JAMES | Journal of Advances in Modeling Earth Systems®

COMMENTARY
10.1029/2024MS004872

Key Gaps in Models' Physical Representation of Climate Intervention and Its Impacts

Sebastian D. Eastham[1], **Amy H. Butler**[2], **Sarah J. Doherty**[3], **Blaž Gasparini**[4], **Simone Tilmes**[5], **Ewa M. Bednarz**[2,6], **Ulrike Burkhardt**[7], **Gabriel Chiodo**[8,9], **Daniel J. Cziczo**[10], **Michael S. Diamond**[11], **David W. Keith**[12], **Thomas Leisner**[13], **Douglas G. MacMartin**[14], **Johannes Quaas**[15], **Philip J. Rasch**[16], **Odran Sourdeval**[17], **Isabelle Steinke**[18], **Chelsea Thompson**[2], **Daniele Visioni**[19], **Robert Wood**[16], **Lili Xia**[20], and **Pengfei Yu**[21]

[1]Department of Aeronautics, Imperial College London, London, UK, [2]NOAA Chemical Sciences Laboratory, Boulder, CO, USA, [3]CICOES (Cooperative Institute for Climate, Ocean and Ecosystem Studies), University of Washington, Seattle, WA, USA, [4]Department of Meteorology and Geophysics, University of Vienna, Vienna, Austria, [5]Atmospheric Chemistry Observations and Modeling Laboratory, NSF National Center for Atmospheric Research, Boulder, CO, USA, [6]Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado-Boulder, Boulder, CO, USA, [7]Institut für Physik der Atmosphäre, Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen, Germany, [8]Institute for Atmospheric and Climate Science, Zurich, Switzerland, [9]Instituto de Geociencias (IGEO), CSIC-UCM, Madrid, Spain, [10]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IL, USA, [11]Department of Earth, Ocean, and Atmospheric Science, Florida State University, Tallahassee, FL, USA, [12]Department of Geophysical Sciences, Climate Systems Engineering Initiative, University of Chicago, Chicago, IL, USA, [13]Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, Karlsruhe, Germany, [14]Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY, USA, [15]Leipzig Institute for Meteorology, Leipzig University, Leipzig, Germany, [16]Department of Atmospheric Sciences, University of Washington, Seattle, WA, USA, [17]UMR 8518-LOA-Laboratory of Atmospheric Optics, CNRS, University of Lille, Lille, France, [18]Faculty of Civil Engineering and Gesosciences, Delft University of Technology, Delft, The Netherlands, [19]Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY, USA, [20]Department of Environmental Sciences, Rutgers University, New Brunswick, NJ, USA, [21]Institute for Environmental and Climate Research, Jinan University, Guangzhou, China

Key Points:

- Agreement across models in the physical responses to solar radiation modification may not reflect high accuracy
- We identify nine key knowledge/modeling gaps where advances would improve understanding of solar radiation modification's physical impacts
- More observations are needed to constrain atmospheric processes uniquely affected by implementation of solar radiation modification

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

S. D. Eastham,
s.eastham@imperial.ac.uk

Citation:

Eastham, S. D., Butler, A. H., Doherty, S. J., Gasparini, B., Tilmes, S., Bednarz, E. M., et al. (2025). Key gaps in models' physical representation of climate intervention and its impacts. *Journal of Advances in Modeling Earth Systems*, *17*, e2024MS004872. https://doi.org/10.1029/2024MS004872

Received 3 DEC 2024
Accepted 26 MAY 2025

Author Contributions:

Conceptualization: Sebastian D. Eastham, Amy H. Butler, Sarah J. Doherty, Simone Tilmes, David W. Keith
Methodology: Sebastian D. Eastham
Project administration: Sebastian D. Eastham
Visualization: Chelsea Thompson

Abstract

Solar radiation modification (SRM) is increasingly discussed as a potential method to ameliorate some negative effects of climate change. However, unquantified uncertainties in physical and environmental impacts of SRM impede informed debate and decision making. Some uncertainties are due to lack of understanding of processes determining atmospheric effects of SRM and/or a lag in development of their representation in models, meaning even high-quality model intercomparisons will not necessarily reveal or address them. Although climate models at multiple scales are advancing in complexity, there are specific areas of uncertainty where additional model development (often requiring new observations) could significantly advance understanding of SRM's effects, and improve our ability to assess and weigh potential risks against those of choosing to not use SRM. We convene expert panels in the areas of atmospheric science most critical to understanding the three most widely discussed forms of SRM. Each identifies three key modeling gaps relevant to either stratospheric aerosols, cirrus, or low-altitude marine clouds. Within each area, key challenges remain in capturing impacts due to complex interactions in aerosol physics, atmospheric chemistry/dynamics, and aerosol-cloud interactions. Across all three, in addition to arguing for more observations, the panels argue that model development work to either leverage different capabilities of existing models, bridge scales across which relevant processes operate, or address known modeling gaps could advance understanding. By focusing on these knowledge gaps we believe the modeling community could advance understanding of SRM's physical risks and potential benefits, allowing better-informed decision-making about whether and how to use SRM.

Plain Language Summary

Solar radiation modification has been suggested as a potential method to reduce climate warming and its associated impacts, with three different types the subject of most research: stratospheric aerosol injection; marine cloud brightening; and cirrus cloud thinning. However, while modeling studies suggest some such methods could be effective, key challenges remain in accurately simulating their impacts due to complex interactions in aerosol physics, atmospheric chemistry, atmospheric dynamics, and aerosol-cloud interactions that are inherent to the three SRM methods. We highlight critical research gaps that must be addressed to improve solar radiation modification modeling, including uncertainties in aerosol-cloud interactions, aerosol microphysics, and their global effects. These gaps, identified by expert panels through the

Writing – original draft: Sebastian D. Eastham, Amy H. Butler, Sarah J. Doherty, Blaž Gasparini, Simone Tilmes, Ewa M. Bednarz, Ulrike Burkhardt, Gabriel Chiodo, Daniel J. Cziczo, Michael S. Diamond, David W. Keith, Thomas Leisner, Douglas G. MacMartin, Johannes Quaas, Philip J. Rasch, Odran Sourdeval, Isabelle Steinke, Daniele Visioni, Robert Wood, Lili Xia, Pengfei Yu
Writing – review & editing: Sebastian D. Eastham, Amy H. Butler, Sarah J. Doherty, Blaž Gasparini, Simone Tilmes, Ewa M. Bednarz, Ulrike Burkhardt, Gabriel Chiodo, Daniel J. Cziczo, Michael S. Diamond, David W. Keith, Thomas Leisner, Douglas G. MacMartin, Johannes Quaas, Philip J. Rasch, Odran Sourdeval, Isabelle Steinke, Daniele Visioni, Robert Wood, Lili Xia, Pengfei Yu

Geoengineering Modeling Research Consortium, emphasize the need for more detailed laboratory and field studies, along with improved models at multiple scales. We specifically outline where additional fundamental research is needed to support decision making around SRM, which will inevitably be made under uncertainty.

1. Introduction

Despite ongoing efforts to arrest climate change, the world is still on track to exceed 2°C of warming before the end of the 21st century (IPCC, 2021). This has motivated research into solar radiation modification (SRM, also referred to as solar radiation management, solar geoengineering, or climate intervention), which would involve a deliberate alteration to the radiative balance of the Earth system to reduce climate warming and the damages associated with this warming. Based on modeling studies, including those within the Geoengineering Modeling Intercomparison Project (GeoMIP), multiple independent scientific assessments (National Academies of Sciences et al., 2021; National Research Council, 2015; The Royal Society, 2009; United Nations Environment Programme, 2023) have focused on three strategies in particular that may be feasible to rapidly reduce some fraction of climate warming from increasing greenhouse gasses: stratospheric aerosol injection (SAI), marine cloud brightening (MCB), and cirrus cloud thinning (CCT). Although CCT relies principally on modification of the longwave radiation budget rather than solar radiation, it is generally included within the definition of SRM (National Academies of Sciences et al., 2021; National Research Council, 2015).

There are many ethical, legal, and political issues that would need to be considered in deciding whether or how to use any of these approaches, even if a strategy were proven to be technically feasible and effective. All of these aspects include their own set of knowledge gaps and uncertainties that would affect decisions around SRM. Here, we are specifically addressing key gaps in the modeling of physical impacts. Importantly, discussions around the other (non-physical) aspects of the problem will be most effective if they are rooted in understanding of the physical efficacy, limits, benefits, and risks of different possible implementations of SRM. A key concern is how well modeling studies can capture the physical response of the Earth system to climate interventions since, as with climate change in general, we must rely on models to project future climate impacts under different climate and SRM scenarios.

All three SRM approaches discussed here induce changes in climate by adding aerosols to the atmosphere in specific locations, thereby aiming to modify either stratospheric aerosols or tropospheric clouds. However, their effects reach far beyond the locations where they are applied, either directly (especially for SAI) or through teleconnections and other feedbacks. Accurate simulations of responses to their implementation rely on understanding aerosol microphysics, atmospheric chemistry, and aerosol-cloud interactions; how these produce changes in Earth's radiative balance; and the local-to-global responses in the atmosphere and Earth system to these changes. This is a challenge because many of the required processes are not well understood and/or simulated in global climate models. Some such processes occur on temporal and spatial scales smaller than can be currently represented in global-scale models, while others simply have not yet been identified as a priority in the context of other, competing model development demands. Many processes that are key in representing the effects of climate intervention are also relevant to accurately capturing the climate impacts of conventional anthropogenic aerosol emissions, volcanic eruptions, and rising greenhouse gas concentrations. However, addressing these process representations solely from the perspective of these other phenomena may not be sufficient to accurately capture the climate impacts of SRM. Doing so incurs additional research priorities potentially aimed at different processes and uncertainties.

Informed decision-making around the use of SRM demands that we understand the efficacy and impacts of different SRM implementations, and are able to quantify the uncertainty in these predictions—which will be made through the use of global-scale Earth System Models and regional-scale climate models. While these models do not need to be—and indeed will never be—perfect, they are the main tool available for understanding the physical responses to global-scale interventions. Robust identification and quantification of uncertainties in the modeled physical and environmental side effects are critical to informed decisions around any potential future application. For this purpose, it is essential to understand where modeling, laboratory experiments, or small-scale field experiments are necessary or useful to reduce uncertainties in the effects of SRM. Identifying where research is specifically needed to improve scientific understanding and model representation of SRM is therefore valuable.

This can inform model development efforts while we work to also develop additional observational constraints and continue performing model intercomparisons.

With this in mind, the Geoengineering Modeling Research Consortium (GMRC) convened groups of experts in each domain—stratospheric aerosols, cirrus clouds, and marine clouds—with the goal of better understanding the modeling knowledge gaps in each area, and what might be done to test models and reduce these gaps. The members of each working group possessed a diverse range of competences, including global- and process-scale modeling, remote sensing, laboratory studies, observational studies, and field studies. Through a series of online meetings, the groups identified the research gaps in each area which are considered likely to compromise the accuracy of simulations of SRM. These gaps were discussed prior to and presented during the 2023 GMRC meeting in Exeter, UK, before a final round of iteration and revision with all of the original group members.

The results of the consultation are given below. We first provide an assessment of two common focus areas which were highlighted independently by all three working groups. We then outline gaps which are specific to either stratospheric aerosols, cirrus clouds, or marine clouds. Specifically, we highlight gaps to which simulations of SRM are expected to be especially sensitive, and which may not be prioritized by work aimed at improving the broader response of climate models to greenhouse gas emissions.

