Satellite and Model Data to Inform Solar Radiation Modification Techniques

STATISTICS

Interim report

prepared by

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Purpose and Objectives

Although the Paris Agreement has set ambitious climate targets, current policies are projected to result in approximately 2.7°C of warming by the end of the century, exceeding those goals. While carbon dioxide removal (CDR) is now recognized as a necessary complement to emissions mitigation, its slow deployment raises concerns about a potential overshoot in global temperatures. In response, solar radiation modification (SRM) is gaining attention as a possible, though controversial, backstop, prompting calls for further research despite its associated risks and uncertainties. The STATISTICS project aims to examine the three main SRM techniques (Stratospheric Aerosol Injection, or SAI, Marine Cloud Brightening, or MCB, Cirrus Cloud Thinning, or CCT) from a fresh perspective with a focus on how spaceborne Earth's observations can be better used and how information from models and satellites can be better integrated together to progress our understanding on these techniques.

Chapter 1. Requirements Baseline Document

As laid out in the STATISTICS proposal, we base the requirements for this project on:

- a review of research gaps from the literature
- a review of existing products, datasets, models and algorithms
- a survey of accessible auxiliary and validation data sets
- an analysis of potential existing observing systems to monitor SRM
- an identification and description of relevant target areas and/or periods
- an analysis of the energy budgets for SAI, MCB, and CCT
- a survey of current and ongoing (public and private) initiatives on SRM research.

This information is summarized in the following subsections, leading to the rationale for the proposed work for the STATISTICS project and an analysis of the potential risks and their impact on the products and project.

1.1 Review of research gaps from the literature

Climate intervention has become a very active field of research with the literature on the topic now growing exponentially. Spontaneous scientific reviews on SRM were regularly published until 2015 to establish our understanding of the physical mechanisms, climate impacts, and uncertainties (e.g., Bellamy et al., 2012; Zhang et al., 2015). As this scientific groundwork matured, governance, ethical considerations, and societal implications also became important, which requires coordinated, transdisciplinary approaches. Consequently, institutional initiatives have superseded individual reviews by addressing

SRM within structured frameworks to inform policy and international dialogue (NASEM, 2021; UNESCO, 2023; UNEP 2024; SAPEA, 2024). To inform the STATISTICS project and guide how it can best contribute to the advancement of the field, we focus on three recent studies that analysed research gaps based on the available literature. This approach allows for a more strategic and policy-relevant research agenda than broad reviews. The three studies in question are Feingold et al. (2024), which deals specifically with the MCB technique, and Haywood et al. (2025) and Eastham et al. (2025), which address all of SAI, MCB, and CCT techniques.

Marine Cloud Brightening (MCB) involves the intentional introduction of aerosol (sea-salt) particles into shallow marine clouds to enhance their cloud droplet number concentration and hence their reflectivity, thereby increasing the amount of solar radiation reflected by the climate system. From a physical science perspective, Feingold et al. (2024) consider that the viability of MCB depends on its potential to scale up from local to more regional or even global scales and how this scalability can be assessed robustly using observations and models. Given the heterogeneous nature of MCB, another issue is how to develop strategies that ensure an equitable geographical distribution of both the benefits and risks associated with potential regional changes in temperature and precipitation. To bridge key physical science knowledge gaps necessary for assessing the societal implications of MCB, Feingold et al. (2024) advocate for a comprehensive and focused research program, encompassing field and laboratory experiments, systematic monitoring, and numerical modeling across multiple spatial and temporal scales. It is clear that Earth's observations from space would have to play a critical role in such an endeavour.

Haywood et al. (2025) examined research gaps associated with each of the SAI, MCB and CCT techniques, the latter being extended with Mixed-phased Cloud Thinning (MCT). We display their findings in Table 1.1 as a list of research gaps in five categories that go from the fine scale to the large scale and more holistic considerations: generation and delivery of particles in the atmosphere, process-level understanding, scale required and deployment strategies, large-scale circulation response, and impacts. CCT and MCT being less mature, the identification of research gaps follows a less structured approach.

Table 1.1. Research gaps identified by Haywood et al (2025).
The research gaps addressed in this study are highlighted with grey shading.

	Generation and delivery Quantification of technical barriers and costs. Credible estimates for delivery timescales for deployment systems. Joined-up collaboration. A framework for evaluating financial risks.
	Process-level understanding Model sophistication (aerosol microphysics, gas-particle interactions).

SAI	Consistency of GCM (General Circulation Model) results. Number of models capable of modelling impacts on stratospheric ozone. Study of alternate particles to sulfates.
	Scale required and deployment strategies The large uncertainties in metrics associated with SAI. The small number of CMIP models that have engaged in GeoMIP simulations. The limitations in scenarios and strategies. Coupling with technical feasibility.
	Large-scale circulation response Characterization of the stratospheric circulation. Understanding of stratospheric circulation response. Representation of stratosphere-troposphere exchange in models. Impacts on dynamics in the troposphere and ocean.
	Impacts Understanding of ecosystem response. The oversimplification of climate-biosphere interactions. The air-quality response to SAI.
MCB	**Generation and delivery** Practical technological limitations of delivery on emission rate, altitude, and particle size distribution and their impact on cloud microphysical and macrophysical properties. Limited experimental evidence from deployments. Consistency between aerosol activation schemes. Paucity of high-resolution modelling studies of MCB. Traceability from process scale to the global scale.
	Process-level understanding Representation of key microphysical processes. Process-level validation of aerosol-cloud-interactions in GCMs. Process-level understanding across a range of cloud-regimes. Understanding large-scale changes in aerosols.
	Scale required and deployment strategies Realism in MCB deployment strategies. The potential synergetic role of Marine Sky Brightening (MSB) Multi-model studies targeting the amelioration of other impacts of global warming such as protecting sea-ice, ecologically sensitive regions such as coral reefs, or cooling specific regions such as the Mediterranean.
	Large-scale circulation response Model dynamical responses of regional cooling and associated inter-model consistency need to be thoroughly investigated using a suitable risk–risk framework. The role of the oceans in redistributing thermal anomalies associated with MCB. The additivity (or lack of) of regional MCB deployments.
	Impacts Engagement with the marine biology/ecological community. Engagement with the community engaged in modelling fisheries.
CCT	**Susceptibility**: It is not clear whether a sufficient number of cirrus and mixed-phase clouds are

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

Eastham et al (2025) further assessed the gaps in SRM research by reviewing sources of uncertainties. They identified two common areas of improvements needed across all three techniques: "a common focus on the demand for more observations to better constrain models and improve process-level understanding" and "improving the consistency of process representation across models of different scales". The research gaps they identify are displayed in Table 1.2.

Table 1.2. Research gaps identified by Eastham et al (2025).
The research gaps addressed in this study are highlighted with grey shading.

SAI	1/ The first modeling gap that has been identified is representation of detailed microphysical changes in the stratospheric aerosol layer that occur when aerosols or their precursors are injected into the stratosphere. 2/ 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. 3/ A third major modeling gap is missing or poorly-simulated aerosol interactions with chemistry.
MCB	1/ A fundamental first need is to improve models' ability to represent MCB aerosol emissions using realistic aerosol size distributions. 2/ A second issue regards accurately representing the point-source nature of MCB. 3/ How cloud macrophysical responses to aerosol perturbations are affected by the timing and spatial distribution of the injection strategy?
CCT	1/ The key dynamical gap is our ability to simulate the occurrence, location, intensity, and extent of ice supersaturated regions. 2/ The key cloud-physics gap is in the microphysics of cirrus cloud formation, which inhibits advances in knowledge on cirrus clouds and CCT. 3/ Central among these gaps is the uncertainty surrounding the properties of cirrus formed on seeded aerosols.

