Assessment of plausible solar radiation modification field experiments from an expert-led workshop reveals the need for differentiated governance

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Key Points:

- Plausible solar radiation modification field experiments across all scales were identified for three leading approaches
- A typology of plausible near-, mid-, and far-term experiments was developed based on technical feasibility and regulatory complexity
- Effective governance requires context-specific, scale-sensitive regulation of solar radiation modification field experiments

Abstract

Proposed solar radiation modification (SRM) field experiments are receiving growing scientific and policy attention, with several localised experiments having occurred or under development. While they may be critical for improving technical understanding and reducing uncertainties, SRM field experiments remain controversial and inadequately captured under current legal, ethical, and political frameworks, which often rely on binary 'small-scale' or 'large-scale' distinctions. In practice, SRM field experiments may vary widely in scale, geography, materials, scientific purpose, and environmental impacts, making uniform governance approaches impractical. Here, we develop a typology of plausible, scientifically motivated SRM field experiments across three leading approaches: stratospheric aerosol injection (SAI), marine cloud brightening (MCB), and cirrus and mixed-phase cloud thinning (CCT/MCT). We identify six SAI, five MCB, and three CCT/MCT experiments across a range of scales, assessing their interaction with existing environmental and legal frameworks, particularly within the EU. The study also addresses governance challenges such as scale perception and stakeholder legitimacy, and highlights procedural tools including exit ramps and transparency requirements. We introduce a phase-based typology of plausible SRM field experiments: early-phase (technically and regulatorily feasible), intermediate-phase (technically feasible but likely to cross regulatory thresholds), and distant-phase (plausible but requiring comprehensive review and new governance mechanisms). The intermediate phase highlights that SRM research cannot be reduced to a small-/large-scale binary: many plausible experiments occupy a grey zone where scientific value is high, but governance remains underdeveloped. Recognising this distinction may help prioritise governance, guide proportionate regulation, and ensure field experiments are evaluated by intent and their regulatory implications.

1 Introduction

The past ten years (2015–2024) have been the warmest on record, with 2024 being the first year to surpass a global mean temperature 1.5°C above the 1850–1900 average (Copernicus Climate Change Service (C3S), 2025). Climate impacts are accelerating, with global temperatures potentially exceeding 2°C of warming by 2045 and the world on course for 2.6–3.1°C of warming by 2100 (United Nations Environment Program, 2024). The potential implications of such warming are severe: 25 of the 35 planetary 'vital signs' tracked annually are now at record extremes (Ripple et al., 2024), and climate damages could cost the global economy $19–59 trillion annually by 2049 (Kotz et al., 2024), while increasing the risk of crossing multiple climate tipping points (e.g., Lenton et al., 2008; Lenton, 2021; Armstrong McKay et al., 2022). In light of these trends, interest is growing in climate interventions to temporarily reduce peak warming while mitigation and carbon removal efforts scale. Among these, field experiments related to solar radiation modification (SRM) are receiving particular attention. SRM refers to a set of proposed techniques intended to temporarily reduce global temperatures or reduce the climate impacts arising from anthropogenic greenhouse gas emissions, particularly under likely overshoot conditions (Shepherd, 2009; Honegger and Pan, 2021; McGrath et al., 2025).

SRM is considered by those who support research to be a potential supplement to long-term mitigation and carbon removal strategies, and the accelerating pace of climate change has led to increased interest in research to evaluate its feasibility, risks, and governance (e.g., NASEM, 2021; United Nations Environment Programme, 2023; SAPEA, 2024). This includes significant new funding programmes such as the UK's Exploring Climate Cooling initiative, launched by the Advanced Research and Invention Agency (ARIA, 2024). Research is critical for developing understanding, as substantial scientific and technical uncertainties surrounding SRM remain (e.g., Feingold et al., 2024; Eastham et al., 2025; Haywood et al., 2025). One area of emerging focus is the design of small-scale field experiments – controlled outdoor studies aimed at improving scientific understanding of SRM processes, materials, or delivery systems. Such experiments are intended to address substantial scientific, technical and governance uncertainties, and to inform future assessments of SRM feasibility, risks, and reversibility (e.g., NASEM, 2021; UNEP, 2023; SAPEA, 2024).

However, SRM field experiments remain contentious: several planned SRM initiatives have been cancelled or suspended following governance disputes or public opposition. These controversies reflect broader disagreements over whether SRM research should proceed at all, and if so, under what conditions. While some argue that small-scale, tightly controlled experiments are necessary to progress our scientific understanding and inform responsible governance as articulated in the Climate Intervention Research Letter (2023), others advocate for precautionary restrictions or a complete ban (e.g., Bierman et al, 2022; Clear Skies Act, 2025).

The AGU Ethical Framework for Climate Intervention Research (Williams et al., 2024) outlines five guiding principles: responsible research, holistic climate justice, inclusive public participation, transparency, and informed governance, which offer a standardising foundation for the conduct and evaluation of SRM field experiments. However, as Brent et al. (2024) argue, the challenge lies in operationalising these principles within diverse legal and institutional contexts, particularly through domestic governance mechanisms. SRM field experiments may vary widely in scale, materials, and intended effects, raising distinct scientific, ethical, and legal challenges. This underscores the importance of addressing not only ethical intent but also the specific, technical, spatial, and regulatory features of different SRM experiments. Understanding this diversity and the governance issues it raises is essential for evaluating SRM field experiments in terms of scientific merit, technical feasibility, and regulatory implications. Against this backdrop, this study aims to identify the key scientific and physical parameters required for a structured review of SRM field experiments.