For each sub-section, although the group mostly addresses issues relevant to the associated form of SRM, the concerns are not necessarily restricted to a specific SRM strategy. For example, aerosol injected for SAI or CCT may ultimately affect low clouds, so while the key modeling gap is in the domain of aerosol-cloud interactions in marine clouds the identified uncertainties could also be relevant to the full effects of SAI and CCT as well as MCB. In addition to the three gaps described in detail by each group below, a complete list of the issues identified by each group is provided in the Supporting Information S2.

2. Research Gaps

Although each group was able to identify key gaps which can be addressed in each area through model development, a common focus was on the demand for more observations to better constrain models and improve process-level understanding. This is elaborated in more detail below for each area, but all three groups pointed out that—regardless of the larger effects of changes in stratospheric aerosols, cirrus clouds, or marine clouds—there are large differences in the representation (and responses to aerosol injection) of stratospheric aerosol, marine clouds, and cirrus clouds between models at the same scale, and between models and observations. While model intercomparisons can reveal differences between different models, a true test of model accuracy requires testing against observations. Such model validation can take the form of testing model accuracy in representing key processes or systems that contribute to planetary albedo changes.

This is complemented by the value that would be gained, again across all three SRM approaches, by improving the consistency of process representation across models of different scales. Different understandings and representations of the underlying physics can produce useful and informative differences in model output, but frequently we find that parameterizations in low-resolution models produce results which are simply inconsistent with higher-resolution models which more accurately resolve the physics. For example, simulations of the effects of cirrus cloud thinning are limited by the low level of confidence in the ability of global models to represent the effect of a perturbation in sub-grid-scale conditions on the formation, properties, and fate of cirrus. Higher-resolution models can be used to constrain these processes but the response is rarely consistent between fine- and coarse-resolution models, and questions remain regarding the accuracy of said models and how to bridge between the scales of localized processes and global responses. Although some process uncertainties can only be reduced through lab experiments, scale consistency is an area where productive work can be carried out now without necessarily needing additional observational data in order to proceed. This applies also to the evaluation of local and regional impacts, where statistical and dynamical downscaling methods are needed which are suitable for simulations of SRM. The application of machine learning and artificial intelligence (ML/AI) may be able to assist in this area, for example, through development of efficient new subgrid parameterizations suitable for downscaling. However, the same challenges apply regarding the need to verify that these approaches are accurate in situations which have never previously been observed.

These two concerns together motivate a general need for targeted observational campaigns which aim to provide stronger constraints on process-level models in each of the three areas, and for novel and/or concerted efforts to bridge the scales between observations, high-resolution modeling, and global-scale models. There furthermore remain multiple gaps, several of which are highlighted in Appendix A of Supporting Information S2, which apply generally to any form of SRM and are not restricted to one of the three science areas below. These can be addressed through model-based investigations of the response to solar dimming without the need to specify the method by which it is achieved, thus providing clearer insights regarding environmental outcomes which would be expected to result from all forms of SRM.

2.1. Stratospheric Aerosols

Authors: Amy Butler, Simone Tilmes, Ewa M. Bednarz, Gabriel Chiodo, Daniele Visioni, Lili Xia, Pengfei Yu.

The focus of the first group is on stratospheric aerosol processes, which will primarily be key for modeling stratospheric aerosol injection (SAI). SAI is a proposed method of counteracting anthropogenic warming of global-mean surface temperatures by increasing the concentration of liquid or solid aerosols in the stratosphere to reflect a small portion of sunlight away from Earth. While many facets of stratospheric aerosol processes and their impacts are in theory understood, uncertainties arise when trying to simulate these processes in models that can't fully resolve the spatial and temporal scales at which the processes occur (Kremser et al., 2016). Although model simulations of SAI (primarily using sulfur injections) show relative reductions in global surface temperatures (Visioni et al., 2021), there remain large uncertainties across models in many aspects of the Earth system response to SAI (Haywood et al., 2022). In order to evaluate which of these uncertainties may be reducible by improving model processes, we consider current modeling gaps for simulating SAI's impacts on the Earth system. These fall within five broad categories of aerosol microphysics, chemistry, dynamics, radiation, and coupling to other components of the Earth system (see Appendix B in Supporting Information S2). While all of these process uncertainties are relevant to improved simulation of SAI, below we highlight the three modeling gaps that are most fundamental to simulating stratospheric aerosol processes and are thus most likely to holistically reduce uncertainties that propagate to the entire Earth system response. Much of this process understanding is also imperative for understanding the effects of increases in stratospheric aerosols from other sources such as volcanic eruptions, stratospheric pyrocumulus (Solomon et al., 2023), and emissions into the stratosphere from the space sector (Maloney et al., 2022; Murphy et al., 2023).

Three broad modeling gaps are shown in Figure 1. The first modeling gap that has been identified is the representation of detailed microphysical changes in the stratospheric aerosol layer that occur when aerosols or their precursors are injected into the stratosphere. These processes include the relative roles of nucleation, coagulation, and aerosol growth/condensation in the injected plume, as well as sedimentation. Global climate models with interactive aerosol-chemistry schemes are not able to reproduce details of the observed aerosol distribution following the Mount Pinatubo eruption (Brown et al., 2024; Quaglia et al., 2023; Stenchikov et al., 2021; Tilmes et al., 2023; Vattioni, Weber et al., 2024). This may be related to how models simulate microphysical processes, the relative roles of which may be dependent on background conditions or the co-presence of other chemical constituents. For example, measurements taken soon after the 2022 Hunga Tonga-Hunga Ha'apai eruption suggested that coagulation may be an important process in the size evolution of the stratospheric aerosols (Legras et al., 2022). However, this eruption was unusual in the amount of water vapor it injected with the aerosols which led to very unique aerosol formation conditions. Another example is the Raikoke eruption in 2019. The co-emission of volcanic ash and mineral dust resulted in additional absorption of solar and terrestrial radiation (Kloss et al., 2021; Wells et al., 2023). In general, explosive volcanic eruptions are not perfect analogs for the aerosol sources associated with SAI. SAI would involve continuous injections over many years at different locations, which may alter the relative importance of condensation, coagulation, and sedimentation of aerosols compared to a singular event like a volcanic eruption. Nonetheless, comparison of model simulations to existing and new observations of aerosol properties in the stratosphere (in particular rapid-response measurements after volcanic eruptions) may be one of the best pathways forward to identify shortcomings in models and improve understanding and parameterizations. Incorporating model developers into measurement field campaigns of stratospheric aerosols would be valuable in order to help in identifying what observations are needed to verify or improve parameterized processes (Sprintall et al., 2021).

An additional challenge is realistically representing precursor injections in global climate models, which treat volumes of ~10,000 km^3 as a single cell (Boulon et al., 2011; Wrana et al., 2023). Comprehensive aerosols models, including sectional aerosol models with comprehensive microphysical aerosol processes, could be used

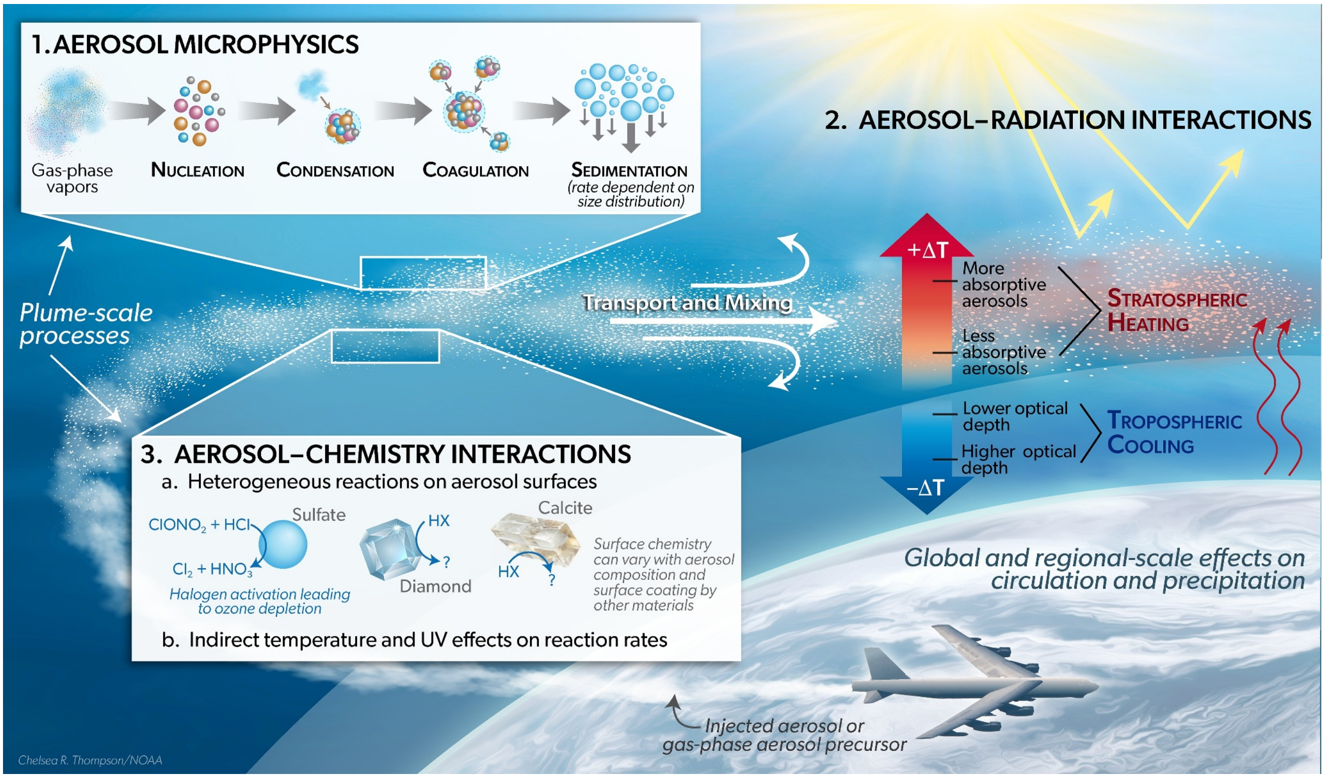

Figure 1. Modeling gaps in the representation of stratospheric aerosol under SRM scenarios.

to compare with and improve less sophisticated but computationally cheaper modal aerosol models often used in global climate models. Plume-scale simulations that resolve small scale transport processes would be a valuable step forward, but are limited to a refined region and are computationally expensive. Chamber experiments (or possibly small, plume-scale field experiments, given the difficulties of replicating stratospheric conditions in the lab) are needed to investigate aerosol microphysical properties, and to assess aerosol microphysics for candidate SAI materials other than sulfate, for example, calcites (Huynh & McNeill, 2024; Keith et al., 2016; Vattioni, Stenke et al., 2024). Model intercomparisons involving small and large injections are needed to compare the effects on aerosol microphysics and size distributions, especially for aerosols composed of materials other than sulfate.

A second key modeling gap to address is model uncertainties in aerosol interactions with radiation, in particular uncertainties under SAI in (a) the radiative heating response in the stratosphere; (b) changes in radiative forcing at the surface; and (c) changes in tropospheric photolysis. For (a), different radiative transfer models give different stratospheric heating responses, which may be due to their assumptions about aerosol properties, for example, the wavelength sensitivity to absorption/reflection/refraction and aerosol composition. It may further depend on how specific aerosol size distributions affect radiative heating in the stratosphere (Haywood et al., 2022). The difference in the heating response in models changes atmospheric circulation and surface climate, including—but not limited to—regional precipitation patterns (Ricke et al., 2023; Simpson et al., 2019). The uncertainty in radiative heating across models is associated with uncertainties in (b) the magnitude of negative radiative forcing at the surface. The magnitude of the cooling that can be achieved with SAI depends on aerosol optical depth, which in turn is dependent on injection material, aerosol size, and on the injection location, altitude and timing (Bednarz, Visioni et al., 2023; Laakso et al., 2022, 2024; Visioni et al., 2023; Zhang et al., 2024). Models also have different sensitivities of surface temperatures to the same magnitude of aerosol forcing, a reflection of the different climate sensitivities across climate models (Zelinka et al., 2020). All these uncertainties in both the forcing and sensitivity may explain the existing large differences in surface temperature response to varying stratospheric backgrounds and SAI perturbations across different models (Visioni et al., 2023), propagating to other systems such as the hydrological cycle (McGraw & Polvani, 2024; Ricke et al., 2023). Finally, the changes in radiation due to SAI will affect (c) tropospheric photolysis rates, an interaction that is currently poorly represented in most climate models, but may have substantial effects on tropospheric air quality, thereby feeding into the third key modeling gap discussed below.