It can be seen from these three studies that research gaps are diverse and encompass a large range of scales and tools. Current approaches have focused on the use of models (from process models to climate models), the analysis of observational datasets, and synergetic uses of both. Natural analogues to SRM techniques (e.g., explosive volcanic eruptions in the stratosphere, passive volcanic degassing in the lower troposphere, soot emissions from commercial aircraft) represent interesting case studies that can inform the processes involved in SAI, MCB and CCT. Studying natural analogues has already contributed a lot of knowledge but they have not been fully exploited yet and continue to provide a useful framework to learn more on relevant processes. However, for some research gaps (e.g., those related to generation and delivery), SRM research is approaching a point where field experiments will be needed if further progress is to be made. While field tests remain controversial, it should be noted that field tests have already taken place (e.g., Great Barrier Reef trials) and that further field tests have been funded or are planned outside the European Union. Within this context, there are several reasons why Earth's observations from space are particularly relevant:

- **Process-level understanding**. Some processes are still poorly understood; the combination of satellite retrievals of aerosols and clouds and modelling will play a crucial role in improving our understanding of aerosol microphysics and aerosol-cloud interactions, in particular from natural analogues.

- **Monitoring of field tests**. Satellite observations could play a role to monitor field tests in a wider environment (and to plan such field tests if this is considered to be a sound approach).

- **Monitoring of deployment**. Monitoring of the potential impacts of SRM on all components of the Earth's system would become critical if there were a deployment (whether it is unilateral or collaborative).

Observing systems need to have the capability to detect small perturbations to be effective. This may be challenging for field tests as such experiments would likely involve fairly small modification of aerosol and clouds fields (e.g., injections of a few hundreds kg of SO_2 in a putative SAI experiment). It is likely that satellite instruments will require enhanced sensitivity to detect and observe such field experiments.

Finally, it should also be noted that a number of research gaps can only be addressed through a coordinated, often interdisciplinary, effort as all components of the Earth's system are potentially affected.

1.2 Review of existing products, datasets, models and algorithms

As discussed above, SRM methods have been primarily evaluated through model simulations and analysis of natural analogues in observational datasets. Specifically, **models** can be used to i) evaluate particular processes, ii) simulate natural analogues to test relevant processes against observations, iii) perform idealised experiments of SRM to gain understanding in the large-scale climate response, and iv) perform more realistic experiments of SRM deployment. The model simulations may be multi-model ensembles (to test the robustness of the findings to uncertainties in model formulations) or initial-condition ensembles (to test the robustness of the findings to climate variability). In order to guide the work to be done in STATISTICS, we compiled in Table 1.3 a list of model datasets relevant to SRM research that are publicly available. STATISTICS will use four of the models involved in GeoMIP and ISA-MIP.

Table 1.3. Model datasets relevant to SRM research.
PR: processes. NA: natural analogues. ID: idealised experiments. RE: realistic experiments. MME: multi-model ensemble. ICE: initial-condition ensemble.
GLENS and ARISE-SAI-1.5 were performed with the Community Earth System Model.

Dataset	**Type**	**Location**	**Reference**
GeoMIP, phase 5	ID, MME	ESGF, https://aims2.llnl.gov/search Then select CMIP5 and GeoMIP project	Kravitz et al. (2013)
GeoMIP phase 6	ID/RE, MME	ESGF, https://aims2.llnl.gov/search Then select CMIP6 and GeoMIP project	Kravitz et al. (2015)
GLENS	RE, ICE	https://www.cesm.ucar.edu/community-projects/glens/diagnostics	Tilmes et al. (2018)
Aerosol injection	PR, MME	https://dataverse.harvard.edu/dataverse/AM-H2SO4_Intercompare_Data	Weisenstein et al. (2021)
ISA-MIP	NA, MME	https://isamip.eu/models	Timmreck et al. (2018)
ARISE-SAI-1.5	RE, ICE	https://doi.org/10.26024/0cs0-ev98 https://doi.org/10.5065/9kcn-9y79 https://registry.opendata.aws/ncar-cesm2-arise/	Richter et al. (2022)

There are a multitude of **observational datasets** that can be used to study SRM-relevant processes and/or SRM analogues though none of the datasets is “SRM-ready” and substantial pre-processing and treatment may be needed. Most studies tend to rely on available satellite datasets, e.g. from ESA or NASA (see below) and/or reanalysis (e.g., CAMS and MERRA-2). The requirements for studying SRM analogues are not different from those to study aerosol and clouds in a general sense. We provide below a list of satellite and ground products useful for SRM related impact monitoring and observational gaps.

Ground-Based & In-situ Products

Ground-based and in-situ instruments and networks can monitor aerosols and radiation. They could potentially detect aerosol and/or radiative changes potentially caused by SRM.

Table 1.4. Ground-based observational datasets relevant to SRM research.

	Instruments/ Networks	**Parameters**	**Notes**
Aerosol Monitoring	Sun-photometers/ AERONET	Aerosol Optical Depth (AOD), Ångström exponent, size distribution, other optical properties (e.g., scattering, absorption) in the atmospheric column	Based on the retrieved aerosol properties, AERONET also provides calculated broadband solar flux at the top and bottom of the atmosphere
	Max-DOAS, Pandora/ Pandonia	Column trace gas (e.g., NO_2, O_3) in the troposphere and in the column	
	LIDAR/ EARLINET, MPLNET	Profiles of aerosol layers (backscatter, extinction)	Useful for detecting stratospheric aerosol layers
	Sun-photometers/ GAWPFR, SKYNET	Direct solar radiation to infer aerosol properties	
	ACTRIS	Measurements of the parameters mentioned above including from in-situ measurements	
Radiation Flux Measurements	BSRN (Baseline Surface Radiation Network)	Surface solar and terrestrial radiation fluxes	High precision. Useful for detecting changes in surface radiation
	SURFRAD	Surface radiation budget	
	Others (Pyranometers / Pyrgeometers)	Incoming shortwave and longwave radiation	

Atmospheric Composition	Dobson and Brewer Spectro-photometers	Total column ozone	Useful in tracking potential ozone depletion from SAI
	Radiosondes	Vertical profiles of temperature, humidity, and pressure	
In-Situ instrumentation	Aircraft and balloon platforms	Direct aerosol particle size, composition, and radiative properties in the stratosphere	Limited spatial and temporal coverage; not feasible for continuous or global monitoring

Satellite-Based Products

Satellites provide global, and potentially long-term datasets that are extremely useful to study natural analogues and could help detect SRM activities, particularly in the stratosphere and in terms of its impact on the radiation budget.

Table 1.5. Satellite-based observational datasets relevant to SRM research.