The primary SRM mechanisms considered to decrease the Earth's energy balance involve increasing the reflectivity (i.e., albedo) of the atmosphere, clouds or the Earth's surface to reduce the net incoming shortwave solar radiation. The most technically and logistically feasible techniques with the potential for substantial climatic effects are stratospheric aerosol injection (SAI) and marine cloud brightening (MCB) (NASEM, 2015). A different mechanism involves increasing the net outgoing longwave radiation from the Earth (i.e., the amount of heat energy radiated from the Earth back into space) by thinning cirrus or mixed-phase clouds, which have a net warming effect in the atmosphere (Gasparini & Lohmann, 2016; Hong et al., 2016). These techniques, known as cirrus and mixed-phase cloud thinning (CCT/MCT), have a smaller potential climatic effect (Gruber et al., 2019). Each technique is evaluated in Sections 4, 5, and 6. Other SRM techniques, such as sea ice modification, surface albedo changes, or space-based reflectors, are excluded from this analysis due to their low technological readiness or modest cooling potential (e.g., Shepherd, 2009; van Wijngaarden et al., 2024a, 2024b).

This review is part of the Co-CREATE Horizon Europe project, which examines the conditions for responsible research into SRM. It draws on both a systematic review of past SRM field experiments (Hernandez-Galindo et al., 2025) and a technical expert workshop convened to explore the design, feasibility, and governance of plausible future experiments. This review builds on an early effort to systematically assess potential SRM field experiments, which resulted from a workshop at Harvard convened by Keith et al. (2014). It shares some commonalities with a more recently proposed framework for defining different scales of field experiments to assess SRM (Doherty et al., 2025). Doherty et al. (2025) define study scales based on their spatial and temporal extent as well as on the energy perturbation introduced to the atmosphere by the study, applies this framework to MCB, and highlights the links between study physical scale, scientific purpose, detectability of different parameters, and other metrics of interest like the mass of material emitted, radiative forcing produced, lifetime of potential impacts, and scale relative to existing analogues. The relevance of this framing to governance considerations is discussed, but the paper does not address the applicability of different regulations, laws, treaties and agreements to the experiments.

Here, as in Keith et al. (2014), we develop a structured typology of plausible future experiments, in this case informed by published proposals and activities between 2008 and 2024, technology readiness levels, and expert input from Co-CREATE workshop contributors. Drawing on the expertise of workshop participants, we identified specific classes of experiments across SAI, MCB, CCT/MCT. These were then analysed by integrating considerations of detectability, reversibility, and legal thresholds to assess how different experiments might be designed, implemented, and governed. The analysis focused on three key questions: (i) which experiments offer clear scientific value; (ii) how such experiments could be implemented in practice; and (iii) what regulatory frameworks may apply. This review complements the broader empirical and historical analysis provided in Hernandez-Galindo et al. (2025), which forms a foundation for identifying a plausible experiment landscape. The aim is to inform the development of governance frameworks capable of distinguishing between different experiments based on their perturbation scale, remote detectability, and associated risks.

The paper proceeds as follows: Section 2 outlines the methods used to develop the typology, drawing on a synoptic review of past SRM experiments and comparisons with cloud seeding. Section 3 describes the expert workshop and technical parameters used to characterise experiments. Section 4–6 presents the typology itself, covering plausible experiments across SAI, MCB, and CCT/MCT. Section 7 examines procedural governance and design safeguards. Section 8 discusses regulatory and governance implications and experimental scale considerations. Section 9 concludes by highlighting the significance of the intermediate phase of experiments and the need for proportionate, context-specific governance.

2 Background: Synopsis of Past SRM Field Experiments

This section summarises past SRM field experiments and highlights their parallels with existing weather modification research. A more detailed technical review of SRM studies is presented in the companion paper by Hernandez-Galindo et al. (2025).

2.1 Synopsis of Past SRM Field Experiments

Since 2008, several SRM field experiments and related activities have been conducted or cancelled (Figure 1). Initial experiments focused on the feasibility of SAI (2008–2010; Izrael et al., 2011). The Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE), conducted in 2011, was arguably the first MCB-related field study to explore aerosol-cloud interactions. However, it used non-representative particle types and sizes and was not designed to assess the feasibility of MCB as an SRM technique (Russell et al., 2013). The UK-based SPICE project, launched in 2010, included a proposed field experiment involving a tethered balloon to loft material into the atmosphere. This experiment was cancelled in 2011 due to conflict of interest concerns regarding an undisclosed patent related to injection technologies, though there had also been public and civil society opposition and broader governance concerns (Stilgoe et al, 2013). While the field experiment component was cancelled, the broader SPICE project continued in modified form.

Following a nine-year hiatus in SRM field research, a new series of experiments began in 2020 in Australia, motivated by the long-term goal of reducing coral bleaching over the Great Barrier Reef (GBR) through marine cloud brightening (Tollefson, 2021). These experiments have primarily focused on generating sea salt aerosol and characterising its behaviour in the lower atmosphere. While no direct observations of cloud brightening or cooling have been made, early experiments indicate that aerosol plumes generated at the sea surface onboard research vessels can be rapidly advected to cloud base height (Hernandez-Jaramillo et al., 2025). The project has also received institutional support as part of a broader GBR adaptation programme and has emphasised engagement with Indigenous Traditional Owners of the GBR.

In 2021, the CLOUDLAB project in Switzerland began a series of field experiments focused on aerosol-cloud interactions and ice formation processes in supercooled low stratus clouds, using glaciogenic cloud seeding as a tool to introduce controlled aerosol perturbations (Henneberger et al., 2023). While similar seeding techniques have long been used in weather modification (e.g., Bruintjes, 1999; Flossmann et al., 2019), CLOUDLAB is distinguished by its focus on process understanding in a highly constrained atmospheric environment. Although not framed by the investigators as SRM research, insights from CLOUDLAB may nonetheless inform future modelling or design of CCT or MCT approaches.