One crucial interaction determining the effects of SAI on climate is the radiative efficiency of stratospheric aerosols. However, radiative transfer is inherently complex and computationally expensive. The broad-band radiation schemes employed in global models can often lead to biases in radiative fluxes, which can have downstream effects on climate. Some modeling improvements could be achieved through model evaluation against detailed line-by-line radiative transfer models (Dykema et al., 2016). Multi-model comparisons to existing and new observations of radiative properties (such as extinction, aerosol optical depth, etc) for different wavelengths and their surface forcing would also be beneficial (Timmreck et al., 2018).

Uncertainties in the surface climate response including the hydrological cycle are due not only to uncertainties in the direct radiative response to SAI but also to uncertainties in coupling to other aspects of the atmosphere and climate system (land, ocean, and cryosphere). Idealized simulations, such as modeling injections in a dry dynamical core (Hollowed et al., 2024), simplified experiments with fixed single-point SO_2 injections, or prescribed aerosol simulations with fixed SSTs, could isolate processes contributing to inter-model uncertainties in simulated SAI responses (Bednarz, Butler et al., 2023; Visioni et al., 2023). The same applies for SAI's other impacts on atmospheric chemistry and dynamics, and can isolate the influence of top-down driven effects from stratospheric heating from slower-evolving feedbacks with the ocean.

A third major modeling gap is missing or poorly simulated aerosol interactions with chemistry. While there is a well-developed understanding of the response of chemistry to sulfur injections based on observations of volcanic sulfate aerosols in the stratosphere, effects of continuous injections on concentrations of chemical species, for example, stratospheric ozone, greenhouse gases, and on tropospheric and surface-level chemistry (Eastham et al., 2018; Moch et al., 2023; Xia et al., 2017), are still not well characterized. For ozone, concentrations are influenced by a range of heterogeneous (including on aerosol surfaces) and gas-phase chemical reactions, as well as changes in temperatures and atmospheric transport. The impact of stratospheric aerosols on ozone is thus the cumulative result of all those processes, leading to disagreement amongst different models (Tilmes et al., 2021). In addition, some models lack certain processes, including interactions of aerosols with photolysis or a comprehensive set of heterogeneous reactions on sulfate, both of which are important for stratospheric and tropospheric chemistry.

Confident assessment of impacts of SAI on atmospheric chemistry thus requires that the performance of current models is thoroughly evaluated, for example, using the observations of past volcanic eruptions and their impacts on composition and chemistry. Specified-dynamics simulations that constrain meteorology and its interannual variability may help isolate model uncertainties to chemical processes, though large-scale transport is not well-constrained in these simulations (Chrysanthou et al., 2019; Tilmes et al., 2012). Additional chemical observations (both "rapid response" and long-term monitoring) after volcanic eruptions, including of SO_2, H_2SO_4, and various related nitrogen and halogen products, could help with model assessment. Meanwhile little is known about how injections of other materials would affect atmospheric chemical processes (Vattioni et al., 2023; Visioni et al., 2024). Lab and small outdoor studies are needed to improve estimates of uptake rates and other chemical reaction rates, especially for injection of materials other than sulfate. Finally, these data need to be integrated into chemistry-climate models and sensitivity and scenario simulations performed to investigate the effects of different aerosol materials on chemistry.

Addressing these key modeling gaps would likely lead to model improvements that would reduce model uncertainties with regards to both SAI forcings and naturally occurring stratospheric aerosols, but this list is not exhaustive. A full list of the stratospheric aerosol modeling gaps identified by the group is provided in Appendix B of Supporting Information S1.

2.2. Cirrus Clouds

Authors: Blaž Gasparini, Sebastian D. Eastham, Ulrike Burkhardt, Daniel J. Cziczo, Thomas Leisner, Odran Sourdeval, Isabelle Steinke.

Cirrus cloud thinning (CCT) is a method of climate intervention aimed at offsetting the anthropogenic greenhouse effect by increasing the emission of longwave radiation to space (Lohmann & Gasparini, 2017; Mitchell &

Finnegan, 2009). Cirrus clouds absorb thermal radiation from the surface but emit relatively little due to their low temperature and reflect only a small fraction of solar radiation due to their (on average) low optical depth, leading to a net positive (globally warming) cloud radiative effect (Hong et al., 2016; Matus & L'Ecuyer, 2017). CCT would aim to reduce the coverage, lifetime, and/or thickness of cirrus clouds by injecting appropriate ice nucleating particles, allowing more cirrus clouds to form through ice nucleation on the surface of these particles by heterogeneous ice nucleation, while suppressing the new formation of cirrus produced by freezing of abundant tiny solution droplets, known as homogeneous ice nucleation. This approach to reducing the number of cirrus ice crystals is in contrast to the effect of air traffic within cirrus clouds, which on average increases the number of cirrus ice crystals (Verma & Burkhardt, 2022) and prolongs their lifetime.

The existing literature on the radiative effectiveness of CCT by injections of ice nucleating particles is inconclusive, ranging from a potential inadvertent warming effect (so-called "overseeding" (Tully et al., 2023)) to an upper bound cooling effect of 1.5°C (Gasparini et al., 2020; Lohmann & Gasparini, 2017; Storelvmo et al., 2014). This uncertainty is mainly because there are many gaps in our understanding of cirrus cloud formation and the role ice nucleating particles play in it. Fundamental gaps in understanding cirrus not only prevent progress and convergence on the assessments of the effectiveness of CCT but also lead to large uncertainties in cirrus-aerosol interactions, including the potential impact of sedimenting SAI particles on cirrus and the impacts of air traffic on cirrus clouds and the radiative balance of the Earth (Kärcher, 2018; Lee et al., 2021).

Although this working group primarily focused on identifying key gaps in research related to CCT, many, if not all, of the conclusions can be applied more broadly to the study of cirrus clouds and their interactions with aerosols. While similar working groups have already reviewed and summarized topics such as cirrus-aerosol interaction (Bellouin et al., 2020; Intergovernmental Panel on Climate Change (IPCC), 2023b), CCT (Intergovernmental Panel on Climate Change (IPCC), 2023a), and cirrus cloud climate feedbacks (Sherwood et al., 2020), none of these efforts have exclusively focused on the question of which model developments could most rapidly advance our understanding of anthropogenic cirrus cloud modification.

The group's findings are summarized in Figure 2. The group first identified an overarching issue that connects all identified gaps and issues: the uncertain role that ice nucleating particles, and thus heterogeneous ice nucleation, play for present-day, unperturbed cirrus clouds (Bacer et al., 2021; Gryspeerdt et al., 2018). Reducing uncertainty in this issue is critical to understanding whether or not CCT could even theoretically produce a climate benefit of the magnitude necessary to warrant further research. The remaining research gaps, listed below, are separated into three groups: dynamical gaps, cloud physics gaps, and CCT-related gaps (see Appendix C in Supporting Information S2 for a full list).

The key dynamical gap is our ability to simulate the occurrence, location, intensity (degree of supersaturation), and extent of ice supersaturated regions in both standard and kilometer-scale climate models. These regions are essential for the formation and maintenance of both naturally occurring and perturbed/seeded cirrus clouds. Not simulating ice supersaturated regions correctly leads to flawed aerosol-cirrus interactions and an incorrect representation of the role of heterogeneous ice nucleation in the climate system. This failure is in turn due to two complementary model shortcomings: the inability to accurately simulate the upper tropospheric water budget, and the inability to resolve the variability and frequency of updrafts necessary for cloud formation. Moreover, the inability of models to reliably simulate upper tropospheric aerosol loading and its influence on ice nucleation and water vapor uptake additionally complicates this issue and connects it to the microphysical gaps described below. These issues particularly apply to coarse-resolution climate models, the tools most often used to estimate the efficacy of CCT. The difficulty of accurately measuring supersaturation, among other critical parameters, is an additional challenge and further research is needed to improve and expand observational data sets.

Despite advancements in sub-grid scale parameterization and the increasing use of data-driven approaches, there is a need to leverage high-resolution (sub-kilometer scale) models which are capable of capturing the variability of updrafts. These can be constrained by already-available updraft data to determine if the inputs to the microphysical schemes are appropriate for simulating cirrus clouds, but would benefit from the acquisition of more in situ measurements of updrafts in the upper troposphere; this is possible with aircraft (Krämer et al., 2016, 2020), balloons (Bramberger et al., 2022), or remote sensing techniques (e.g., using products from the EarthCare and INCUS missions including satellite-derived updraft velocity data).

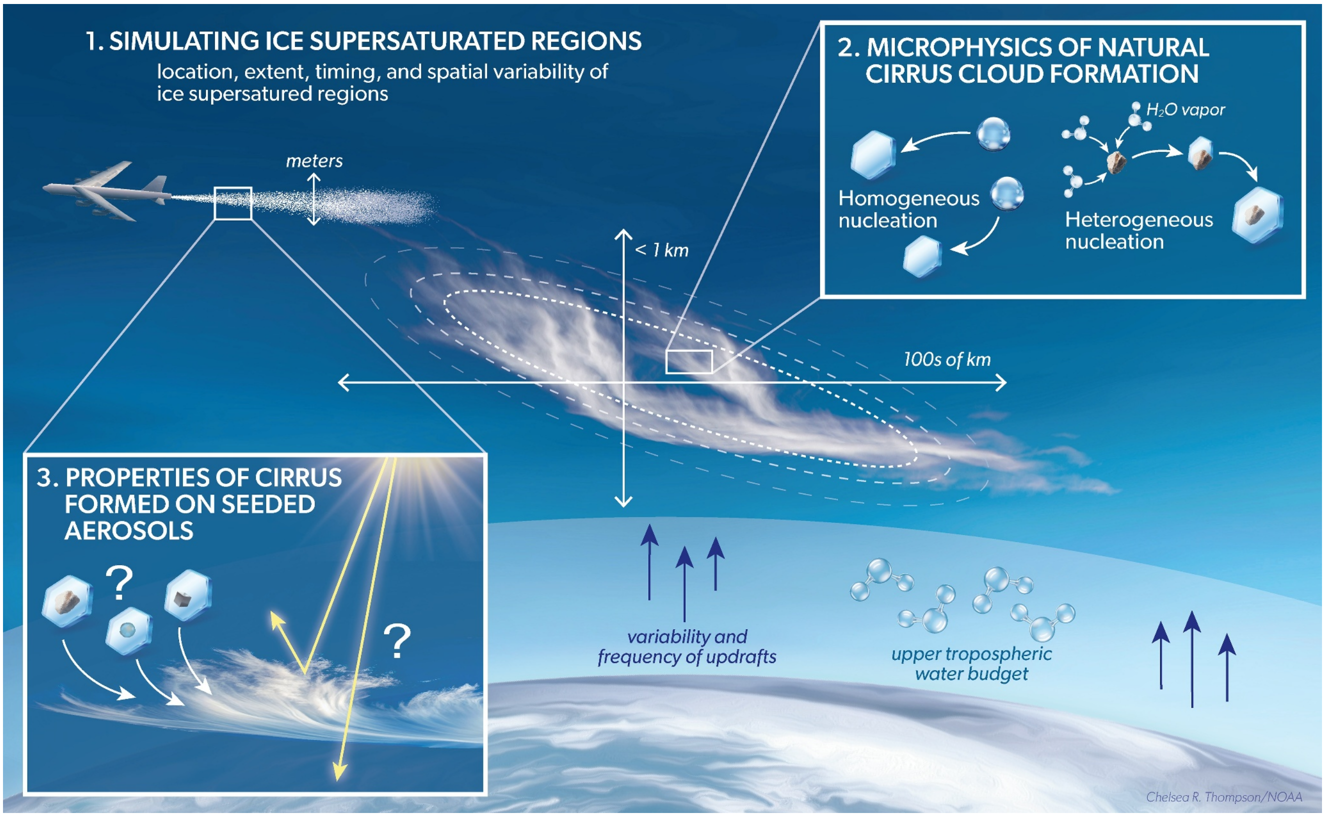

Figure 2. Modeling gaps in the representation of cirrus under SRM scenarios.