	Instruments/ Satellites	**Parameters**	**Notes**
Missions/ datasets relevant to aerosol and cloud studies	CALIOP/CALIPSO	Profiles of aerosol and cloud layers	Useful for detecting high-altitude particles; Challenging to distinguish ash/sulphate mixtures (Tackett et al., 2023)
	MODIS/ Aqua, Terra	Aerosol column properties, cloud properties, surface albedo	
	OMPS Limb Profiler / Suomi-NPP, NOAA-20	Stratospheric aerosol and ozone profiling	
	SAGE III / ISS (International Space Station)	Vertical profiles of aerosols, ozone and other trace gases	“Errors at the peak of the stratospheric aerosol layer range from 20-25% for median radius and 5-7% for mode width”. These retrieval uncertainties limit the

			precision of aerosol size distribution estimates – important for identifying engineered aerosol vs. volcanic or natural background sources (Wrana et al., 2021). Detects 1-2 Tg S/y in steady state globally, it cannot detect injections <1 Tg S/y during initial phases (Lange et al., 2025).
	ATLID, CPR, MSI / EarthCare	AOD, aerosol profiles, TOA radiation, cloud structures	
	OMI/Aura	Ozone, aerosols, and UV radiation	
	GOME-2/MetOp	Atmospheric composition	UV-visible spectra; Useful for ozone and aerosol tracking
	AIRS, MLS/Aqua	Trace gases (total column & vertical profiles), water vapor profiles	
	MISR/Terra	Aerosol and cloud properties	Moroney et al., 2012; Kahn et al., 2010;
	IASI/MetOp-A/B/C	SO_2 total column and layer height	Other trace gases too
	POLDER /PARASOL	Polarimetric aerosol and cloud properties; Derived aerosol composition (fraction and volume concentration of soluble aerosol (ammonium, sulfate, nitrate), non-absorbing dust and absorbing components (BC, BrC, FeOx) in total atmospheric column	Buriez et al., 1997; Deuzé et al., 2000; GRASP/Components algorithm (Li et al., 2019) developed and applied to POLDER/ PARASOL;

	3MI (Multi-viewing, Multi-channel, Multi-polarization Imager) mission (future)	Polarimetric monitoring of clouds/tropospheric aerosols	GRASP/component to be applied to future 3MI (day+1 product); Fougnie et al., 2018
	HARP2, SpexOne, OCI/PACE	Plankton, aerosol, cloud properties	Multi-angle polarimeters & spectrometer; Hasekamp et al., 2019
	ALADIN Lidar/Aeolus	Aerosol properties	First high-spectral resolution lidar in space (2018-2023); Flament et al., 2021; Gkikas et al., 2023
	OSIRIS/ODIN	Stratospheric aerosol extinction at 750 nm with vertical profiles	Limited to the Northern/Southern Hemisphere seasonally; lacks continuous global coverage. Bourassa et al., 2012.
	CERES (Clouds and the Earth's Radiant Energy System)	Direct measurements of reflected solar and emitted thermal radiation across UV to far-infrared wavelengths	Can detect large-scale SRM deployment but require substantial effects for small experiments; Siedel et al., 2014.
	GloSSAC (Global Space-based Stratospheric Aerosol Climatology)	Stratospheric aerosol dataset	1979–present; Kovilakam et al., 2020, 2023
Sentinel Satellites (Copernicus Programme)	MSI/Sentinel-2	Surface reflectance, NDVI, Albedo, land cover classifications	High-resolution (10–60m) multispectral imagery; Detection of vegetation changes from altered radiation, detection of cloud brightening or surface reflectivity interventions.

	OLCI, SLSTR /Sentinel-3A/B	AOD, sea/land surface temperature, Cloud cover and cloud top properties, Radiation budget elements (radiance, reflectance)	Atmospheric aerosol retrievals, water vapor, and ocean color can be helpful for indirect detection of SRM effects over oceans
	TROPOMI/ S5-P	SO_2, NO_2, O_3, HCHO, CH4, aerosol layers	High-resolution trace gas monitoring
	UVN Spectrometer /Sentinel-4 (upcoming)	O_3, SO_2, aerosol properties	High temporal resolution; Useful for continuous monitoring of rapid changes associated with regional SRM trials.

1.3 Survey of accessible auxiliary and validation data sets

For SAI and MCB natural analogues, SO_2 data represent an important auxiliary input. An example of a coupled SO_2 and sulphate aerosol can be the RAL-Space IMS product, which has been used in the context of the Hunga Tunga eruption (Sellitto et al., 2024). The Volcplume web platform, developed by collaboration of Univ.Lille/LOA and AERIS national center for atmospheric data and services (Boichu and Mathurin 2022, see https://dx.doi.org/10.25326/655), and the associated SO_2 flux calculator can inform on daily SO_2 mass time series from various polar orbiting Low Earth Orbit satellite sensors including the most recent S5P/TROPOMI. This is particularly useful for recurrent or long-term eruptions to diagnose periods when the volcano is actively erupting or degassing. The methodology is described in Grandin et al. (2024).

Ground-based FTIR instrument lidar measurements from NDACC, and the AERONET sunphotometer network can provide useful information to measure SO_2 (and other gases) as well as aerosol optical and microphysical properties. Boichu et al. (2023) provide an example of how SO_2, aerosol size distribution and composition could be informed using a synergy of instruments.

Other datasets are potentially useful to study SRM methods such as

- reanalysis data (e.g., ECMWF ERA5, CAMS, MERRA-2) that synthesize atmospheric data integrating model, satellite and ground data,

- UV index measurements that can indicate changes in stratospheric ozone.

1.4 Analysis of existing observing systems to monitor SRM

Monitoring SRM (whether a field test or at deployment stage) would require an observing system that is not necessarily the same as for progressing the scientific knowledge on the topic. Different satellite observing systems exist that can be used to detect, monitor and track SRM interventions and their impacts on the atmospheric composition and the radiative balance, but a more comprehensive system would be needed for a thorough monitoring.

The most obvious natural analogues for SAI interventions are from stratospheric volcanic eruptions. The stratospheric aerosol perturbations resulting from moderate volcanic eruptions have been observed primarily with existing: 1) solar occultation, 2) limb scattering, 3) limb emission, and 4) space LiDAR sensors. These different techniques all have their own sensitivity to stratospheric aerosols and have their own horizontal, vertical and temporal resolution. As an example, solar occultation observations of sensors like SAGE III on the International Space Station (SAGE III/ISS) have proven very sensitive to the stratospheric aerosol perturbations resulting from moderate volcanic eruptions but can miss the crucial small-spatial-scales phases occurring during and immediately after the volcanic SO_2 injection (e.g., Kloss et al., 2021). A scarce spatiotemporal coverage is also a strong limitation of the otherwise very sensitive space LiDAR observations, such as those from CALIOP-CALIPSO, in the recent past, and EarthCare-ATLID, at present. On the contrary, limb scattering observations, such as those from the OMPS-LP sensor, have a scarcer sensitivity but much better spatial coverage than solar occultation or space LiDAR instruments (e.g., Sellitto et al., 2022). These instrumental techniques are all based on the observation of the ultraviolet/visible range of the Earth's spectra. This range, unfortunately, is not sensitive to the composition of the aerosol perturbation and can only bring a limited information on the aerosol microphysical properties (even if recently methodologies have been proposed to derive stratospheric aerosol size distribution information from solar occultation observations, see e.g., Duchamp et al., 2023). Specific composition information, and then a specific aerosol-type detection, can be obtained using the infrared range of the Earth's spectra, with limb emission observations, such as those from ACE-FTS (e.g., Bernath et al., 2023). Some column-integrated information can also be derived from infrared nadir-looking instruments, like the IASI (e.g., Sellitto et al. 2024). With infrared observations, the simultaneous retrieval of SO_2 injections and the resulting sulphate aerosols, as well as their spatiotemporal evolutions, can also be obtained. For all these different techniques, it might be, nevertheless, quite arduous to detect small-intensity "near-term" SAI interventions (i.e. thousands or millions or times smaller than a moderate volcanic eruption.), including unilateral interventions or experiments, due to their relatively large detection limits. It was recently shown that new-generation high-spectral-resolution limb emission sensors, like CAIRT, presently under evaluation for funding in the context of ESA's Earth Explorer 11 call, are expected to be able to detect these "near-term" experiments, with limited uncertainties on spatiotemporal location and mass of the SO_2 injection (CAIRT Report for Mission Selection, under review). In practice a combination of satellite instruments, i.e. from nadir and limb observing geometries, or from active and passive techniques, is required to bring the most reliable information.

