al., 2021), knowledge and inequitable power relationships (Vincent et al., 2020). However, the WCRP have recognised that the global south has a critical contribution to make to the SRM research arena in terms of understanding both global and regional impacts. To address this, the Degrees Initiative (DEveloping country Governance REsearch and Evaluation for SRM) has, since 2018, funded 25 climate intervention research projects in global south countries involving over 150 researchers that have addressed SRM impacts on the physical climate (Pinto et al., 2020; Clarke et al., 2021; Camilloni et al., 2022; Kuswanto et al., 2022), oceans (Ayissi et al., 2023), extremes (Patel et al., 2023) and agriculture (Egbebiyi et al., 2023). Several researchers in the Degrees Initiative programme participate in WCRP structures and have been able to present global south perspectives and as such have had a role in framing the research agenda and narrative developed for the WCRP lighthouse as well as the WCRP endorsed GeoMIP programme.

While the initiatives noted above are an encouraging start to global inclusivity, the WCRP recognises that a significant and sustained effort in improving the current situation is required to fully support truly global research in the contentious area of SRM.

Author contributions

JH: Writing – original draft, Writing – review & editing. OB: Writing – original draft, Writing – review & editing. CL: Writing – original draft, Writing – review & editing. TS: Writing – original draft, Writing – review & editing. ST: Writing – original draft, Writing – review & editing. DV: Writing – original draft, Writing – review & editing.

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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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