The key cloud-physics gap is in the microphysics of cirrus cloud formation, which inhibits advances in knowledge on cirrus clouds and CCT. Many of the CMIP-type models used to simulate CCT (and most high-resolution kilometer-scale models) only have basic representations of ice nucleation and the subsequent cirrus cloud evolution. Addressing some subset of the key issues related to cirrus parameterizations may therefore already be feasible with limited changes to model code and relatively low computational expense (R. L. Atlas et al., 2024). However, there are still significant gaps in our understanding which originate in the lack of observations: currently, information on naturally present ice nucleating particles at cirrus conditions are extremely rare and not sufficient to constrain global models despite many dedicated measurement campaigns (Cziczo et al., 2013; Kiselev et al., 2017; Schneider et al., 2021; Wagner et al., 2018, 2020). These global models in turn have to use numerous assumptions to simulate cirrus formation, resulting in large model spread in the relative importance of the two cirrus nucleation mechanisms (Gasparini et al., 2020; Penner et al., 2015).

The issue can begin to be resolved by creating a global ice nucleating particle climatology under cirrus conditions. This could be achieved through numerous in situ ice-nucleating particle (INP) measurements at cirrus conditions across all latitudinal bands and seasons, possibly complemented by measurements of cirrus ice residuals that could determine the ice nucleating particles present in ice crystals (Cziczo et al., 2013). Such measurements are urgently needed particularly in high latitude regions during winter, when CCT schemes are thought to be most effective (Storelvmo & Herger, 2014).

Moreover, cirrus clouds are affected by cloud adjustments beyond nucleation. These may be strong enough to substantially change the radiative forcing of CCT, either magnifying or mitigating CCT's intended cooling effect. Cloud adjustments could for example, modify the lifetime of cirrus clouds, for example, through changes in uncertain ice crystal loss processes. Such adjustments are currently unknown for high clouds. A possible model framework to investigate this issue could include a global kilometer-scale simulation for studying CCT impacts at large scales, paired with limited-area LES domain simulations focused on simulating microphysics and turbulence. Such modeling studies would also benefit from a Lagrangian, cloud-evolution-following perspective. Process-based, cloud-evolution perspectives could also yield benefits, especially if applied consistently both to model output and observational (in situ and remote-sensing) data containing collocated measurements of dynamical, microphysical, and radiative properties.

Assuming that the first two gaps are resolved, we would still be left with a number of important concerns related to determining the efficacy and impacts of CCT. Central among these gaps is the uncertainty surrounding the properties of cirrus formed on seeded aerosols. This includes the conditions under which they nucleate ice, their optical properties, the effects of atmospheric aging, and potentially the effect of in-contrail processing if delivered by aircraft. This is not surprising given that, to our knowledge, no research has yet been conducted to find the most appropriate ice nucleating particle for use in CCT. Furthermore, it is currently unclear whether the seeded INPs can be controlled to achieve a target concentration over large areas without causing the unwanted "overseeding" effect. This could either lead to the formation of additional (unwanted) cirrus or thicken the existing cirrus near the sources of seeded INP, where the concentration of injected INPs may be very high (Tully et al., 2023).

To address this CCT-specific gap, we propose a multi-faceted approach. Laboratory experiments can elucidate the behavior of INPs under different conditions, while large eddy model simulations will allow the exploration of particle dispersion dynamics, which is critical for thinking about the engineering of CCT. Such experiments could also constrain the potential impact of seeded particles on lower-lying mixed phase clouds, which were shown to be substantial in one modeling study (Gruber et al., 2019). Finally, small-scale field experiments could serve as a benchmark for such process-based model simulations.

The gaps listed above are complemented by a more extensive list of research gaps in Appendix C of Supporting Information S2. Resolving the gaps in cirrus cloud modeling will require a concerted effort to bridge gaps in our understanding of cirrus cloud formation and aerosol interactions, extending far beyond models to the satellite, in situ observation, and laboratory communities. Only through such efforts can we advance our understanding of CCT and its potential as a climate intervention strategy.

2.3. Marine Clouds

Authors: Sarah J. Doherty, Michael S. Diamond, Robert Wood, Johannes Quaas, Philip J. Rasch.

Marine clouds would be most directly affected by the form of SRM known as marine cloud brightening (MCB). MCB leverages an effect that is currently observed in the atmosphere where aerosol pollution mixes into clouds and increases their albedo (reflectivity), such as in "ship tracks" (Conover, 1966). These ship tracks were the original inspiration behind the MCB concept (Latham, 1990). The modern definition of MCB involves intentionally brightening low marine clouds with sub-micron sized aerosol, likely using sea salt generated from ocean water using ship-based spray systems.

The clouds expected to be most susceptible to albedo increases from the addition of aerosols are clean stratocumulus clouds (Alterskjær et al., 2013; Oreopoulos & Platnick, 2008), which cover about 20% of the Earth's oceans (Wood, 2012). These clouds have therefore been the focus of most MCB studies. Approximately 60% of present-day effective radiative forcing from pollution via aerosol-cloud interactions is estimated to occur in stratocumulus clouds (Diamond et al., 2020). However, there is growing evidence that other types of low marine clouds may also be amenable to brightening (Chen et al., 2024; Malavelle et al., 2017), and any form of SRM involving aerosol injection could cause a response in marine clouds. As such, the discussions of this working group focused on the uncertainties around aerosol-cloud interactions in low marine clouds more broadly, where "low" refers to clouds that are confined to approximately the lowermost two km of the atmosphere. A better understanding of impacts from both possible deliberate (MCB) and expected inadvertent (pollution) changes in marine clouds is important, highlighting the "dual purpose" of studying aerosol-cloud interactions in this type of cloud.

Many of the uncertainties around both the present-day climate forcing through aerosol-cloud interactions and in the potential for intentional marine cloud brightening to cool climate revolve around processes occurring at scales ranging from that of the aerosols themselves (<1 μm) through the scales of cloud features (e.g., up- and downdrafts at 10–100 m), up to the scales of broad cloudy regions (10–100 km). It has long been understood that adding sub-micron diameter sized aerosols can increase the cloud droplet number concentration in clouds thereby increasing the water surface area for a given cloud volume and thus its reflectivity, particularly when background aerosol concentrations are low (Twomey, 1974, 1977). This "Twomey effect" was the basis for the concept of intentionally brightening low marine clouds with sea salt aerosols (Latham, 1990). We now understand that cloud

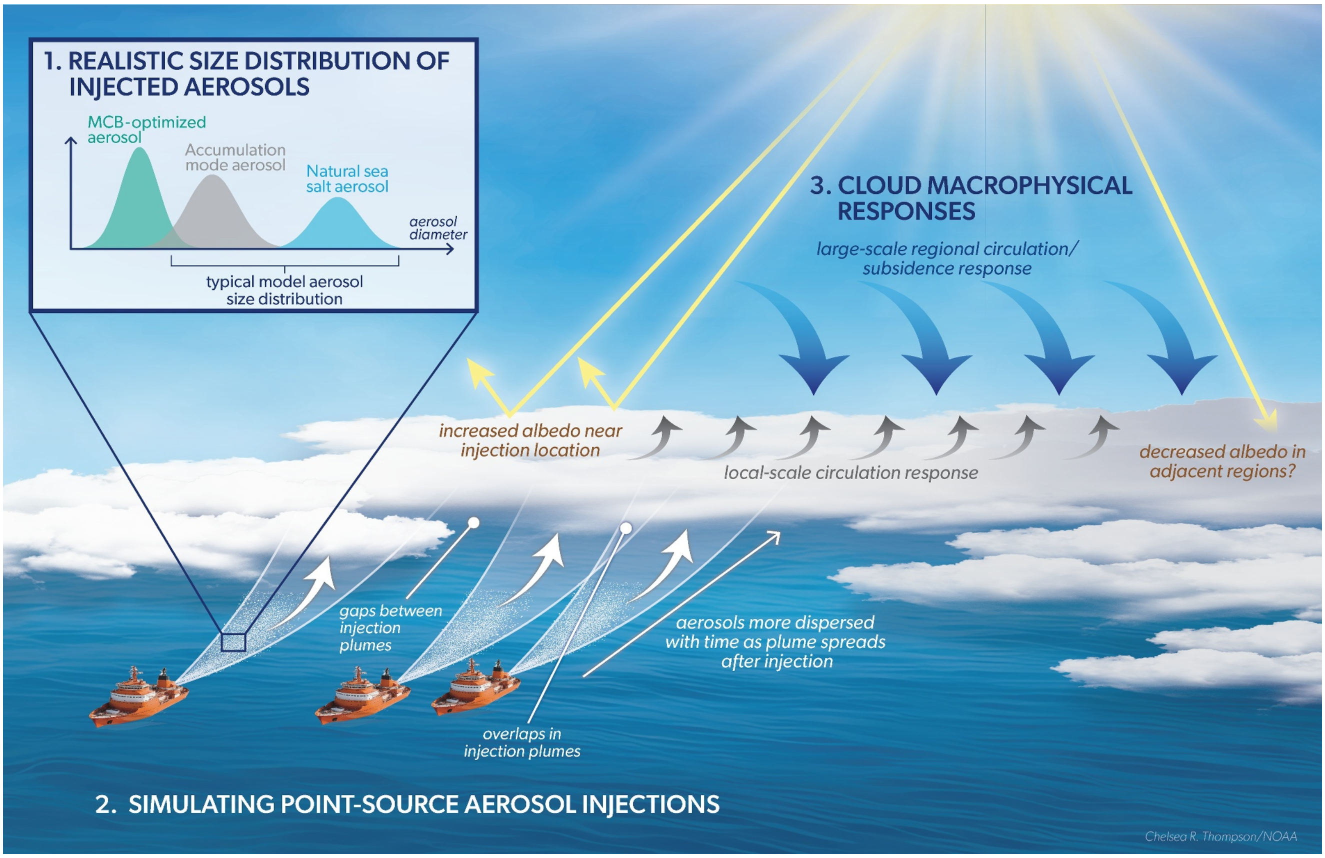

Figure 3. Modeling gaps in the representation of marine clouds under SRM scenarios.

macrophysical properties (i.e., the horizontal and vertical extent of clouds, where the latter is often expressed in terms of liquid water path) can subsequently respond to this change in cloud microphysics in ways that can either offset or add to Twomey brightening. The total change in cloud albedo depends strongly on the background meteorological conditions (especially updraft velocities, propensity to precipitate, and above-cloud humidity). Cloud responses also depend strongly on background aerosol concentrations and the size and concentration of added aerosols (e.g., Hoffman and Feingold, 2021; Wood, 2021). As such, although MCB's efficacy is more certain than that of CCT, there is much greater uncertainty in the potential efficacy and capacity for MCB to cool climate than for SAI.