The US-based SCoPEx project, also initiated in 2021, planned to conduct equipment tests and eventually release ≤2 kg of calcium carbonate or sulphates into the atmosphere (Keith et al., 2014). It became the second SAI experiment to be cancelled, after the Swedish Space Corporation withdrew from a planned balloon launch in Kiruna, following objections from the Saami Council and other stakeholders concerning a lack of prior engagement, potential socio-environmental impacts, and broader governance and moral hazard concerns – the fear that research into SRM could reduce political will to pursue mitigation. The experiment was officially cancelled later that year (Jinnah et al., 2024). In 2024, a US-based experiment related to MCB was initiated to assess the feasibility of generating a plume with the desired particle size (Wood et al., 2024). However, following public concerns about transparency and the absence of prior consultation, the experiment became the first field experiment related to MCB to be cancelled, following a unanimous vote by the Alameda City Council (Burns and Talati, 2025).

Since 2021, several private-sector activities related to SAI have emerged. These include the UK-based Stratospheric Aerosol Transport and Nucleation (SATAN) initiative and the US-based company Make Sunsets, both of which have released small amounts of sulphur dioxide into the atmosphere via high-altitude balloons. The Israeli-US enterprise Stardust Solutions has reportedly conducted initial hardware test flights, although no technical details or peer-reviewed data have been publicly disclosed (Burns and Talati, 2025). These three activities may not meet standard definitions of scientific experiments, as they lack either transparent design, monitoring, or data analysis, and have not resulted in any peer-reviewed publications. As a result, these private-sector experiments are not considered further in either this study or the Hernandez-Galindo et al. (2025) companion study.

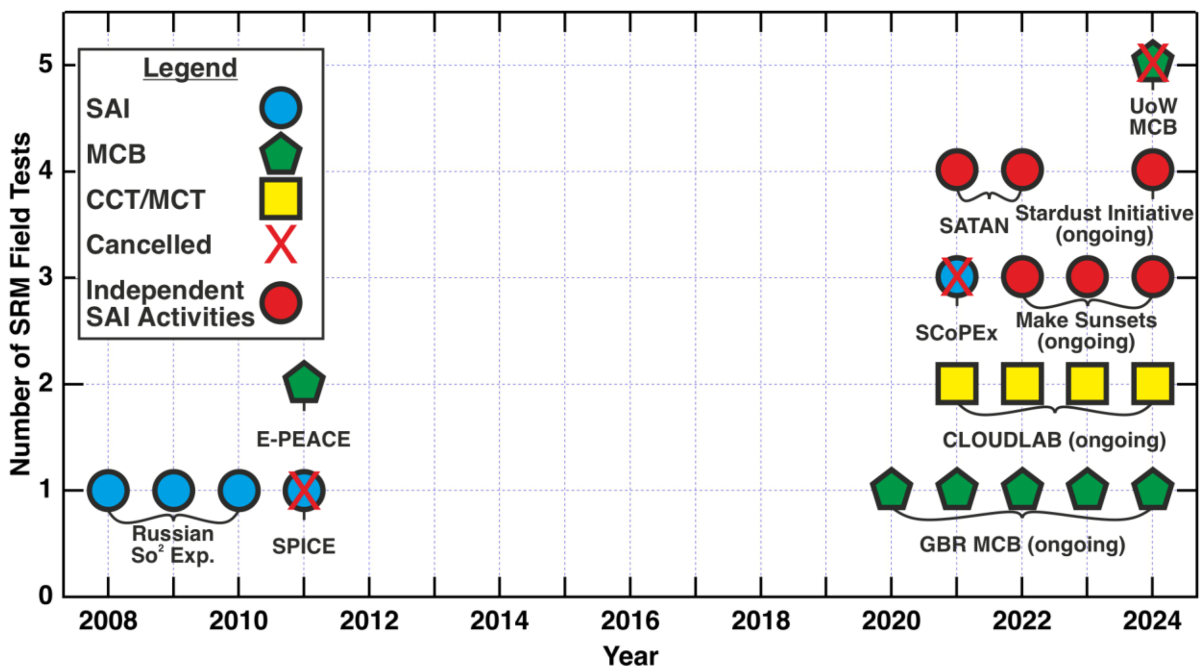

Figure 1. A list of previous solar radiation modification (SRM) field experiments and activities. Experiments have increased since their inception in 2008 and are likely to increase in the future. 'Independent SAI Activities' refer to privately initiated releases that lack peer-reviewed protocols, instrumentation, or transparent monitoring and are not considered formal experiments in this typology. These cases are included solely for comparative context. CLOUDLAB is not framed by its investigators as an SRM experiment, but is included here as a CCT/MCT-adjacent process study due to methodological relevance. SAI – stratospheric aerosol injection; MCB – marine cloud brightening; CCT/MCT – cirrus and mixed-phase cloud thinning.

2.2 Parallels with Cloud Seeding

Although this paper focuses on experiments explicitly related to SRM, it is important to recognise the strong similarities between small-scale SRM field studies and long-standing weather modification practices. Since the 1940s, cloud seeding has been used in over 50 countries to alter precipitation patterns, using aerosol injection (typically silver iodide or hygroscopic salts) to enhance rainfall or snowfall (e.g., Bruintjes 1999; French et al. 2018; Rasmussen et al. 2018; Flossmann et al. 2019; Rauber et al. 2019; Tessendorf et al., 2019; Xue et al., 2022), or to reduce hail damage in both cold and warm cloud systems (e.g., Vonnegut & Chessin, 1971; Marwitz, 1973; Dessens, 1986; Federer et al., 1986; Dessens et al. 2016; Haupt et al. 2018; Lu et al., 2023). These activities often involve aircraft or ground-based generators, target well-defined atmospheric processes, and are designed to produce measurable environmental effects – in some cases, over populated or agriculturally significant regions.