Understanding MCB and CCT also benefits from Earth's observations that characterise and monitor cloud amount and properties on a global scale by focusing on regions where aerosols are perturbed, either for natural or anthropogenic reasons. By providing consistent, high-resolution data across temporal and spatial domains, satellites enable the retrieval of key cloud parameters such as cloud fraction, optical thickness, effective radius, cloud top height and temperature, and phase (liquid or ice). Passive sensors, including radiometers and spectrometers operating in the visible, infrared, and microwave domains, contribute significantly to long-term climatologies and trend analyses, while active sensors such as spaceborne lidars (e.g., CALIOP) and radars (e.g., CloudSat) offer vertical profiling capabilities essential for understanding cloud vertical structure and microphysical properties. ML techniques have proved useful to bridge between different instruments that have different strengths but also varying swaths and revisit times. As discussed above, the new generation of polarimeters has a large potential to monitor aerosols and clouds and would represent an important element in a monitoring system. Table 1.6 outlines the observational limitations, gaps and highlights the improvements needed for SRM monitoring.

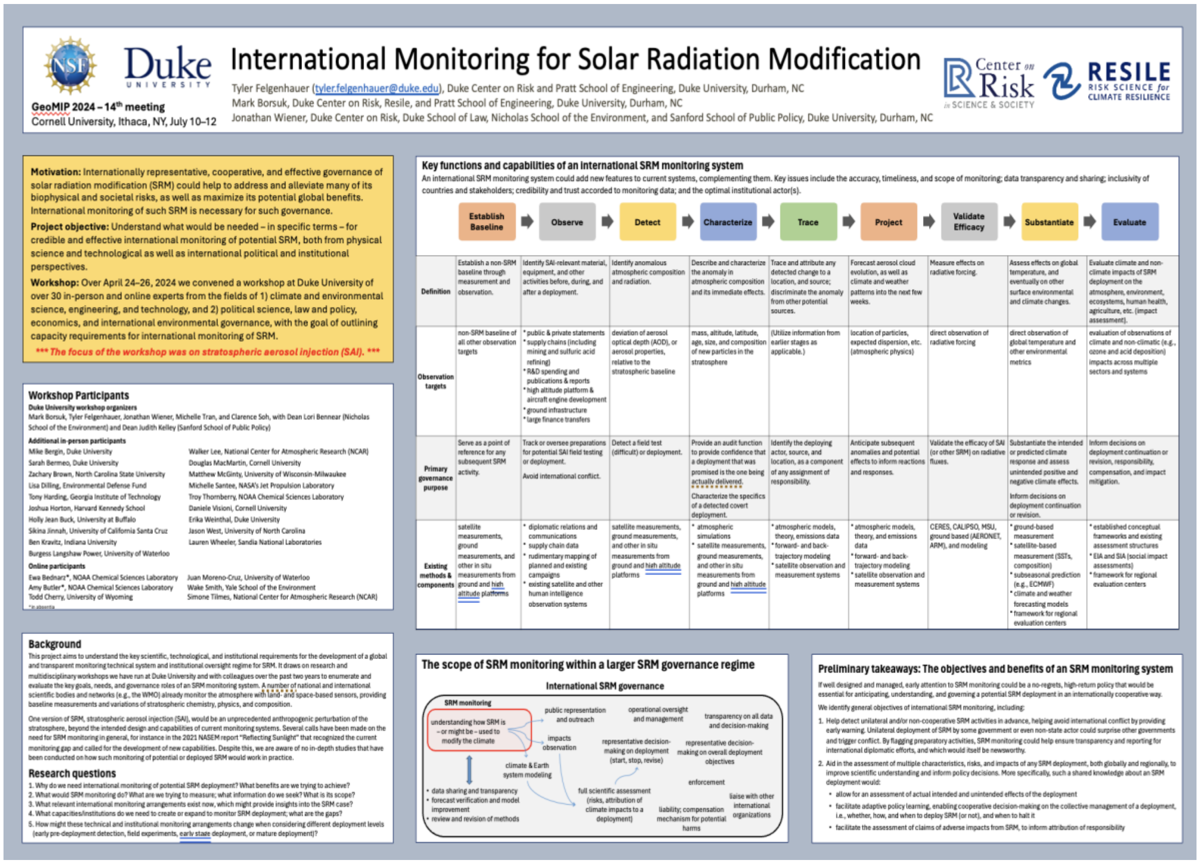
Table 1.6. Current observational gaps, limitations, and monitoring needs relevant to SRM research.

Category	Limitations	Needs for SRM monitoring
Stratospheric Aerosol Profiling Limitations	No continuous, high-resolution global monitoring of stratospheric aerosols, especially in the upper stratosphere or over the poles.	Global high-vertical-resolution limb and occultation sensors for continuous stratospheric aerosol tracking.
Temporal Resolution	Lack of high-frequency (hourly or better) monitoring from polar satellites, especially over oceans. Geostationary satellites for air quality are still emerging.	Deployment of geostationary aerosol and gas sensors over under-monitored regions like the Pacific and Southern Hemisphere.
Low AOD detection &	Difficult to detect localized low AOD from experimental SRM due to low	Improvement of satellite based AOD and especially other (absorption,

lack of absorption properties	contrast with background aerosols. Accurate satellite absorption metrics (e.g., SSA) are lacking.	SD) properties.
Ground-based solar network	Sparse coverage of ground-based solar networks in remote areas and developing countries especially in Africa and parts of Asia.	Expansion of ground-based radiation and aerosol networks, especially in Africa and the Southern hemisphere.
Trace Gas high resolution detection related uncertainties	Source attribution models are underdeveloped for small-scale or covert SRM activities.	Unmanned aerial systems (UAS) and stratospheric balloons for in situ aerosol and gas measurements.
Satellite data validation in Key Areas	Validation and calibration of satellite data in these regions are poor, increasing uncertainty in global detection.	
Satellite retrieval limitations	Limitations of satellite retrievals in polar areas and bright surfaces.	
Stratospheric AOD change detection sensitivity	Changes of less than 20% in stratospheric AOD levels cannot be detected confidently, which means that small-scale or early-stage SRM activities (e.g., trial SAI deployments) may fall below satellite detectability thresholds (Kremser et al., 2016).	

Data assimilation systems such as CAMS or MERRA-2 would also play a critical role in any monitoring system by optimally combining model and information. However, this implies adapting the underlying models so that it includes the best available information on how SRM is deployed.

Finally, it should be noted that international monitoring of SRM would involve a lot more than an observing system. Felgenhauer et al. have fleshed a framework for such international monitoring, which is reproduced here, as it represents an interesting framing for this and subsequent projects on SRM methods (see their poster below).



1.5 Identification and description of relevant target areas and/or periods

In order to define the work to be done in STATISTICS, we compiled and present below a list of natural (and industrial) analogues for SAI, MCB and CCT in Tables 1.7 to 1.9. Many of these have already been studied (see references) but it may still be possible to get new knowledge by revisiting some of these using better or synergetic satellite products. These natural analogues may also be modelled to evaluate relevant processes and their uncertainties. This analysis forms the basis to define the content of WP2100/2200/2300 and 3100/3200/3300 (see Section 1.8).