These uncertainties in how MCB would play out locally under different conditions directly affect what spatial and temporal patterns of forcing could be produced using MCB, and therefore what patterns of climate impacts are possible. In turn, climate changes from both greenhouse gases and other sources of climate forcing, including SRM approaches, are expected to affect clouds (Klein et al., 2017; Schneider et al., 2019) and background aerosols (Bodas-Salcedo et al., 2019; Li et al., 2022) in ways that could then alter the efficacy and potential range of impacts of different MCB implementations.

Here, we highlight three areas, summarized in Figure 3, where focused efforts are needed specifically to assess MCB as a climate intervention that are unlikely to be addressed through more general efforts to reduce uncertainties in inadvertent climate forcing in low marine clouds. Further, while the broad scope of research needed to assess MCB was recently described by Feingold et al. (2024), here we focus on three specific areas of research that would address deficiencies specifically in accurately representing MCB in models.

A fundamental first need is to improve models' ability to represent MCB aerosol emissions using realistic aerosol size distributions. It's currently estimated that optimal MCB implementation would involve the generation of a large number (~10^{15}–10^{16} s^{-1}) of sea salt aerosols sized between approximately 10 and 200 nm dry diameter from individual point sources at the ocean surface (Connolly et al., 2014; Wood, 2021). While some coarse resolution climate models have investigated the sensitivity of the radiative forcing and cooling impact to injections of sea-salt aerosol of different sizes (Haywood et al., 2023), many climate models lack the ability to represent the injection of sea-salt aerosols at the optimal size range. Instead, MCB aerosol injection is usually represented through either an enhancement in the number of accumulation-mode aerosols, such as sulfate, or by enhancing or scaling the natural sea salt aerosol source (e.g., Jones & Haywood, 2012). However, MCB-optimized aerosols are smaller than natural accumulation mode aerosols (e.g. see Ueda et al., 2016, Table 1), and much smaller than naturally produced sea salt aerosols.

There are multiple consequences to using incorrectly sized aerosols in simulations of MCB. The efficacy of aerosols as cloud condensation nuclei is very strongly dependent on their size (e.g., Dusek et al., 2006), so this can significantly affect conclusions about the efficacy of MCB for cooling climate. Where models have the ability to represent the effects of larger aerosols (so-called "giant CCN") in inducing precipitation, using incorrectly sized aerosols can also produce biases in how MCB would affect cloud water amount and lifetime (e.g., Feingold et al., 2024; Hoffmann & Feingold, 2021). Small differences in the injected aerosol geometric mean diameter and mode width will also yield very large differences in the injected mass of sea salt aerosol, since the mass scales with the cube of the aerosol diameter. Finally, use of larger aerosol than is realistic can lead to biased conclusions about the relative roles of forcing through direct aerosol-radiation versus through aerosol-cloud interactions (as in Ahlm et al., 2017; Alterskjær et al., 2013; Hill & Ming, 2012), since the former is optimized for larger-sized aerosols than the latter. Currently, no GCMs have the ability to represent the effects of giant CCN on precipitation, which is a significant gap.

A second issue regards accurately representing the point-source nature of MCB. Model studies don't currently account for the fact that the sea salt aerosols for MCB would be coming from a point source at the ocean surface, and that the resulting aerosol at cloud base likely would have variations in aerosol concentration and possibly size. High-resolution modeling studies ground-tested against observations are needed to determine how the generated aerosol size distribution changes in transit from the aerosol spray system to cloud base. Aerosol evolution in the very near field (first 10's of meters) downwind of the spray system, where most coagulation would likely take place, is particularly important and effectively unstudied at this time. Also lacking are studies on the plume dispersion rate and how aerosol properties (size, concentration) will vary within the plume under different ambient conditions. Specific to MCB is that evaporative cooling (Jenkins & Forster, 2013) could cause the plume to subside, preventing the generated aerosol from reaching cloud-base. While one initial study (Hernandez-Jaramillo et al., 2023) found this was not a significant issue at aerosol generation rates of 10^{14} s^{-1}, this question has not yet been rigorously assessed under flow rates needed for large-scale MCB. These questions need to be addressed through a combination of higher-resolution (e.g., computational fluid dynamics, CFD, and large-eddy simulation, LES) modeling studies (e.g., Dhandapani et al., 2025) and focused observational studies, then accounted for in the representation of MCB implementations in global models.

The third issue identified as specific to MCB, but that also pertains to climate forcing by "ship tracks", is the need to be able to model how cloud macrophysical responses to aerosol perturbations are affected by the timing and spatial distribution of the injection strategy (Prabhakaran et al., 2024). LES modeling studies have shown that mesoscale circulations can develop in response to locally isolated injections of aerosols (Wang et al., 2011; Wang & Feingold, 2009), such that cloud albedo can, for example, be increased in the region with enhanced aerosol concentrations, but decreased in adjacent regions. Cloud responses to aerosol injections can also induce atmospheric buoyancy perturbations that then affect the overall cloud evolution and albedo. LES simulations will include these buoyancy perturbations—but not necessarily their compensation by a response in large-scale subsidence induced through gravity wave activity (Sobel & Bretherton, 2000), because this response cannot be captured over the smaller domain size covered by typical LES simulations. While it is possible to parameterize this larger-scale circulation response, this is not routinely done, and not doing so can significantly bias the resulting cloud albedo response to aerosol injections (Chun et al., 2024).

At the same time, regional-to global-scale models, which are capable of capturing the large-scale dynamical responses, lack the ability to represent the detailed dynamical and microphysical responses and feedbacks to aerosol-cloud interactions. This is a specific case of the broader need for greater focus on how to bridge the different scales of modeling in order to better represent aerosol-cloud interactions and their effects on the climate system.

In addition to the need for improved capabilities for modeling multi-scale thermodynamic and dynamical responses to aerosol injections, this is simply an area where the needed model runs haven't been done. Almost all high resolution MCB modeling studies to date have simulated either cloud responses to a single plume of aerosol, usually in LES simulations (Berner et al., 2015; Chun et al., 2023; Erfani et al., 2022; Jenkins et al., 2013), or cloud responses to a uniform perturbation in aerosol concentrations over broad regions, as is generally done in global modeling studies (Alterskjær et al., 2013; Bower et al., 2006; Jones & Haywood, 2012; Rasch et al., 2009, 2024). In reality, MCB would likely be implemented as a series of point sources generating multiple, possibly overlapping, plumes distributed over a broader region (Salter et al., 2008; Wang et al., 2011; Wood, 2021). Regional simulations of North Atlantic ship tracks by Possner et al. (2016) found large differences in simulated aerosol forcing from cloud changes as horizontal resolution decreased from GCM to convection-permitting scales. The dynamical responses to these different configurations, and how they feed back to changes in cloud albedo and climate forcing, are not currently known.

As for SAI, addressing these challenges—and in particular the third gap—would likely yield improvements in the representation of climate change and SRM more broadly. Work on all three would specifically also improve the representation of ship tracks in global models, an issue of current interest given the finding of a potentially climatically significant contribution to recent warming trends resulting from reduced ship emissions (Diamond, 2023; Yuan et al., 2024). While these three gaps are considered the most pressing, in Appendix D of Supporting Information S2 we provide a more comprehensive list of research areas that are important to assessing MCB but are more likely to be addressed by general research into inadvertent climate forcing through aerosol-cloud interactions.

3. Conclusions

The gaps described here are by no means all of the issues which currently limit the accuracy of simulations of SRM. Other key uncertainties include insufficient or missing coupling to surface models and the associated lack of feedbacks between SRM and processes such as land ice, the carbon and nitrogen cycles, or wildfires. A full list of modeling gaps identified by the three working groups can be found in the Appendices.

Three key findings have emerged from this work. First, there are clear gaps which can be addressed to improve model-based assessments of SRM. Across all three fields, we have identified an extensive list of specific areas which, if addressed, would improve our quantitative understanding of the likely efficacy and physical impacts of an SRM strategy and their uncertainties. Importantly, some gaps in process understanding are identified that could be partially or largely addressed through model development without the need for new observations.

Second, more observational field studies are needed to verify that models are capable (or incapable) of reproducing real world responses to aerosol injections with high fidelity, and for improved understanding of key processes under real-world conditions. Observational data sets are needed to test and improve model simulations of how both the stratospheric aerosol layer and tropospheric clouds respond to concentrated and diffuse sources of aerosol of carefully specified composition and size, in pristine and polluted/perturbed conditions with varying meteorology. In the meantime, careful comparisons of model responses to different injection scenarios (e.g., differing aerosol size and concentration) in well defined meteorological regimes with well defined specification of background aerosol concentrations are useful for quantifying model differences and sensitivities to different representations of key processes, and are useful for planning of observational field studies.

Finally, work is needed to harmonize the representation of key SRM-related processes across spatial scales. Differences across high resolution models in simulated responses provide information about uncertainties in understanding of the basic processes that are relevant to SRM specifically, and differences in responses between low (e.g., GCM or Earth System model resolutions) and high (LES resolution) resolution models provide information about how well or poorly those processes are approximated in models used for climate studies (of SRM or otherwise), compared to our current understanding of the underlying processes. However, even where high-resolution models of key phenomena are shown to perform well against observations, this performance may not propagate to simulations at the coarser spatial resolutions necessary for Earth system models to capture decadal, global-scale change. Examples are the representation of specific injection sites for stratospheric aerosol, cirrus modification by aircraft, and point-source salt injections into the marine boundary layer. Dedicated model development is needed to evaluate and harmonize existing models so that the simulated effects of SRM in global scale models accurately reflect the complexities of the small-scale processes which are fundamentally driving the large-scale response.

For all of the gaps discussed above, even a comprehensive and well-funded research effort supported by ample observational data would only reduce, rather than eliminate, uncertainty in the physical impacts of an strategy. However, a detailed quantification of uncertainties will frame the range of possible outcomes. As with all policy, including on other questions relating to anthropogenic climate change, decisions about the use of SRM will need to be made based on imperfect information. But also as with other policy-relevant research, the goal should be to quantify and reduce uncertainties. In addition to exploring other methods to reduce uncertainties such as through emergent constraints (Plazzotta et al., 2018), we believe that the knowledge gaps presented here constitute those which can be most readily and productively addressed by the modeling and observational communities in order to reduce key uncertainties in SRM approaches, and therefore increase confidence in model-based projections of the likely physical effects of SRM.

Data Availability Statement

No new data or code were produced as part of this research.

Acknowledgments
We would like to thank the GeoMIP organizers and community who hosted the 2023 GMRC workshop as part of the GeoMIP annual meeting, and who provided valuable feedback at said event. Similarly, we would like to thank the members of the Geoengineering Modeling Research Consortium who have provided the input necessary to produce this list. We would particularly like to thank Prof. Jim Haywood for his invaluable input during the writing and refinement of this manuscript. Co-author Sarah J. Doherty's effort on this publication is partially funded by the Cooperative Institute for Climate, Ocean, & Ecosystem Studies (CICOES) under NOAA Cooperative Agreement NA20OAR4320271, Contribution No. 2024-1420. Support for Ewa M. Bednarz has been provided by the National Oceanic and Atmospheric Administration (NOAA) cooperative agreement (NA22OAR4320151) and the Earth's Radiative Budget (ERB) program. Gabriel Chiodo acknowledges support from the US Simons Foundation (Grant ref. MPS-MP-SRM-00005208), the Spanish Ministry of Science and Innovation (Grant ref. RYC2021-033422-I) and the European Commission (ERC StG Grant ref. 101078127). Simone Tilmes acknowledges support from the US Simons Foundation (grant ref.MPS-SRM-00005203), the NOAA Climate Program Office Earth's Radiation Budget Awards Number 03-01-07-001 and NA22OAR4310477, and the National Center for Atmospheric Research, which is a major facility sponsored by the NSF under Cooperative Agreement No. 1852977.