In physical terms, many cloud seeding deployments are highly similar to plausible small-scale SRM field studies of CCT and MCT (e.g., Villanueva et al, 2022; Schäfer et al, 2025). The CLOUDLAB project – while not framed as SRM – contributes to process-level understanding of aerosol–cloud interactions in persistent stratiform systems and may generate insights relevant to CCT and MCT research (Henneberger et al., 2023). Similarly, while the previously mentioned studies were primarily aimed at rainfall enhancement or hail suppression, many employed near-identical techniques and targeted similar atmospheric conditions. It is therefore important to acknowledge their relevance here, even if their intended purpose was not explicitly related to SRM. More generally, cloud seeding research offers a governance analogue for SRM experimentation. Domestic permitting systems, environmental impact assessments, and post-operation evaluations are common requirements in cloud seeding jurisdictions (Simon et al., 2020). These frameworks frequently mandate monitoring, public transparency, and adaptive management practices that enable iterative learning and adaptation over time.

Governance of cloud seeding also highlights important institutional features that may inform SRM governance: multiscale coordination across jurisdictions, mechanisms for stakeholder engagement and conflict resolution, and flexible oversight structures that evolve with scientific understanding. Perhaps most importantly, these programs show that small-scale activities that physically alter the atmosphere can be responsibly regulated – not solely based on intent, but on physical scale, risk, and reversibility. As such, weather modification potentially offers a valuable, underutilised reference point in emerging SRM governance debates.

3 Methodology: Distinguishing Types of SRM Field Experiments

3.1 Workshop approach and key research questions

In September 2024, a two-day workshop was held at UCL, convening 25 experts, primarily from scientific and technical fields, alongside experts in social science, governance, policy, and legal perspectives. Participants were separated into three technical groups (SAI, MCB, and CCT/MCT), and were asked to address the following questions:

1. What field experiments would be useful for improving the understanding of the selected SRM technique and advancing the development of the associated technology?
2. Can these ideas be bundled into broad classes of experiments defined by their scale?
3. What are the key physical and technical characteristics of these different classes of field experiments?

A small fourth group, comprising the social science, governance, policy, and legal experts, was asked to explore the following questions to help contextualise the technical discussions and support the broader Co-CREATE project:

1. What characteristics of SRM field experiments are most relevant to shaping future research governance across the different techniques?
2. What types of activities should be considered within the scope of SRM?
3. How should non-technical aspects of field experiments be addressed through case studies?

The groups then reconvened in plenary, where holistic discussions led to the definitions of six SAI, five MCB, and three CCT/MCT experiments that could plausibly be conducted in the future. These were characterised by their primary scientific and technological goals, the type and quantity of material released, injection method, experiment type, estimated cost, and any potential environmental regulations that may apply. The experiments are described in sections 4 to 6. In addition, five field experiment Case Studies were developed as part of the Co-CREATE project and are described in Redmond Roche and Irvine (2025).

3.2 Field experiment characteristics: key scientific and technical distinctions

SRM experiment classifications have previously been categorised into five broad types: laboratory experiments, technology development, process studies, scaling tests, and climate response tests (Latham et al., 2012; Keith et al., 2014). These categories provide a helpful conceptual framework for structuring early-stage research and establishing distinctions between levels of complexity, risk, and potential climate impacts. Laboratory experiments involve computational modelling, indoor measurements, and bench-scale tests to explore fundamental processes and potential risks. Technology development refers to the outdoor testing of equipment or operational systems that may support either scientific research (e.g., instrumentation for controlled experiments) or, potentially, future deployment scenarios. For instance, the planned initial phase of the SCoPEx project focused on developing instrumentation specifically for experimental use (Burns and Talati, 2025). Process studies include both the observation of natural or anthropogenic analogues (e.g., volcanic eruptions, ship tracks) and the controlled release of materials into the environment to investigate specific processes. These studies aim to improve understanding of aerosol microphysics, atmospheric transport, and short-term interactions between aerosols, clouds, and radiation. While observations of natural analogues provide valuable insights, they often involve multiple variables that cannot be isolated or manipulated. Controlled process studies, by contrast, offer a means to test specific hypotheses under constrained conditions, helping to evaluate and refine process-level models that may inform larger-scale simulations. Scaling tests aim to evaluate model accuracy across spatial and temporal scales, integrating physical processes from microphysics to mesoscale dynamics over horizontal distances ranging from approximately 10 m to 1000 km downwind of the release point. These may involve larger material releases or more complex experiments. Climate response tests, which are significantly larger in both spatial extent (>1000 km) and duration, are intended to produce impacts on climate-relevant variables and system feedbacks. These experiments are among the most controversial - both because they may generate tangible climate impacts and because they risk blurring the line between research and deployment. In practical terms, they may be indistinguishable from small-scale deployment, raising fundamental concerns about governance, consent, and legitimacy.

This study builds on that framework by focusing specifically on outdoor field experiments that involve the intentional release of material into the atmosphere. These are grouped into three broad categories for analytical clarity: (i) *technology development*, which focuses on testing and refining delivery systems and monitoring platforms; (ii) *process studies*, aimed at improving understanding of aerosol-cloud interactions and the effects of atmospheric dynamics and chemistry on emitted aerosol; and (iii) *scaling tests*, which assess whether induced perturbations produce measurable localised environmental or radiative effects, and whether such effects are detectable given the sensitivity and resolution of current measurement approaches. Detectability will vary depending on the parameter and the measurement method. In the experiment descriptions presented in Sections 4–6, the latter two categories are presented as 'Process' and 'Signal' experiments, respectively. 'Process' experiments are designed to examine specific physical or chemical mechanisms in detail, while 'Signal' experiments aim to distinguish whether a deliberate perturbation produces a measurable atmospheric response – such as changes in aerosol properties, cloud characteristics, or radiative fluxes – that rises above background variability. This terminology reflects the primary scientific goals and aligns with that used during the workshop. Climate response tests – or 'Impact' experiments – are excluded from this assessment due to the ambiguous boundary with deployment. Such climate response tests raise geopolitical and ethical issues, as well as potentially conflict with international frameworks such as the Convention on Environmental Impact Assessment in a Transboundary Context (Espoo Convention, 1991) and the Convention on Long-range Transboundary Air Pollution (LRTAP, 1979).