Table 1.7. Natural analogues for Stratospheric Aerosol Injection. The natural analogue selected for this project is indicated with grey shading (see Section 1.8).

Eruption	Eruption periods	References
Pinatubo, Philippines	June 1991	Quaglia et al. (2023) Kleinschmitt et al. (2017) Many other articles

Sarychev, Japan	June 2009	Haywood et al. (2010)
Raikoke, Russia	20 - 21 June 2019	Wrana et al. (2023)
Ulawun, Papua New Guinea	26 June 2019, 3 August 2019	Wrana et al. (2023)

Table 1.8. Natural analogues for Marine Cloud Brightening. The natural analogue selected for this project is indicated with grey shading (see Section 1.8).

Eruption / Event	**Eruption periods**	**Reference**
Holhauraun, Iceland (North Atlantic)	Fissure eruption, 2014-2015	Malavelle et al. (2017) (10.1038/nature22974) Schmidt et al. (2015)
Kilauea, Hawaï, Tropical West Pacific	June 2008 May 2018 29 Sept 2021 - 9 Dec 2021 5 Jan 2023 - 7 March 2023 (61 days) 7 June 2023 - 19 June 2023 (13 days) 10 Dec 2023 - 16 Dec 2023 (7 days) 15 Sept 2024 - 20 Sept 2024 (6 days) 23 Dec 2024 => January 2025	Breen et al. (2021) (10.5194/acp-21-7749-2021) Flower et al. (2021) (10.1016/j.jvolgeores.2021.107247) Chen et al. (2024) (10.1038/s41561-024-01427-z)
Ambrym, Vanuatu, Tropical East Pacific	Continuous since 2013 with peaks in 2018 (not sure after 2018)	
Ambae and Yasur	Much lower emissions than Ambrym.	
Composites	900 volcanic plumes	Toll et al. (2017) (10.1002/2017GL075280)
IMO 2020	Rapid reduction in sulphur content of shipping fuels following IMO 2020 regulation. Comparison of pre-2020 and post-2020 cloud albedo in shipping regions. Comparison of the contrast across shipping lanes before and after 2020.	Yuan et al. (2022) (10.1126/sciadv.abn7988) Watson-Parris et al. (2022) (10.1073/pnas.2206885119) Diamond (2023) (10.5194/acp-23-8259-2023)

Table 1.9. Natural analogues for Cirrus/Mixed-phase Cloud Thinning.

Event	Eruption/event period	Reference
COVID-19 aircraft traffic reduction (reduced soot)	Reduced global aircraft emissions (soot specifically) in 2020 - analogues for CCT in reverse	Zhu et al. (2022) (10.1029/2021AV000546)
Industrial INP point-source emissions observed by MODIS	Mixed-phase cloud glaciation events observed by MODIS at industrial point sources in the mid/high northern latitudes over the period 2000-2021. Analogues for mixed-phase cloud thinning.	Toll et al. (2024) (10.1126/science.adl0303)

1.6. Analysis of the energy budgets for SAI, MCB and CCT

For each of SAI, MCB and CCT, we estimate from thermodynamic principles the minimum energy budget required to conduct a unit SAI, MCB or CCT (E_i, energy invested) and by how much it may cool the planet (E_r, energy returned to the planet). We define the leverage of SRM techniques as the energy returned on energy invested (ERoEI, a concept that we borrow from energy economics). In a second step we also estimate by how much this minimum energy budget could be reduced by piggy-backing on natural processes or in contrast increased in a more realistic implementation. To put these numbers in perspective, we then estimate the power required to cool the planet by 1 Wm^{-2} as this represents a typical value to cool the Earth by about 1°C if applied in the long term. For the sake of comparison, the current estimate of the total anthropogenic radiative forcing is ~3 Wm^{-2} and that of the Earth Energy Imbalance is ~1 Wm^{-2}. We also compare the required power to sustain a 1 Wm^{-2} radiative forcing to the world's consumption of energy. Indeed SRM techniques are only viable if they have a strong leverage and do not involve too strong a feedback on greenhouse gas emissions.

Energy budget for SAI

Injection of aerosols in the stratosphere can be achieved from a few locations but requires at least some injection in the Tropics where the tropopause is the highest. We consider here an injection point at an altitude of 20 km. The minimum energy necessary to actively lift m=1 kg of sulfur (S) to a height z=20 km is given by its change in potential energy:

$$E_i = m\ g\ z \simeq 1 \times 10 \times 20000 = 2\ 10^5\ J \quad (1.1)$$

It would cause a radiative cooling (energy forcing) that can be estimated from the radiative efficiency of sulfate aerosols in the stratosphere:

$$E_r = (M_{SO4} / M_S)\ RE_{SO4}\ t_{SO4} \simeq 10^{13}\ J \quad (1.2)$$

with M_{SO4} / M_S = 3 is the ratio of the molecular masses of SO_4 and S, RE_{SO4} = 100 W/g is the typical cooling efficiency of stratospheric sulfate aerosols and t_{SO4} = 1 year is the typical lifetime of sulfate aerosols in the stratosphere.

Hence the maximum leverage of SAI or ERoEI is estimated to be 5 10^7 (1 joule used for lifting the S to the stratosphere would bring a maximum of 50 million joules of cooling for the planet). This estimate should be qualified for several reasons. First the cost of lifting the sulphur to the stratosphere could be much larger as the most likely delivery method is through aircraft which have a limited payload and efficiency. Smith (2020), building on Smith and Wagner (2018), estimated that 250 gallons of jet fuel were needed to lift 1 ton S using a fleet of aircraft, which would correspond to 3.3 10^7 J/kg (computed as 250 x 3.78 l/gallon x 35 MJ/l /1000 kg/ton) and would bring additional CO_2 emissions. The energy cost would be twice larger if SO_2 were to be lifted instead of S. Therefore a more conservative estimate could be 10^8 J/kg to account for various inefficiencies, which would give a leverage or ERoEI of 10^5.

The power necessary to maintain a radiative forcing $\Delta F = -1\ Wm^{-2}$ would be

$$P_i = E_i * Flux_S = E_i * \Delta F * S_T / E_s = 5\ GW \quad (1.3)$$

where S_T is the Earth's surface area.

The energy cost of lifting the S could be less if it could be emitted at a lower altitude. This could be the case if the S is emitted at high latitudes where the tropopause is lower but the efficacy of the method would be significantly less because of a shorter aerosol lifetime. It could also be the case if the S gets transported into the stratosphere (e.g. due to self-lofting) but the scientific basis for this option is missing.

Alternatively the sulfur could be emitted as a chemical compound that is inert in the troposphere, gets transported to the stratosphere through the global circulation where it gets broken down and can be oxidised to sulphuric acid. Surface emissions of carbonyl sulfide (COS) have been proposed as such an alternative approach that would alleviate the need for the deployment of stratospheric aircraft (Quaglia et al., 2022). However the rate of COS uptake by soils and plants and the negative impact of prolonged human exposure to this chemical are not known. For these reasons we do not consider this option further to quantify the energy budget for SAI.

In all cases, the energy cost of mining and manufacturing the sulfur compounds would also need to be accounted for.