References

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

Alterskjær, K., Kristjánsson, J. E., Boucher, O., Muri, H., Niemeier, U., Schmidt, H., et al. (2013). Sea-salt injections into the low-latitude marine boundary layer: The transient response in three Earth system models. *Journal of Geophysical Research: Atmospheres*, *118*(21). https://doi.org/10.1002/2013jd020432

Atlas, R. L., Bretherton, C. S., Sokol, A. B., Blossey, P. N., & Khairoutdinov, M. F. (2024). Tropical cirrus are highly sensitive to ice microphysics within a nudged global storm-resolving model. *Geophysical Research Letters*, *51*(1), e2023GL105868. https://doi.org/10.1029/2023GL105868

Bacer, S., Sullivan, S. C., Sourdeval, O., Tost, H., Lelieveld, J., & Pozzer, A. (2021). Cold cloud microphysical process rates in a global chemistry–climate model. *Atmospheric Chemistry and Physics*, *21*(3), 1485–1505.

Bednarz, E. M., Butler, A. H., Visioni, D., Zhang, Y., Kravitz, B., & MacMartin, D. G. (2023a). Injection strategy – A driver of atmospheric circulation and ozone response to stratospheric aerosol geoengineering. *Atmospheric Chemistry and Physics*, *23*(21), 13665–13684.

Bednarz, E. M., Visioni, D., Kravitz, B., Jones, A., Haywood, J. M., Richter, J., et al. (2023b). Climate response to off-equatorial stratospheric sulfur injections in three Earth system models – Part 2: Stratospheric and free-tropospheric response. *Atmospheric Chemistry and Physics*, *23*(1), 687–709.

Bellouin, N., Quaas, J., Gryspeerdt, E., Kinne, S., Stier, P., Watson-Parris, D., et al. (2020). Bounding global aerosol radiative forcing of Climate Change. *Reviews of Geophysics*, *58*(1), e2019RG000660. https://doi.org/10.1029/2019RG000660

Berner, A. H., Bretherton, C. S., & Wood, R. (2015). Large eddy simulation of ship tracks in the collapsed marine boundary layer: A case study from the monterey area ship track experiment. *Atmospheric Chemistry and Physics*, *15*(10), 5851–5871.

Bodas-Salcedo, A., Mulcahy, J. P., Andrews, T., Williams, K. D., Ringer, M. A., Field, P. R., & Elsaesser, G. S. (2019). Strong dependence of atmospheric feedbacks on mixed-phase microphysics and aerosol-cloud interactions in HadGEM3. *Journal of Advances in Modeling Earth Systems*, *11*(6), 1735–1758. https://doi.org/10.1029/2019MS001688

Boulon, J., Sellegri, K., Hervo, M., & Laj, P. (2011). Observations of nucleation of new particles in a volcanic plume. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(30), 12223–12226.

Bower, K., Choularton, T., Latham, J., Sahraei, J., & Salter, S. (2006). Computational assessment of a proposed technique for global warming mitigation via albedo-enhancement of marine stratocumulus clouds. *Atmospheric Research*, *82*(1–2), 328–336.

Bramberger, M., Alexander, M. J., Davis, S., Podglajen, A., Hertzog, A., Kalnajs, L., et al. (2022). First super-pressure balloon-borne fine-vertical-scale profiles in the upper TTL: Impacts of atmospheric waves on cirrus clouds and the QBO. *Geophysical Research Letters*, *49*(5), e2021GL097596. https://doi.org/10.1029/2021GL097596

Brown, H. Y., Wagman, B., Bull, D., Peterson, K., Hillman, B., Liu, X., et al. (2024). Validating a microphysical prognostic stratospheric aerosol implementation in E3SMv2 using observations after the Mount Pinatubo eruption. *Geoscientific Model Development*, *17*(13), 5087–5121.

Chen, Y., Haywood, J., Wang, Y., Malavelle, F., Jordan, G., Peace, A., et al. (2024). Substantial cooling effect from aerosol-induced increase in tropical marine cloud cover. *Nature Geoscience*, *17*(5), 404–410.

Chrysanthou, A., Maycock, A. C., Chipperfield, M. P., Dhomse, S., Garny, H., Kinnison, D., et al. (2019). The effect of atmospheric nudging on the stratospheric residual circulation in chemistry–climate models. *Atmospheric Chemistry and Physics*, *19*(17), 11559–11586.

Chun, J.-Y., Wood, R., Blossey, P., & Doherty, S. J. (2023). Microphysical, macrophysical, and radiative responses of subtropical marine clouds to aerosol injections. *Atmospheric Chemistry and Physics*, *23*(2), 1345–1368. https://doi.org/10.5194/acp-23-1345-2023

Chun, J.-Y., Wood, R., Blossey, P. N., & Doherty, S. J. (2024). Impact on the stratocumulus-to-cumulus transition of the interaction of cloud microphysics and macrophysics with large-scale circulation. *EGUsphere*. https://doi.org/10.5194/egusphere-2024-2439

Connolly, P. J., McFiggans, G. B., Wood, R., & Tsiamis, A. (2014). Factors determining the most efficient spray distribution for marine cloud brightening. *Philosophical Transactions of the Royal Society A*, *372*, 20140056. https://doi.org/10.1098/rsta.2014.0056

Conover, J. H. (1966). Anomalous cloud lines. *Journal of the Atmospheric Sciences*, *23*(6), 778–785.

Cziczo, D. J., Froyd, K. D., Hoose, C., Jensen, E. J., Diao, M., Zondlo, M. A., et al. (2013). Clarifying the dominant sources and mechanisms of cirrus cloud formation. *Science (New York, N.Y.)*, *340*(6138), 1320–1324.

Dhandapani, C., Kaul, C. M., Pressel, K. G., Blossey, P. N., Wood, R., & Kulkarni, G. (2025). Sensitivities of large eddy simulations of aerosol plume transport and cloud response. *Journal of Advances in Modeling Earth Systems*, *17*(2), e2024MS004546. https://doi.org/10.1029/2024MS004546

Diamond, M. S. (2023). Detection of large-scale cloud microphysical changes within a major shipping corridor after implementation of the International Maritime Organization 2020 fuel sulfur regulations. *Atmospheric Chemistry and Physics*, *23*(14), 8259–8269.

Diamond, M. S., Director, H. M., Eastman, R., Possner, A., & Wood, R. (2020). Substantial cloud brightening from shipping in subtropical low clouds. *AGU Advances*, *1*(1), e2019AV000111. https://doi.org/10.1029/2019av000111

Dusek, U., Frank, G. P., Hildebrandt, L., Curtius, J., Schneider, J., Walter, S., et al. (2006). Size matters more than chemistry for cloud-nucleating ability of aerosol particles. *Science*, *312*(5778), 1375–1378.

Dykema, J. A., Keith, D. W., & Keutsch, F. N. (2016). Improved aerosol radiative properties as a foundation for solar geoengineering risk assessment. *Geophysical Research Letters*, *43*(14), 7758–7766. https://doi.org/10.1002/2016GL069258

Eastham, S. D., Weisenstein, D. K., Keith, D. W., & Barrett, S. R. H. (2018). Quantifying the impact of sulfate geoengineering on mortality from air quality and UV-B exposure. *Atmospheric Environment*, *187*, 424–434.

Erfani, E., Blossey, P., Wood, R., Mohrmann, J., Doherty, S. J., & Wyant, M. (2022). Simulating aerosol lifecycle impacts on the subtropical stratocumulus-to-cumulus transition using large-eddy simulations. *Journal of Geophysical Research: Atmospheres*, *127*(21), e2022JD037258. https://doi.org/10.1029/2022JD037258

Feingold, G., Ghate, V. P., Russell, L. M., Blossey, P., Cantrell, W., Christensen, M. W., et al. (2024). Physical science research needed to evaluate the viability and risks of marine cloud brightening. *Science Advances*, *10*(12), eadi8594.

Gasparini, B., McGraw, Z., Storelvmo, T., & Lohmann, U. (2020). To what extent can cirrus cloud seeding counteract global warming? *Environmental Research Letters: ERL [Web Site]*. https://doi.org/10.1088/1748-9326/ab71a3

Gruber, S., Blahak, U., Haenel, F., Kottmeier, C., Leisner, T., Muskatel, H., et al. (2019). A process study on thinning of Arctic winter cirrus clouds with high-resolution ICON-ART simulations. *Journal of Geophysical Research: Atmospheres*, *124*(11), 5860–5888. https://doi.org/10.1029/2018JD029815

Gryspeerdt, E., Sourdeval, O., Quaas, J., Delanoë, J., Krämer, M., & Kühne, P. (2018). Ice crystal number concentration estimates from Lidar–radar satellite remote sensing–Part 2: Controls on the ice crystal number concentration. *Atmospheric Chemistry and Physics*, *18*(19), 14351–14370.

Haywood, J., Tilmes, S., Keutsch, F., Niemeier, U., Schmidt, A., Visioni, D., et al. (2022). Stratospheric Aerosol injection and its potential effect on the stratospheric ozone layer. In V. Aquila & K. H. Rosenlof (Eds.), *Scientific assessment of ozone Depletion: 2022* (pp. 325–383). World Meteorological Organization.

Haywood, J. M., Jones, A., Jones, A. C., Halloran, P., & Rasch, P. J. (2023). Climate intervention using Marine Cloud Brightening (MCB) compared with Stratospheric Aerosol Injection (SAI) in the UKESM1 climate model. *Atmospheric Chemistry and Physics*, *23*(24), 15305–15324.

Hernandez-Jaramillo, D. C., Harrison, L., Kelaher, B., Ristovski, Z., & Harrison, D. P. (2023). Evaporative cooling does not prevent vertical dispersion of effervescent seawater aerosol for brightening clouds. *Environmental Science & Technology*, *57*(49), 20559–20570.

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

Hoffmann, F., & Feingold, G. (2021). Cloud microphysical implications for marine cloud brightening: The importance of the seeded particle size distribution. *Journal of the Atmospheric Sciences*, *78*, 3247–3262. https://doi.org/10.1175/jas-d-21-0077.1

Hollowed, J. P., Jablonowski, C., Brown, H. Y., Hillman, B. R., Bull, D. L., & Hart, J. L. (2024). HSW-V v1.0: Localized injections of interactive volcanic aerosols and their climate impacts in a simple general circulation model. *Geoscientific Model Development*, *17*(15), 5913–5938.

Hong, Y., Liu, G., & Li, J.-L. F. (2016). Assessing the radiative effects of global ice clouds based on CloudSat and CALIPSO measurements. *Journal of Climate*, *29*(21), 7651–7674.

Huynh, H. N., & McNeill, V. F. (2024). The potential environmental and climate impacts of stratospheric aerosol injection: A review. *Environmental Sciences: Atmosphere*. https://doi.org/10.1039/d3ea00134b

Intergovernmental Panel on Climate Change (IPCC). (2023a). Future global climate: Scenario-based projections and near-term information. In *Climate change 2021 – the physical science basis* (pp. 553–672). Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2023b). Short-lived climate forcers. In *Climate change 2021 – the physical science basis* (pp. 817–922). Cambridge University Press.

IPCC. (2021). Summary for policymakers. In C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, et al. (Eds.), *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change* (pp. 3–32). Cambridge University Press.

Jenkins, A. K. L., & Forster, P. M. (2013). The inclusion of water with the injected aerosol reduces the simulated effectiveness of marine cloud brightening. *Atmospheric Science Letters*, *14*(3), 164–169.

Jenkins, A. K. L., Forster, P. M., & Jackson, L. S. (2013). The effects of timing and rate of marine cloud brightening aerosol injection on albedo changes during the diurnal cycle of marine stratocumulus clouds. *Atmospheric Chemistry and Physics*, *13*(3), 1659–1673.