To analyse the differences between the experiments considered in this study, we characterise them in terms of a number of scientific, technical, and legal parameters. These include:

- *Perturbation scale*. The spatial and temporal extent of the experiment's direct and indirect effects, ranging from localised and short-lived to regional in scale and sustained over a defined period.
- *Remote Detectability*. A qualitative assessment of whether the radiative or microphysical signal from an experiment is distinguishable from natural variability. This refers specifically to the local perturbation within the experiment area and reflects the likelihood of remote detection using available monitoring platforms. Detectability is

classified into three ordinal levels: 0 – *Negligible detectability*: the signal cannot be distinguished from natural variability by remote detection, only by localised in situ measurements; I – *Potentially detectable*: the signal may be observable under certain conditions or through cumulative effects, but is likely to be near or below typical detection thresholds; II – *Clearly detectable*: the signal exceeds background variability and is expected to be measurable using remote sensing or in situ instrumentation. In most experiments considered here, potential signals are expected to be microphysical rather than radiative. For example, Level I detectability may correspond to local perturbations in droplet number, size distribution, or liquid water content, detectable via in situ aircraft or UAV sampling. Signal strength depends not only on instrument sensitivity but also on experiment scale, background variability, and integration time (see Seidel et al., 2014; Zhang et al., 2025)

- *Material released and quantity*. Both the physical form of the material (e.g., gas, solid or liquid aerosol) and the total mass released.
- *Estimated operational cost (in USD)*. An estimated financial range required to conduct the experiment, including equipment, logistics, and personnel, based on prior literature (e.g., NASEM, 2015; Nalam et al., 2018).
- *Technical feasibility and phase classification*. We classify experiments into three indicative phases of development based on technical feasibility and likely governance exposure. *Early-phase* experiments are small-scale, technically feasible with existing infrastructure, and likely permissible under current rules. *Intermediate-phase* experiments are larger, technically feasible but more complex, and likely to cross regulatory thresholds or raise governance sensitivities. *Distant-phase* experiments remain technically plausible but would almost certainly require a comprehensive legal review and new multilateral governance arrangements. These phases are analytical categories rather than chronological predictions: the timing of progression depends on both technological readiness and governance context.
- *Existing environmental regulations*. The degree of legal oversight that may be required based on the scale, materials, and location of an experiment. This can range from minimal oversight for very small-scale trials to formal screening-level assessments and full Environmental Impact Assessments (EIAs) where legal thresholds are exceeded. These thresholds can vary by jurisdiction and are discussed further in Section 3.3.

These parameters guide the analysis of proposed experiments across SAI, MCB, and CCT/MCT, as presented in Sections 4–6 and support the comparative analysis developed in the Discussion.

3.3 Legal and Regulatory Frameworks Relevant to SRM Experiments

While formal governance frameworks for SRM remain limited, several existing environmental and chemical safety regimes may apply depending on the characteristics of a given experiment, and typically operate at the level of national implementation or through obligations placed on States rather than directly on researchers. The United Nations Convention on Biological Diversity (CBD), through Decision IX/16 C and reaffirmed in Decision X/33 (CBD, 1992, 2008, 2010), calls for a precautionary pause on all climate-related geoengineering activities that may affect biodiversity unless supported by adequate scientific evidence, prior impact assessment, and are governed through transparent and effective regulatory mechanisms. An exception is made for 'small-scale' scientific research conducted in controlled settings, where the objective is to gather specific data and the risks are well-characterised.

Similarly, the London Convention (1972) and the London Protocol (1996) have addressed emerging geoengineering techniques, notably through a 2013 amendment that established a framework for assessing and regulating marine geoengineering (London Convention and Protocol, 2013). A 2023 statement expanded concern to techniques such as MCB and albedo enhancement, citing their potential for significant harm and endorsing strict application of existing assessment procedures (London Convention and Protocol, 2023). While currently limited to ocean fertilisation, the framework allows only scientifically justified, small-scale research conducted under a rigorous environmental assessment process and subject to both national and international oversight.

Depending on scale and geography, larger experiments may also invoke national or international frameworks (e.g., UNCLOS, 1982; Montreal Protocol, 1987, 2023; Espoo Convention, 1991; CBD, 1992, 2008, 2010). While the UNFCCC (1992) does not explicitly address SRM, its principles on research cooperation and precautionary action may become relevant, and as an important body in climate governance, will likely play a key role in SRM governance (Sipra and Talati, 2024). The European context is used here as a structured case study to illustrate how existing regulations may apply and to assess the legal feasibility of plausible experiments, potentially offering guidance for emerging governance frameworks elsewhere. Within this frame of reference, several EU Directives may apply depending on the characteristics of the experiment (e.g., Habitats Directive, 1992; SEA Directive, 2001; Environmental Liability Directive, 2004; REACH Regulation, 2006; Ambient Air Quality Directive, 2008; Birds Directive, 2009; Industrial Emissions Directive, 2010; EIA Directive, 2011, 2014).

The Aarhus Convention (1998) also establishes binding international obligations on public access to environmental information, participation in decision-making, and access to justice in environmental matters. While adopted under the UNECE framework, it is implemented across EU member states and underpins procedural transparency and public participation requirements within directives such as the EIA Directive (2011, 2014) and SEA Directive (2001). A particular challenge lies in determining who qualifies as an 'affected party' in the context of atmospheric SRM experiments, where dispersal may occur far from the injection site. This uncertainty has significant implications for consent procedures, public participation under Aarhus, and transboundary consultation requirements under the Espoo Convention (1991), especially where impacts are diffuse, delayed, or geographically widespread. For additional discussion of legal implications across global contexts, see Redmond Roche and Irvine (2025) and Vinders et al. (2025).