Energy budget for MCB

We now perform a similar analysis for MCB. The minimum energy requirement for spraying one unit mass of seawater from bulk water is given by the surface energy associated with surface tension of the sprayed droplets and their kinetic energy:

$$Ei = \gamma \cdot 4 \pi r^2 + 1/2\ m\ v^2 \quad (1.4)$$

where γ is the surface tension of seawater, *r* is the radius of the sprayed particle, *m* its mass and *v* its speed. When expressed per unit mass of seawater and assuming the distribution is monomodal, the minimum energy requirement takes the form:

$$Ei = 3\ \gamma / (\rho\ r) + 1/2\ v^2 \quad (1.5)$$

where ρ is the seawater density. For submicronic particles, the required energy is generally dominated by the first term. Using γ = 73 mN/m, the surface tension energy is 850 J/kg for 0.25 µm radius seawater particles (corresponding to a dry sea salt particle radius of 70 nm). The values are 1150 and 1930 J/kg for 0.18 and 0.11 µm radius seawater particles (corresponding to dry seasalt particle radii of 30 nm). In comparison the kinetic energy for a release speed of 10 m/s would be 50 J/kg. The minimal energy requirement is thus estimated to be of the order of 1 to 2 10^3 J/kg seawater for optimally-sized sea spray particles. This corresponds to 28-57 10^3 J per sprayed kg of dry seasalt particles after accounting for the seawater salinity of 35 ‰. It is assumed here that the water in the sea spray evaporates naturally in the boundary layer depth at no energetic cost.

For this aerosol size range, Wood (2021) tentatively estimated that a flux of 50-70 Tg/a of dry seasalt particle was needed to offset 3.7 Wm^{-2} forcing, which is much less than in climate model experiments. This corresponds to a cooling expressed per kg of dry seasalt particles of

$$Er = \triangle F_{2xCO2} * S_T / Flux \quad (1.6)$$

where S_T is the Earth's surface and the flux is now estimated in kg/s. The energy returned in this optimistic scenario is therefore 850 10^9 J per kg dry seasalt particles. The maximum theoretical leverage or ERoEi is therefore 1.5 10^7 (1 joule used for producing the seasalt particles would bring a maximum of 15 million joules of cooling for the planet).

The development of spraying technologies aimed at marine cloud brightening has emerged as a new field of research. However there are to date few estimates of their energetic requirements. Salter et al (2008) estimated the power of a ship to spray at a rate of 30 kg s^{-1} to be 150 kW. However this did not correspond to any proven or tested spraying technology. More recently Medcraft et al. (2025) demonstrated a system that, if scaled up, could spray 10^{17} particles per second with a power of 3.6 MW (a factor 10 improvement compared to a previous technology). However the size distribution of the sprayed particles is far from being monomodal and would translate into an energetic cost of 2.5 10^5 J/kg sea spray (to be compared to our best thermodynamic estimate of 1-2 10^3 J/kg). Accounting for various other inefficiencies, the ERoEI is reduced to the order of 10^5.

Energy budget for CCT

CCT works as intended only for large solar zenith angles, corresponding to high latitudes and preferentially in the winter hemisphere. Storelvmo and Herger (2014) concluded that an optimal seeding strategy (at least in the CESM atmospheric model CAM5) would be to seed these areas with approximately 20 particles per liter, corresponding to approximately 40% of Earth's surface at any given time. At the latitudes in question, the tropopause is relatively low, located at an altitude of approximately 9 km. Seeding would ideally be introduced in a layer just below the tropopause, for example between 7 and 9 km. Research on ice nucleating particles (INPs) indicate that dust particles with an approximate radius of 0.5 μm or larger are efficient INPs, and the approximate dust density is $\rho =$ 2500 kg/m^3. Given the relatively short lifetime of medium-sized dust particles in the troposphere (approximately 1 week, Kok et al., 2021), dust particles would have to be re-injected approximately once a week. 40% of Earth's surface area corresponds to approximately 200 million km^2. The volume that should be seeded once per week is thus 400 million km^3 or $4 \cdot 10^8$ km^3. This volume should be seeded with 20 particles per liter, i.e. $2 \cdot 10^{13}$ km^{-3}. Multiplying this with the volume to be seeded, the total number of seeded particles per week would be $8 \cdot 10^{21}$ particles. The mass of a particle is approximately $\rho \pi r^3$, so about $2500 \cdot 4 \cdot 10^{-19}$ kg or 10^{-15} kg. Multiplying this with the total number of particles, we end up with a mass of seeding particles per week of 8 million kg, or 8 metric tons. Per year, the mass that needs to be lifted would therefore be approximately 400 metric tons. The energy required to lift 400 metric tons to a mean altitude of 8 km is:

$$E_i = m\ g\ z \simeq 4\ 10^8 \times 10 \times 8000 = 3.2\ 10^{13}\ \text{J} \quad (1.7)$$

Since this is the mass lifted over a year, the corresponding power would be obtained by dividing by the number of seconds in a year, $3.1\ 10^7$, which yields 1 MW.

The cooling achieved for the above seeding scenario is highly model dependent (-2 Wm^{-2} in CESM/CAM5, significantly less in ECHAM-HAM, see e.g. Gasparini et al., 2020). We choose an intermediate value of -1 Wm^{-2} here. When multiplying with Earth's surface area ($5\ 10^{14}$ m^2), the cooling power becomes $5\ 10^{14}$ W.

This yields an ERoEI of approximately $5\ 10^8$, but this number comes with significant uncertainty, as every single step in the above reasoning is quite uncertain. Optimal seeding concentrations, atmospheric lifetimes, global negative forcing achieved and altitude of delivery are examples of uncertain quantities, but varying these within their plausible ranges would not change the ERoEI by many orders of magnitude.

Summary

A summary of the energy budgets is available in Table 1.10. The maximum theoretical leverages (ERoEi) come out fairly similar for the three techniques (within a factor 10). It is somewhat less for MCB than for SAI but the difference could be compensated by SAI being less efficient so that our estimates of the practical ERoEi are of the same magnitude at 10^5. The practical power needed to maintain a -1 Wm^{-2} cooling is estimated to be 5 GW. This may be compared to the world consumption of primary energy which is about 160,000 TWh[1] that corresponds to 576 EJ or a power of 18,000 GW. Hence the power needed to SAI and MCB is small compared to the world's primary energy. It should be remembered that all these estimates are very uncertain and could be off by at least one order of magnitude.

Table 1.10. Summary table for ERoEI and required power for the three SRM techniques considered in the STATISTICS project.

Method	**Max theoretical ERoEI**	**Min theoretical power for -1 Wm^{-2} cooling**	**Practical ERoEI**	**Practical power for -1 Wm^{-2} cooling**
SAI	5 10^7	10 MW	10^5	5 GW
MCB	1.5 10^7	33 MW	10^5	5 GW
CCT	5 10^8	1 MW	Not evaluated	Not evaluated

1.7 Survey of current and ongoing (public and private) initiatives on SRM research

The SRM landscape is evolving rapidly and gaining some understanding of this evolution is critical for making progress and calibrating the R&D effort adequately. We list in Tables 1.11 some past and ongoing initiatives on SRM research worldwide. We adopt a relatively broad definition for "initiatives" but categorize these into professional organisations that have provided an opinion on SRM, private actors operating under a foundation or philanthropy hat, international initiatives, and for-profit companies. In addition some research funding agencies have been funding SRM-related projects as part of their operations at the national or international (e.g. EU) levels.