Jones, A., & Haywood, J. M. (2012). Sea-Spray geoengineering in the HadGEM2-ES earth-system model: Radiative impact and climate response. *Atmospheric Chemistry and Physics*, *12*(22), 10887–10898. https://doi.org/10.5194/acp-12-10887-2012

Kärcher, B. (2018). Formation and radiative forcing of contrail cirrus. *Nature Communications*, *9*(1), 1824.

Keith, D. W., Weisenstein, D. K., Dykema, J. A., & Keutsch, F. N. (2016). Stratospheric solar geoengineering without ozone loss. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(52), 14910–14914.

Kiselev, A., Bachmann, F., Pedevilla, P., Cox, S. J., Michaelides, A., Gerthsen, D., & Leisner, T. (2017). Active sites in heterogeneous ice nucleation-the example of K-rich feldspars. *Science (New York, N.Y.)*, *355*(6323), 367–371.

Klein, S. A., Hall, A., Norris, J. R., & Pincus, R. (2017). Low-cloud feedbacks from cloud-controlling factors: A review. *Surveys in Geophysics*, *38*(6), 1307–1329.

Kloss, C., Berthet, G., Sellitto, P., Ploeger, F., Taha, G., Tidiga, M., et al. (2021). Stratospheric aerosol layer perturbation caused by the 2019 Raikoke and Ulawun eruptions and their radiative forcing. *Atmospheric Chemistry and Physics*, *21*(1), 535–560.

Krämer, M., Rolf, C., Luebke, A., Afchine, A., Spelten, N., Costa, A., & Avallone (2016). A microphysics guide to cirrus clouds–Part 1: Cirrus types. *Atmospheric Chemistry and Physics*, *16*(5), 3463–3483.

Krämer, M., Rolf, C., Spelten, N., Afchine, A., Fahey, D., Jensen, E., & Sourdeval (2020). A microphysics guide to cirrus–Part 2: Climatologies of clouds and humidity from observations. *Atmospheric Chemistry and Physics*, *20*(21), 12569–12608.

Kremser, S., Thomason, L. W., von Hobe, M., Hermann, M., Deshler, T., Timmreck, C., et al. (2016). Stratospheric aerosol—Observations, processes, and impact on climate. *Reviews of Geophysics*, *54*(2), 278–335. https://doi.org/10.1002/2015RG000511

Laakso, A., Niemeier, U., Visioni, D., Tilmes, S., & Kokkola, H. (2022). Dependency of the impacts of geoengineering on the stratospheric sulfur injection strategy – Part 1: Intercomparison of modal and sectional aerosol modules. *Atmospheric Chemistry and Physics*, *22*(1), 93–118.

Laakso, A., Visioni, D., Niemeier, U., Tilmes, S., & Kokkola, H. (2024). Dependency of the impacts of geoengineering on the stratospheric sulfur injection strategy–Part 2: How changes in the hydrological cycle depend on the injection rate and model used. *Earth System Dynamics*, *15*(2), 405–427.

Latham, J. (1990). Control of global warming? *Nature*, *347*(6291), 339–340.

Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., et al. (2021). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, *244*, 117834.

Legras, B., Duchamp, C., Sellitto, P., Podglajen, A., Carboni, E., Siddans, R., & Ploeger (2022). The evolution and dynamics of the Hunga Tonga–Hunga Ha'apai sulfate aerosol plume in the stratosphere. *Atmospheric Chemistry and Physics*, *22*(22), 14957–14970.

Li, H., Yang, Y., Wang, H., Wang, P., Yue, X., & Liao, H. (2022). Projected aerosol changes driven by emissions and climate change using a machine learning method. *Environmental Science & Technology*, *56*(7), 3884–3893.

Lohmann, U., & Gasparini, B. (2017). A cirrus cloud climate dial? *Science*, *357*(6348), 248–249.

Malavelle, F. F., Haywood, J. M., Jones, A., Gettelman, A., Clarisse, L., Bauduin, S., et al. (2017). Strong constraints on aerosol-cloud interactions from volcanic eruptions. *Nature*, *546*(7659), 485–491. https://doi.org/10.1038/nature22974

Maloney, C. M., Portmann, R. W., Ross, M. N., & Rosenlof, K. H. (2022). The climate and ozone impacts of black carbon emissions from global rocket launches. *Journal of Geophysical Research*, *127*(12). https://doi.org/10.1029/2021jd036373

Matus, A. V., & L'Ecuyer, T. S. (2017). The role of cloud phase in Earth's radiation budget. *Journal of Geophysical Research: Atmospheres*, *122*(5), 2559–2578. https://doi.org/10.1002/2016JD025951

McGraw, Z., & Polvani, L. M. (2024). How volcanic aerosols globally inhibit precipitation. *Geophysical Research Letters*, *51*(13), e2023GL107930. https://doi.org/10.1029/2023GL107930

Mitchell, D. L., & Finnegan, W. (2009). Modification of cirrus clouds to reduce global warming. *Environmental Research Letters*, *4*(4), 045102.

Moch, J. M., Mickley, L. J., Eastham, S. D., Lundgren, E. W., Shah, V., Buonocore, J. J., et al. (2023). Overlooked long-term atmospheric chemical feedbacks Alter the impact of solar geoengineering: Implications for tropospheric oxidative capacity. *AGU Advances*, *4*(5), e2023AV000911. https://doi.org/10.1029/2023AV000911

Murphy, D. M., Abou-Ghanem, M., Cziczo, D. J., Froyd, K. D., Jacquot, J., Lawler, M. J., et al. (2023). Metals from spacecraft reentry in stratospheric aerosol particles. *Proceedings of the National Academy of Sciences of the United States of America*, *120*(43), e2313374120.

National Academies of Sciences, Medicine, & Others. (2021). Reflecting sunlight: Recommendations for solar geoengineering research and research governance. nap.nationalacademies.org.

National Research Council. (2015). *Climate intervention: Reflecting sunlight to cool Earth*. National Academy of Sciences.

Oreopoulos, L., & Platnick, S. (2008). Radiative susceptibility of cloudy atmospheres to droplet number perturbations: 2. Global analysis from MODIS. *Journal of Geophysical Research*, *113*(D14). https://doi.org/10.1029/2007JD009655

Penner, J. E., Zhou, C., & Liu, X. (2015). Can cirrus cloud seeding be used for geoengineering? *Geophysical Research Letters*, *42*(20), 8775–8782. https://doi.org/10.1002/2015GL065992

Plazzotta, M., Séférian, R., Douville, H., Kravitz, B., & Tjiputra, J. (2018). Land surface cooling induced by sulfate geoengineering constrained by major volcanic eruptions. *Geophysical Research Letters*, *45*, 5663–5671. https://doi.org/10.1029/2018GL077583

Possner, A., Zubler, E., Lohmann, U., & Schär, C. (2016). The resolution dependence of cloud effects and ship-induced aerosol-cloud interactions in marine stratocumulus. *Journal of Geophysical Research: Atmospheres*, *121*(9), 4810–4829. https://doi.org/10.1002/2015jd024685

Prabhakaran, P., Hoffmann, F., & Feingold, G. (2024). Effects of intermittent aerosol forcing on the stratocumulus-to-cumulus transition. *Atmospheric Chemistry and Physics*, *24*(3), 1919–1937.

Quaglia, I., Timmreck, C., Niemeier, U., Visioni, D., Pitari, G., Brodowsky, C., et al. (2023). Interactive stratospheric aerosol models' response to different amounts and altitudes of SO_2 injection during the 1991 Pinatubo eruption. *Atmospheric Chemistry and Physics*, *23*(2), 921–948.

Rasch, P., Hirasawa, H., Wu, M., Doherty, S., Wood, R., Wang, H., et al. (2024). *A protocol for model intercomparison of impacts of marine cloud brightening climate intervention*. EGUsphere. https://doi.org/10.5194/egusphere-2024-1031

Rasch, P. J., Latham, J., & Chen, C.-C. (2009). Geoengineering by cloud seeding: Influence on sea ice and climate system. *Environmental Research Letters*, *4*(4), 045112. https://doi.org/10.1088/1748-9326/4/4/045112

Ricke, K., Wan, J. S., Saenger, M., & Lutsko, N. J. (2023). Hydrological consequences of solar geoengineering. *Annual Review of Earth and Planetary Sciences*, *51*(1), 447–470.

Salter, S., Sortino, G., & Latham, J. (2008). Sea-going hardware for the cloud albedo method of reversing global warming. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, *366*(1882), 3989–4006. https://doi.org/10.1098/rsta.2008.0136

Schneider, J., Höhler, K., Wagner, R., Saathoff, H., Schnaiter, M., Schorr, T., et al. (2021). High homogeneous freezing onsets of sulfuric acid aerosol at cirrus temperatures. *Atmospheric Chemistry and Physics*, *21*(18), 14403–14425.

Schneider, T., Kaul, C. M., & Pressel, K. G. (2019). Possible climate transitions from breakup of stratocumulus decks under greenhouse warming. *Nature Geoscience*, *12*(3), 163–167.

Sherwood, S. C., Webb, M. J., Annan, J. D., Armour, K. C., Forster, P. M., Hargreaves, J. C., et al. (2020). An assessment of Earth's climate sensitivity using multiple lines of evidence. *Reviews of Geophysics*, *58*(4), e2019RG000678. https://doi.org/10.1029/2019rg000678

Simpson, I. R., Tilmes, S., Richter, J. H., Kravitz, B., MacMartin, D. G., Mills, M. J., et al. (2019). The regional hydroclimate response to stratospheric sulfate geoengineering and the role of stratospheric heating. *Journal of Geophysical Research: Atmospheres*, *124*(23), 12587–12616. https://doi.org/10.1029/2019JD031093

Sobel, A., & Bretherton, C. (2000). Modeling tropical precipitation in a single column. *Journal of Climate*, *13*(24), 4378–4392.

Solomon, S., Stone, K., Yu, P., Murphy, D. M., Kinnison, D., Ravishankara, A. R., & Wang, P. (2023). Chlorine activation and enhanced ozone depletion induced by wildfire aerosol. *Nature*, *615*(7951), 259–264.

Sprintall, J., Coles, V. J., Reed, K. A., Butler, A. H., Foltz, G. R., Penny, S. G., & Seo, H. (2021). Using process studies to improve climate modeling: Strategies for success. *Bulletin of the American Meteorological Society*, *102*(6), 523–526.

Stenchikov, G., Ukhov, A., Osipov, S., Ahmadov, R., Grell, G., Cady-Pereira, K., et al. (2021). How does a Pinatubo-size volcanic cloud reach the middle stratosphere? *Journal of Geophysical Research: Atmospheres*, *126*(10), e2020JD033829. https://doi.org/10.1029/2020JD033829

Storelvmo, T., Boos, W. R., & Herger, N. (2014). Cirrus cloud seeding: A climate engineering mechanism with reduced side effects? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *372*, 20140116.

Storelvmo, T., & Herger, N. (2014). Cirrus cloud susceptibility to the injection of ice nuclei in the upper troposphere. *Journal of Geophysical Research: Atmospheres*, *119*(5), 2375–2389. https://doi.org/10.1002/2013JD020816

The Royal Society. (2009). *Geoengineering the climate: Science, governance and uncertainty* (pp. 1–98). The Royal Society. https://doi.org/10.1007/s10098-010-0287-3

Tilmes, S., Richter, J. H., Kravitz, B., MacMartin, D. G., Glanville, A. S., Visioni, D., et al. (2021). Sensitivity of total column ozone to stratospheric sulfur injection strategies. *Geophysical Research Letters*, *48*(19), e2021GL094058. https://doi.org/10.1029/2021GL094058

Tilmes, S., Kinnison, D. E., Garcia, R. R., Salawitch, R., Canty, T., Lee-Taylor, J., et al. (2012). Impact of very short-lived halogens on stratospheric ozone abundance and UV radiation in a geo-engineered atmosphere. *Atmospheric Chemistry and Physics*, *12*, 10945–10955.