4 Stratospheric Aerosol Injection (SAI)

4.1 Scientific basis and key uncertainties

SAI aims to increase the Earth's albedo by injecting sulphur dioxide (SO_2) or other sulphate precursors into the stratosphere, where they oxidise into sulphuric acid (H_2SO_4) and form minuscule aerosol particles, either by nucleating to form tiny liquid droplets or condensing onto existing particles (Seinfeld and Pandis, 2006). Alternative solid aerosols – including calcite ($CaCO_3$), alumina (Al_2O_3), and diamond dust (C) – have also been proposed (Keith et al., 2016; Stefanetti, 2024). These materials are generally more chemically stable than sulphates, but their behaviour under stratospheric conditions remains poorly understood compared to sulphates, which are supported by natural analogues from major volcanic eruptions (Rasch et al., 2008). For example, coatings such as sulphuric acid or oxidative processes may alter their optical and radiative properties (Shepherd et al., 2025). Calcite, in particular, may react with stratospheric species (e.g., HCl, HOCl, H_2SO_4) to form mixed particles (Dai et al., 2020; Stuckey et al., 2024). Aerosol morphology, including changes to surface roughness or particle shape, may further influence coagulation and light scattering. Addressing these uncertainties will require bridging the gap between laboratory studies and real stratospheric conditions through well-characterised field experiments.

Uncertainties surrounding SAI include both the climatic response and the technical/engineering feasibility arising from a lack of observational data and scientific field experiments. These uncertainties represent a major motivation behind SRM field experiments (e.g., Eastham et al., 2025). First, there are uncertainties in stratospheric processes, including aerosol microphysics, spatial and temporal variability, interactions with stratospheric chemistry, and aerosol-radiation interactions – particularly absorption and scattering properties (Määttänen et al., 2024; Dykema et al., 2016). Second, there are challenges related to technological feasibility – particularly surrounding the delivery systems to release aerosol in a controlled, repeatable and scalable manner (Robock et al., 2009; Janssens et al., 2020; Smith et al., 2022a, 2022b). Third, there are questions regarding the Earth system response to sustained stratospheric aerosol forcings, including impacts on the hydrological cycle, and large-scale circulation patterns such as the Atlantic Meridional Overturning Circulation, the Intertropical Convergence Zone (ITCZ) or monsoonal dynamics (e.g., Haywood et al., 2002; Ricke et al., 2023). SAI could also influence tropospheric circulation, with possible shifts in precipitation and temperature in case of uneven deployment patterns (Visioni et al., 2023a), that could generate regionally uneven outcomes – potentially benefitting some populations while disadvantaging others (e.g., Ferraro et al., 2014; Wei et al., 2018; Sun et al., 2020). Only 'climate response' experiments would be relevant to this third category, while more targeted 'process' and 'signal' experiments may help constrain the first two; however, for this category, the scale at which such changes would be observable is, in terms of magnitude and length of sustained injection needed, indistinguishable from a deployment. A higher degree of certainty over the Earth System response at this scale is therefore more likely attainable through improvements in Earth System models, as well as a better mechanistic understanding of the underlying processes at play (for similar discussions related to climate change, see Shaw et al., 2024 and Simpson et al., 2025).

4.2 Plausible SAI field experiments

Building in part from the lessons of past SAI experiments (e.g., Hernandez-Galindo et al., 2025), this section outlines a set of proposed field experiments designed to advance scientific understanding while integrating technical, environmental, and legal considerations. To assess their feasibility and potential value, the experiments are classified according to their scientific and technical objectives, characteristics and location of the material released, perturbation scale (detectability), and regulatory context.

Experiment 1 is a small-scale, short-duration, single-release of sulphur dioxide (SO_2), designed to improve understanding of early-stage aerosol formation and plume transport in the stratosphere. A small quantity (<1 kg) would be released from a high-altitude balloon to study gas-phase injection, subsequent oxidation, and initial particle nucleation under real stratospheric conditions. While SO_2 is injected as a gas, the experiment targets the conversion process and resulting dispersion patterns, which are often simplified in climate models, assuming homogeneous distributions over large grid cells.

The experiment shares key design features with the previously proposed Stratospheric Controlled Perturbation Experiment (SCoPEx; Keith et al., 2014) and is therefore considered a near-term experiment, with high feasibility and estimated operational costs of $0.5–1 million. The perturbation is expected to be imperceptible relative to natural variability (Level 0 detectability), owing to rapid dispersion by stratospheric winds. However, actual detectability will depend on the release quantity and local stratospheric mixing, which governs how quickly the plume dilutes into the background. Prior studies show this mixing varies significantly with time and location (e.g., Haynes and Shuckburgh, 2000a, 2000b). In this case, SO_2 is used primarily to test controlled-release behaviour and plume evolution, with the balloon platform serving as a low-cost, near-term testbed (Jinnah et al., 2024). The results could also inform the development of effective nozzles for future SAI delivery systems by providing empirical data on gas-phase dispersion under stratospheric conditions.

In the European context, existing regulations could apply to this experiment. For example, the EIA Directive 2011/92/EU, as amended by 2014/52/EU (2011, 2014), could see a small-scale experiment involving the release of less than one tonne of material per year being classified as an Annex II Project. While SRM is not explicitly listed under the Directive, the activity may be analogised to several Annex II categories, including: surface storage of chemicals (10(f), e.g., ground-based storage of precursor gas); disposal of waste (10(h), e.g., if the intentional release into the atmosphere is interpreted as a form of waste); and changes or extensions of existing projects (13, e.g., iterative or scaled expansions of earlier atmospheric tests). Projects falling under Annex II are not automatically subject to an EIA, but require a screening procedure by national authorities, who assess factors such as project scale, the environmental sensitivity of the location, and the nature and significance of impacts. In accordance with Article 6(4), public participation must be ensured at an early stage in the decision-making process, with the public given the opportunity to express comments and opinions – highlighting the importance of transparent SRM experiments and research programmes. Where ambiguity exists, national law may nonetheless require screening or a full EIA on a precautionary basis – e.g., if conducted near ecologically sensitive areas, such as Natura 2000 network sites (Habitats Directive, 1992).