Professional bodies have shaped the scientific, governance, and ethics discourse on SRM with a few standing out in particular: The Royal Society published its seminal 2009 report, "Geoengineering the Climate," providing one of the earliest comprehensive assessments of SRM. The American Geophysical Union (AGU) has issued position statements since 2009, with a notable ethical framework for climate intervention research

[1] https://ourworldindata.org/grapher/global-primary-energy

proposed in October 2024. The US National Academies advanced governance discussions with their 2021 report, “Reflecting Sunlight,” emphasizing research and oversight needs. The World Climate Research Programme (WCRP), through initiatives like the Geoengineering Model Intercomparison Project (GeoMIP), drives critical SRM modeling efforts. A more recent lighthouse activity seeks to coordinate research on “climate interventions”. UNESCO’s 2023 report on climate engineering ethics underscores global governance challenges and the UN Environment Programme (UNEP) has also contributed through its “One Atmosphere” review and SRM discussions at the UN Environment Assembly (UNEA) in 2019 and 2024 highlighting political complexities. Finally the SAPEA (Science Advice for Policy by European Academies) report offers a European perspective and recommendations on SRM.

Public and private funding, alongside non-governmental and for-profit entities, further define the SRM landscape. The UK’s ARIA (£56.8m) and UKRI (£10m) programs fund SRM research, while the Simons Foundation supports natural science studies. An interesting resource is the SRM funding tracker from srm360.org that is available online (https://srm360.org/funding-tracker/) highlighting the different sources of funding worldwide and their amount. Non-governmental organizations like DEGREES, which evolved from the Solar Radiation Management Governance Initiative (SRMGI), prioritize developing countries in SRM research capacity development. The Climate Overshoot Commission advocates for risk reduction strategies including a moratorium on SRM deployment as well as public SRM research funding. Organizations such as Silver Lining and SRM360 also support public discussion and informed research, while SRMYouthWatch amplifies youth voices in governance. For-profit ventures like Make Sunsets and Stardust explore commercial SRM applications, reflecting growing private-sector interest. Together, these actors—spanning academia, policy, philanthropy, advocacy, and industry—shape a complex and rapidly evolving SRM ecosystem.

Table 1.11. Past and ongoing initiatives on SRM.

Professional bodies and international organisations

Royal Society	Published the “Geoengineering the climate” report in 2009.	https://royalsociety.org/news-resources/publications/2009/geoengineering-climate/
American Geophysical Union (AGU)	Early statement adopted in December 2009 in collaboration with the AMS, revised and reaffirmed in February 2012. Position statement adopted in January 2018; revised and reaffirmed in April 2023.	https://www.agu.org/share-and-advocate/share/policymakers/position-statements/climate-

	Ethical framework proposed in October 2024.	intervention-requirements https://news.agu.org/press-release/ethical-framework-climate-intervention-research/
American Meteorological Society (AMS)	Early statement adopted by the AMS Council in July 2009. Policy statement adopted in January 2022.	https://www.ametsoc.org/ams/about-ams/ams-statements/statements-of-the-ams-in-force/climate-intervention
US National Academies	Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance (2021)	https://nap.nationalacademies.org/catalog/25762/reflecting-sunlight-recommendations-for-solar-geoengineering-research-and-research-governance
WMO ozone assessment	Chapter 6. Stratospheric Aerosol Injection and Its Potential Effect on the Stratospheric Ozone Layer. Published in 2022.	https://ozone.unep.org/sites/default/files/2023-02/Scientific-Assessment-of-Ozone-Depletion-2022.pdf
UNESCO	Report of the World Commission on the Ethics of Scientific Knowledge and Technology (COMEST) on the ethics of climate engineering (2023)	https://www.unesco.org/en/articles/cop28-new-unesco-report-warns-ethical-risks-climate-engineering
Chief Scientific Advisors (GCSA)	Informed by the evidence review report by the Scientific Advice Mechanism and the SAPEA (Science Advice for Policy by European Academies). Published in December 2024.	https://scientificadvice.eu/advice/solar-radiation-modification/
European Group on Ethics (EGE)	Opinion on Solar Radiation Modification	https://op.europa.eu/en/publication-detail/-/publication/80988f27-b5e3-11ef-acb1-01aa75ed71a1/language-en
World Climate Research Programme	Lighthouse Activity on Climate Intervention; WCRP in general coordinates global climate research. The Lighthouse Initiative addresses CDR and	https://www.wcrp-climate.org/ci-overview

	SRM.	
UNEP	One Atmosphere: An Independent Expert Review on Solar Radiation Modification Research and Deployment; UNEA - the political body - has discussed draft resolutions twice to date (2019, 2024)	https://www.unep.org/resources/report/Solar-Radiation-Modification-research-deployment
GeoMIP	The Geoengineering Model Intercomparison Project is a sub-project of the Climate Modelling Intercomparison Project, which itself is a project of WCRP; its work is critical for SRM modelling.	https://climate.envsci.rutgers.edu/GeoMIP/about.html

Public and private funders active on the topic

ARIA	Research funding program: Exploring Climate Cooling (£56.8m).	https://www.aria.org.uk/opportunity-spaces/future-proofing-our-climate-and-weather/exploring-climate-cooling
Simons foundation	Funds natural science indoors research on SRM	https://www.simonsfoundation.org/grant/solar-radiation-management/
UKRI	Modelling environmental responses to solar radiation management – programme (£10m)	https://www.ukri.org/what-we-do/browse-our-areas-of-investment-and-support/modelling-environmental-responses-to-solar-radiation-management/
Silver Lining	Advocating for better information on SRM including through research	https://www.silverlining.ngo/
Reflective	Developing SRM knowledge and technology research and development	https://reflective.org/
Harvard global empowerment	University Incubation fund has supported SRM related projects	https://www.hks.harvard.edu/centers/cid/voices/2023-gem-incubation-fund-award-recipients#solar-radiation-modification-impacts-based-dashboard-1847900
University of Chicago, Climate System Engineering Initiatives	CSEi is funding interdisciplinary research projects to advance our understanding of climate	https://climateengineering.uchicago.edu/research/

	systems engineering.	
University of Cambridge, Centre for Climate Repair	Advancing research on solutions for a warming world	https://www.climaterepair.cam.ac.uk/

Non-governmental organizations

Carnegie Climate Governance Initiative	Operated 2016-2023 (concluded its activities)	https://c2g2.net/
The Solar Radiation Management Governance Initiative (SRMGI)	Co-convened by the Environmental Defense Fund, the Royal Society and TWAS, the Academy of Sciences for the Developing World	Set up in 2010, later converted into DEGREES
DEGREES	Formerly SRMGI. Aims to put developing countries at the centre of the SRM conversation.	https://www.degrees.ngo/
Gordon Research Conference	Hosts specialized meetings focussed on natural sciences, some of which cover SRM.	https://www.grc.org/climate-engineering-conference/2024/
Planetary Sunshade Foundation	Space-based SRM	https://www.planetarysunshade.org/
Climate Overshoot Commission	Reducing the risks of climate overshoot (2023). The CARE agenda.	https://www.overshootcommission.org/report
SRM360	Not-for-profit organization.	https://srm360.org/
Centre for Future Generations	Think tank / not-for-profit organisation	https://cfg.eu/
The Alliance for Just Deliberation on Solar Geoengineering	Advocating for inclusive discussion of SRM	https://sgdeliberation.org/
Silver Lining	Advocating for better information on SRM including through research	https://www.silverlining.ngo/
Reflective	Developing SRM knowledge	https://reflective.org/