Tilmes, S., Mills, M. J., Zhu, Y., Bardeen, C. G., Vitt, F., Yu, P., et al. (2023). Description and performance of a sectional aerosol microphysical model in the Community Earth System Model (CESM2). *Geoscientific Model Development*, *16*(21), 6087–6125.

Timmreck, C., Mann, G. W., Aquila, V., Hommel, R., Lee, L. A., & Schmidt, A., & Weisenstein. (2018). The Interactive Stratospheric Aerosol Model Intercomparison Project (ISA-MIP): Motivation and experimental design. *Geoscientific Model Development*, *11*(7), 2581–2608.

Tully, C., Neubauer, D., Villanueva, D., & Lohmann, U. (2023). Does prognostic seeding along flight tracks produce the desired effects of cirrus cloud thinning? *Atmospheric Chemistry and Physics*, *23*(13), 7673–7698.

Twomey, S. (1974). Pollution and the planetary Albedo. *Atmospheric Environment*, *41*, 1251–1256.

Twomey, S. (1977). The influence of pollution on the shortwave albedo of clouds. *Journal of the Atmospheric Sciences*, *34*(7), 1149–1152.

Ueda, S., Miura, K., Kawata, R., Furutani, H., Uematsu, M., Omori, Y., et al. (2016). Number–size distribution of aerosol particles and new particle formation events in tropical and subtropical Pacific Oceans. *Atmospheric Environment*, *142*, 324–339.

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

Vattioni, S., Luo, B., Feinberg, A., Stenke, A., Vockenhuber, C., Weber, R., et al. (2023). Chemical impact of stratospheric alumina particle injection for solar radiation modification and related uncertainties. *Geophysical Research Letters*, *50*(24), e2023GL105889. https://doi.org/10.1029/2023GL105889

Vattioni, S., Stenke, A., Luo, B., Chiodo, G., Sukhodolov, T., Wunderlin, E., & Peter, T. (2024a). Importance of microphysical settings for climate forcing by stratospheric SO_2 injections as modeled by SOCOL-AERv2. *Geoscientific Model Development*, *17*(10), 4181–4197.

Vattioni, S., Weber, R., Feinberg, A., Stenke, A., Dykema, J. A., Luo, B., et al. (2024b). A fully coupled solid-particle microphysics scheme for stratospheric aerosol injections within the aerosol–chemistry–climate model SOCOL-AERv2. *Geoscientific Model Development*, *17*(21), 7767–7793.

Verma, P., & Burkhardt, U. (2022). Contrail formation within cirrus: ICON-LEM simulations of the impact of cirrus cloud properties on contrail formation. *Atmospheric Chemistry and Physics*. https://doi.org/10.5194/acp-22-8819-2022

Visioni, D., Bednarz, E. M., Lee, W. R., Kravitz, B., Jones, A., Haywood, J. M., & MacMartin, D. G. (2023). Climate response to off-equatorial stratospheric sulfur injections in three Earth system models – Part 1: Experimental protocols and surface changes. *Atmospheric Chemistry and Physics*, *23*(1), 663–685.

Visioni, D., MacMartin, D. G., Kravitz, B., Boucher, O., Jones, A., Lurton, T., et al. (2021). Identifying the sources of uncertainty in climate model simulations of solar radiation modification with the G6sulfur and G6solar Geoengineering Model Intercomparison Project (GeoMIP) simulations. *Atmospheric Chemistry and Physics*, *21*(13), 10039–10063.

Visioni, D., Quaglia, I., & Steinke, I. (2024). A living assessment of different materials for stratospheric aerosol injection—Building bridges between model world and the messiness of reality. *Geophysical Research Letters*, *51*(10), e2024GL108314. https://doi.org/10.1029/2024GL108314

Wagner, R., Bertozzi, B., Höpfner, M., Höhler, K., Möhler, O., Saathoff, H., & Leisner, T. (2020). Solid ammonium nitrate aerosols as efficient ice nucleating particles at cirrus temperatures. *Journal of Geophysical Research: Atmospheres*, *125*(8), e2019JD032248. https://doi.org/10.1029/2019JD032248

Wagner, R., Kaufmann, J., Möhler, O., Saathoff, H., Schnaiter, M., Ullrich, R., & Leisner, T. (2018). Heterogeneous ice nucleation ability of NaCl and sea salt aerosol particles at cirrus temperatures. *Journal of Geophysical Research: Atmospheres*. https://doi.org/10.1002/2017JD027864

Wang, H., & Feingold, G. (2009). Modeling mesoscale cellular structures and drizzle in marine stratocumulus. Part II: The microphysics and dynamics of the boundary region between open and closed cells. *Journal of the Atmospheric Sciences*, *66*(11), 3257–3275.

Wang, H., Rasch, P. J., & Feingold, G. (2011). Manipulating marine stratocumulus cloud amount and albedo: A process-modelling study of aerosol-cloud-precipitation interactions in response to injection of cloud condensation nuclei. *Atmospheric Chemistry and Physics*, *11*(9), 4237–4249.

Wells, A. F., Jones, A., Osborne, M., Damany-Pearce, L., Partridge, D. G., & Haywood, J. M. (2023). Including ash in UKESM1 model simulations of the Raikoke volcanic eruption reveals improved agreement with observations. *Atmospheric Chemistry and Physics*, *23*(7), 3985–4007.

Wood, R. (2012). Stratocumulus clouds. *Monthly Weather Review*, *140*(8), 2373–2423.

Wood, R. (2021). Assessing the potential efficacy of marine cloud brightening for cooling Earth using a simple heuristic model. *Atmospheric Chemistry and Physics*, *21*(19), 14507–14533. https://doi.org/10.5194/acp-21-14507-2021

Wrana, F., Niemeier, U., Thomason, L. W., Wallis, S., & von Savigny, C. (2023). Stratospheric aerosol size reduction after volcanic eruptions. *Atmospheric Chemistry and Physics*, *23*(17), 9725–9743.

Xia, L., Nowack, P. J., Tilmes, S., & Robock, A. (2017). Impacts of stratospheric sulfate geoengineering on tropospheric ozone. *Atmospheric Chemistry and Physics*, *17*(19), 11913–11928.

Yuan, T., Song, H., Oreopoulos, L., Wood, R., Bian, H., Breen, K., et al. (2024). Abrupt reduction in shipping emission as an inadvertent geoengineering termination shock produces substantial radiative warming. *Communications Earth & Environment*, *5*(1), 281.

Zelinka, M. D., Myers, T. A., McCoy, D. T., Po-Chedley, S., Caldwell, P. M., Ceppi, P., et al. (2020). Causes of higher climate sensitivity in CMIP6 models. *Geophysical Research Letters*, *47*(1), e2019GL085782. https://doi.org/10.1029/2019GL085782

Zhang, Y., MacMartin, D. G., Visioni, D., Bednarz, E. M., & Kravitz, B. (2024). Hemispherically symmetric strategies for stratospheric aerosol injection. *Earth System Dynamics*, *15*(2), 191–213.

References From the Supporting Information

Abdul-Razzak, H., & Ghan, S. J. (2000). A parameterization of aerosol activation: 2. Multiple aerosol types. *Journal of Geophysical Research: Atmospheres*, *105*(D5), 6837–6844.

Ackerman, A. S., Kirkpatrick, M. P., Stevens, D. E., & Toon, O. B. (2004). The impact of humidity above stratiform clouds on indirect aerosol climate forcing. *Nature*, *432*, 1014–1017. https://doi.org/10.1038/nature03174

Aswathy, V., Boucher, O., Quaas, M., Niemeier, U., Muri, H., Mülmenstädt, J., & Quaas, J. (2015). Climate extremes in multi-model simulations of stratospheric aerosol and marine cloud brightening climate engineering. *Atmospheric Chemistry and Physics*, *15*, 9593–9610. https://doi.org/10.5194/acp-15-9593-2015

Bretherton, C. S., Blossey, P. N., & Uchida, J. (2007). Cloud droplet sedimentation, entrainment efficiency, and subtropical stratocumulus albedo. *Geophysical Research Letters*, *34*, L03813. https://doi.org/10.1029/2006GL027648

Chen, Y., Haywood, J., Wang, Y., Malavelle, F., Jordan, G., Partridge, D., et al. (2022). Machine learning reveals climate forcing from aerosols is dominated by increased cloud cover. *Nature Geoscience*. https://doi.org/10.1038/s41561-022-00991-6

Dipu, S., Quaas, J., Quaas, M., Rickels, W., Mülmenstädt, J., & Boucher, O. (2021). Substantial climate response outside the target area in an idealized experiment of regional radiation management. *Climate*, *4*, 66. https://doi.org/10.3390/cli9040066

Gryspeerdt, E., Goren, T., Sourdeval, O., Quaas, J., Mülmenstädt, J., Dipu, S., et al. (2019). Constraining the aerosol influence on cloud liquid water path. *Atmospheric Chemistry and Physics*, *19*, 5331–5347. https://doi.org/10.5194/acp-19-5331-2019

Hastenrath, S., Wu, M. C., & Chu, P. S. (1984). Towards the monitoring and prediction of North–East Brazil droughts. *Quarterly Journal of the Royal Meteorological Society*, *110*(464), 411–425.

Hastenrath, S. (2012). Exploring the climate problems of Brazil's Nordeste: A review. *Climatic Change*, *112*(2), 243–251.

Horowitz, H. M., Holmes, C., Wright, A., Sherwen, T., Wang, X., Evans, M., et al. (2020). Effects of sea salt aerosol emissions for marine cloud brightening on atmospheric chemistry: Implications for radiative forcing. *Geophysical Research Letters*, *47*, e2019GL085838. https://doi.org/10.1029/2019gl085838

Jia, H., Quaas, J., Gryspeerdt, E., Böhm, C., & Sourdeval, O. (2022). Addressing the difficulties in quantifying droplet number response to aerosol from satellite observations. *Atmospheric Chemistry and Physics*, *22*, 7353–7372. https://doi.org/10.5194/acp-22-7353-2022

Jordan, G., Malavelle, F., Chen, Y., Peace, A., Duncan, E., Partridge, D. G., et al. (2024). How well are aerosol-cloud interactions represented in climate models? Part 1: Understanding the Sulphate aerosol production from the 2014-15 Holuhraun eruption. *Atmospheric Chemistry and Physics*, *24*(3), 1939–1960.

Nenes, A., & Seinfeld, J. H. (2003). Parameterization of cloud droplet formation in global climate models. *Journal of Geophysical Research*, *108*.

Quaas, J., Quaas, M., Boucher, O., & Rickels, W. (2016). Regional climate engineering by radiation management: Prerequisites and prospects. *Earth's Future*, *4*, 618–625. https://doi.org/10.1002/2016EF000440

Seidel, D. J., Feingold, G., Jacobson, A. R., & Loeb, N. (2014). Detection limits of albedo changes induced by climate engineering. *Nature Climate Change*, *4*. https://doi.org/10.1038/NCLIMATE2076

Yamaguchi, T., Feingold, G., & Larson, V. E. (2017). Framework for improvement by vertical enhancement: A simple approach to improve representation of low and high-level clouds in large-scale models. *Journal of Advances in Modeling Earth Systems*. https://doi.org/10.1002/2016MS000815

Zhang, J., & Feingold, G. (2023). Distinct regional meteorological influences on low-cloud albedo susceptibility over global marine stratocumulus regions. *Atmospheric Chemistry and Physics*, *23*, 1073–1090. https://doi.org/10.5194/acp-23-1073-2023