Monitoring would rely on high-resolution in situ instrumentation, including airborne LiDAR, mid-infrared spectrometers (with ~0.2 ppmv H2O precision), submicron aerosol counters capable of capturing particle number concentrations and size distributions (e.g., DPOPS; NASA, 2024) and in situ measurement of the chemical composition of individual aerosol particles (e.g., PALMS; NOAA, 2024; Dykema et al., 2014)

Experiment 2 is another small-scale, short-lived, process-level injection test involving releases of either solid (e.g., $CaCO_3$, Al_2O_3, diamond dust) or liquid (H_2SO_4) aerosols. The experiment would involve releasing approximately one kilogram of each aerosol type from a stratospheric balloon in separate single-release events to enable comparative analysis. In contrast to Experiment 1, which uses a gas-phase precursor to study aerosol formation through oxidation, this experiment would directly inject pre-formed aerosols, enabling immediate observation of particle behaviour, microphysics, and chemical interactions. While the overall platform design remains comparable, different aerosol types would require tailored dispersion mechanisms (e.g., fluidisation for solids, controlled atomisation for liquids). The primary objective is to characterise the physical and chemical properties of different particle types, assess their atmospheric reaction rates, and improve understanding of delivery mechanisms (e.g., Vattioni et al., 2023; Visioni et al., 2024). The estimated cost, near-term feasibility, detectability (level 0), monitoring approach, and regulatory implications under EIA Directive (2011, 2014) remain consistent with those described for Experiment 1.

Experiment 3 is a larger, near-term, process-level injection test, involving the release of less than one tonne of SO_2 from stratospheric balloons. The primary objective is to improve understanding of microphysical changes within the aerosol plume in the stratosphere, including particle nucleation, coagulation, growth, condensation, and sedimentation processes (e.g., Vattioni et al., 2023). The increased scale would allow the plume to be tracked over several days over distances of tens of kilometres, enabling in situ characterisation of its evolution and supporting validation of dispersion models (e.g., Weisenstein et al., 2022). The resulting data would also improve representation of aerosol microphysics in global climate models (e.g., Stenchikov et al., 2021; Quaglia et al., 2023; Tilmes et al., 2023; Brown et al., 2024; Vattioni et al., 2024).

The estimated cost of this experiment would likely exceed $1 million, reflecting the extended monitoring period relative to Experiments 1 and 2. However, the monitoring equipment, detectability of the aerosol plume and its microphysical evolution (Level 0), and near-term feasibility are expected to remain similar. Under the EIA Directive (2011, 2014), such an experiment would likely still fall under Annex II and be subject to screening procedures by national authorities. While a full EIA may not be triggered, national regulators may apply stricter oversight depending on the project's location or potential impacts. More significantly, under the Registration, Evaluation, Authorisation and Restriction of Chemicals Regulation (EC) No

1907/2006 (REACH Regulation, 2006), the obligation to register chemical substances with the European Chemicals Agency (ECHA) applies to manufacturers and importers producing or bringing in more than one tonne per annum. As this experiment involves quantities below that threshold and qualifies as scientific research under Article 56 of the REACH Regulation, it would not trigger registration requirements at the manufacturing or import stage. The one-tonne threshold is potentially an important legal benchmark when evaluating the regulatory implications of SRM field experiments.

Experiment 4 is a larger, medium-term, process- and signal-level injection test. The experiment would involve releasing at least one to ten tonnes of SO_2 using stratospheric balloons with multi-ton payloads, or aircraft, distributed across up to 100 repeated injections. The primary objective is to characterise plume physics under a range of meteorological conditions to assess natural variability in dispersion and microphysical evolution. In addition to resolving microphysical processes, the experiment would include coordinated radiative flux measurements – bot h in situ and via remote sensing – to assess the detectability of short-term, localised changes in top-of-atmosphere radiative forcing. This would support testing whether measured plume properties – such as particle size, concentration, and optical depth – can explain observed changes in atmospheric radiative flux. Repeated injections would allow assessment of variability across controlled events and support more robust parameterisation of aerosol-radiation interactions. While major volcanic eruptions like Mount Pinatubo and Hunga Tonga-Hunga Ha'apai provide useful analogues, they tend to be singular and infrequent. In contrast, this experiment would generate localised, well-characterised data under known conditions using in situ instrumentation (e.g., Legras et al., 2022; Brown et al., 2024).

While small in scale, these tests could nonetheless inform the design of real-world injection scenarios by providing critical empirical data on aerosol behaviour and variability across different regions, even if they may not fully capture the complexity of operational-scale deployments. At all experiment scales, directly comparing model simulations to observations of injected aerosol properties is critical for advancing predictive capability – and in this case, the repeated injections would enable more robust model evaluation across varying atmospheric conditions. In addition, the experiments could provide empirical evidence on potential side effects, such as the formation of polar stratospheric clouds, which can exacerbate ozone depletion (e.g., Hamill and Toon, 1991), or unintended changes to cirrus clouds affecting regional radiative balance (e.g., Kuebbeler et al., 2012; Visioni et al., 2018). While the plume scale for individual injections would remain comparable to Experiment 3, the cumulative mass released across cumulative events (1–100 tonnes) would improve the likelihood of detecting microphysical signals – such as changes in aerosol number, size distribution, or optical properties – using in situ instrumentation over distances of several hundreds of kilometres. Detectability would likely increase (Level I), reflecting the enhanced signal-to-noise ratio from repeated, time-resolved release under known conditions. The expanded scope and scale of Experiment 4 introduce greater logistical complexity: stratospheric balloons remain the most realistic near-term platform, despite an estimated operational cost of $40,000 per tonne of lofted material, leading to total estimated experimental costs approaching $10 million (Smith and Wagner, 2018).