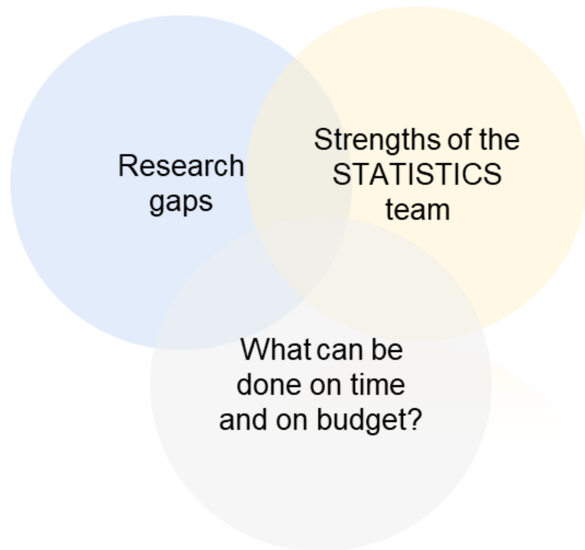
	and technology research and development	
SRMYouthWatch	Demanding youth voices be heard in SRM governance (incl. research)	https://www.srmyouthwatch.org/
Operaatio Arktis	Advocating for climate strategies to reality and integrating research and development of climate interventions.	https://www.operaatioarktis.fi/
Resources for the Future	Holds an annual conference on the social science aspects of SRM in Washington DC	https://www.rff.org/events/conferences/2025-rff-and-harvard-srm-social-science-research-workshop-governance-in-a-fractured-world/

For-profit companies

Make Sunsets	Start-up	https://makesunsets.com/
Stardust	For-profit company	https://www.stardust-initiative.com/
MEER	For-profit (cooling) company	https://www.meer.org/

1.8 Rationale for the work proposed in STATISTICS

The work content proposed for the STATISTICS proposal has been refined based on the analyses performed above. It aims to address research gaps that were identified so far, while exploiting the strengths of the STATISTICS team and achieving the results on time and on budget keeping in mind the short timeframe for the project.



Measurements from spaceborne polarimeters and lidars were identified as being good candidates to provide further insight into SRM analogues. CALIOP-CALIPSO and EarthCare-Atlid would represent natural choices to study marine areas downwind of low-level passive degassing volcanoes. In particular it would be interesting to separate marine boundary-layer (MBL) and free-troposphere (FT) aerosols to understand how CCN populations affect low-level and mid-level clouds. Current cloud retrievals have limitations to diagnose the evolution of the cloud droplet size distribution (e.g. its effective dispersion). The new generation of polarimeters (PACE SpexOne and 3MI) are quite promising in that respect. While such research avenues are promising, it was considered to be too early to go in that direction as PACE data are only becoming available now and 3MI is yet to be launched.

Instead we focus the research objectives in STATISTICS on two under-studied natural analogues and three research topics that address critical gaps in our understanding and for which rapid progress can be made. For SAI, the project will revisit the Raikoke and Ulawun eruptions using different climate models to assess the evolution of aerosol size distributions under detailed microphysical processes and contrast it with observations. Preliminary work has shown that one model fails to reproduce the evolution of the aerosol size distribution In the MCB context, the project tackles the current paucity of observational constraints on aerosol properties and their interactions with clouds by focusing on the post-2018 Kilauea degassing. Only data for degassing episodes before 2018 have been considered in the literature. Leveraging TROPOMI-derived SO_2 dataset and the Volcplume service, aerosol retrievals will be performed using the GRASP algorithm to improve aerosol characterization. Furthermore, the project will investigate potential changes in cloud fraction using cloud masking products. For CCT and MCT, where the susceptibility of cirrus and mixed-phase clouds to intervention remains poorly constrained, the project will utilize newly available satellite-derived datasets of cloud microphysical properties. These data will be used to evaluate the fidelity of modelled cloud susceptibility and to quantify the associated uncertainty in negative radiative forcing, thereby contributing to a more robust assessment of the cooling potential of these techniques.

In addition we will perform state-of-the-art radiative transfer calculations to quantify aerosol-radiation interactions, including heating rates and perturbations to surface and top-of-atmosphere (TOA) radiative fluxes. A novel contribution of the project is the integration of PV yield modelling, going beyond traditional PV indicators, to evaluate the impact of modified radiative fluxes on PV production and mitigate these effects through PV system design optimization. Finally, detectability studies will be conducted to assess the potential for observing SAI signals in the climate system with new observing systems.

The research gaps addressed by the STATISTICS project are shaded in grey in Tables 1.1 and 1.2. Likewise the natural analogues that are being looked at are shaded in grey in Tables 1.7 and 1.8.

1.9 Analysis of potential risks and their impact on the products and project

The proposed research on Solar Radiation Modification (SRM) techniques —such as stratospheric aerosol injection (SAI), marine cloud brightening (MCB), and cirrus cloud thinning (CCT)— aims to bridge critical knowledge gaps and contribute to international assessments of SRM's uncertain potential as a climate intervention. The project faces some risks in regards to the achievement of its overall objectives.

Insufficient data utilization and resolution limitations
Existing observational data, including satellite datasets with resolutions of 100m-1km, remain under-utilized, while climate models often fail to resolve fine-scale processes critical to SRM (e.g., aerosol-cloud interactions near injection points). This risk could lead to incomplete or inaccurate assessments of SRM techniques if high-resolution modeling and synergistic data retrievals (e.g., via the GRASP algorithm) are not effectively integrated. Delays in accessing or processing these datasets within the project's short timeframe could further exacerbate this issue.

Uncertainty in natural and anthropogenic analogues
The project relies on analogues like passive volcanic degassing (e.g., Holuhraun 2014–2015) and shiptrack emissions to infer SRM effects. However, the project may find these analogues may not fully replicate SRM conditions, introducing uncertainty in extrapolating findings to intentional deployment scenarios. If discrepancies between analogues and

SRM processes are not reconciled, the validity of resulting insights could be questioned, weakening the evidence base for international assessments.

Ethical and governance controversies

SRM remains highly controversial due to ethical concerns (e.g., unintended regional climate impacts) and governance challenges (e.g., lack of international frameworks). The project's exploration of field experiments and detectability assessments could inadvertently fuel public or political backlash, especially if perceived as endorsing deployment over mitigation. Failure to address these sensitivities transparently may limit stakeholder buy-in and hinder collaboration with policymakers and the broader scientific community.

Technical feasibility and scalability constraints

Assessing the energy budgets and scalability of SRM techniques (e.g., lofting aerosols for SAI or spraying sea particles for MCB) depends on realistic technological assumptions. Current technologies exhibit low efficiency, and the project's thermodynamic analyses may reveal impractical energy requirements or deployment challenges. If these technical limitations are underestimated, the research could overstate SRM's viability, misguiding future efforts.

Collaboration and stakeholder alignment risks

The project's success hinges on coordination with ongoing initiatives (e.g., CCI, Horizon Europe projects like Co-CREATE) and stakeholder engagement (e.g., via workshops). Misalignment or insufficient input from these groups could lead to duplicated efforts, overlooked gaps, or findings irrelevant to policy needs. Given the short project duration, delays in establishing these synergies could jeopardize the delivery of actionable outcomes.

Mitigating these risks requires prioritizing data integration, validating analogues rigorously, embedding ethical considerations, grounding technical analyses in current capabilities, and fostering robust collaboration. By addressing these challenges, the project can strengthen its contribution to SRM research and climate action.

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