Given that this experiment could release up to 100 tonnes per annum of SO_2, it would likely trigger a mandatory EIA under the EIA Directive (2011, 2014), interpreted via Annex I(6) (i.e., chemical installations for the production of basic inorganic chemicals) in conjunction with Annex II(13), due to the scale and chemical nature of the activity, which could be interpreted as functionally equivalent to a temporary or pilot-scale industrial installation. Under the REACH Regulation (2006), the one-tonne ECHA registration threshold would be exceeded, and if the total exceeded 10 tonnes, a Chemical Safety Report would also be required. Importantly, although scientific research activities may be exempt from authorisation under Article 56 of the REACH Regulation, researchers using SO_2 would likely be considered downstream users rather than manufacturers or importers. Consequently, they would be required to ensure their use falls within the conditions of a registered exposure scenario under Article 37.

These larger-scale activities may also raise concerns under the Convention on Biological Diversity (CBD, 1992, 2008, 2010), which – under Decision IX/16C and reaffirmed in Decision X/33 – calls for a precautionary pause on climate-related geoengineering activities that may affect biodiversity, unless they are supported by an adequate scientific basis, have undergone prior environmental assessment, and are subject to effective regulatory oversight. While such experiments may not produce measurable climate effects, their scale and intent could nonetheless place them within the scope of the CBD's precautionary provisions, particularly where prior assessment and regulatory oversight are lacking.

Given these challenges, Experiment 4 is classified as a medium-term experiment, contingent on platform availability, cost, and regulatory approval. It also raises unresolved questions under the Convention on Biological Diversity regarding the permissible scale and scope of research activities permissible under current international guidance.

Having explored near-term and medium-term experiments designed to characterise plume microphysics, the final proposed experiments move towards larger, longer-term scaling tests. These larger activities would represent operational-scale trials akin to a hypothetical 'day one' of deployment – for example, releasing approximately 1,000 tonnes of SO_2 from modified aircraft, such as the SAIL platform described in Smith and Wagner (2018). While this release volume would not be expected to produce a measurable global temperature response, it is intended to mimic the scale, logistics, and operational scale that a sustained deployment scenario involving 1 megatonne or more of SO_2 per year would entail (e.g., MacMartin et al., 2022). These experiments share key design features with the previously proposed Mesoscale Stratospheric Geoengineering Experiment (MSGX), which proposed releasing 500 tonnes of sulphates as a quantitative test for stratospheric mixing, aerosol heating impacts on dynamics, ozone chemistry, and radiative forcing (Keith et al., 2014; Haywood et al, 2022).

The main objective here is to quantify plume tracing and the macroscale effects of stratospheric SO_2 injection on radiative forcing, capturing both process-level dynamics (e.g., aerosol evolution, mixing) and signal-level effects (e.g., detectable radiative perturbation). The experiment is also conceptually comparable to studies of natural analogues (e.g., Kloss et al., 2022; Baron et al., 2023; Duchamp et al., 2023). These perturbations would represent some of the first cases where direct comparisons to global climate model outputs become conditionally feasible, as the injected SO_2 mass approaches the typical grid-cell scale of models such as CESM2-

WACCM6, GISS-E2.1G, and UKESM1.0 (Keith et al., 2014; Visioni et al., 2023b). However, such comparisons must be made cautiously given known limitations of global models – including coarse resolution, unresolved microphysics, and limitations in how atmospheric transport processes are represented. Interpreting these experiments meaningfully would require a process-model hierarchy: a coordinated use of models at different scales, each aligned with the resolution of available observations. This approach helps ensure that the processes observed in the field – such as plume evolution or cloud microphysics – can be accurately captured in models and meaningfully inform larger-scale climate simulations (Feingold et al., 2024). Fundamentally, these studies aim to isolate processes contributing to inter-model uncertainties (Bednarz et al., 2023), particularly in plume dispersion, SO_2 oxidation, and aerosol–radiation interactions.

Experiment 5 focuses on injections at high-latitude (>60° N/S) and lower stratospheric altitudes (~13 km), potentially achievable with existing aircraft such as the Boeing 777F freighters, capable of delivering payloads of over 100 tonnes (Smith, 2024; Duffey et al., 2025). While such strategies offer lower aerosol forcing efficiency compared to low-latitude approaches, they present a more immediate feasibility pathway, as existing jets could be modified and certified within a few years (Moriyama, 2017; Smith, 2024; Duffey et al., 2025). The estimated cost for this experiment would approach £100 million (e.g., Keith et al., 2014). Although low-altitude/high-latitude injection would be significantly less efficient for global cooling (approximately 35% of the forcing efficiency of low-latitude injections), it remains of strategic research interest due to the shorter time horizon for feasibility (Duffey et al., 2025).

Experiment 6 proposes injections at low latitudes (<30◦ N/S) and higher stratospheric altitudes (~20 km). This experiment would require the development of specialised, modified high-altitude aircraft such as SAIL (Smith and Wagner, 2018), a process that could take decades and incur development costs estimated at $100–1,000+ million when technology development costs are accounted for (e.g., McClellan et al., 2010, 2012). While technically more challenging and expensive, the low-latitude approach offers substantially greater forcing efficiency and remains essential for achieving certain climate outcomes – particularly those requiring effective cooling of the tropics or specific spatial temperature profiles (e.g., Duffey et al. 2025).

For both experiments 5 and 6, the plume would extend horizontally over 1,000 kilometres and persist for several months. Here, plume 'extent' refers to the region within which aerosol concentrations remain significantly elevated above background levels and can still support meaningful observational analysis. Detectability is expected to be high (Level II), significantly exceeding that of Experiments 1–4, particularly with respect to aerosol optical properties, radiative perturbations, and chemical interactions. Monitoring would require a combination of airborne in situ platforms, satellite remote sensing, and ground-based radiative observations, such as networks of pyranometers to detect changes in surface solar flux. More specifically, global, continuous satellite observations would be required to track aerosol dispersion, radiative effects, and ozone impacts (SAPEA, 2024). Existing instruments such as OMPS/LP, CALIOP, and SAGE III/ISS could provide vertical aerosol profiles but lack the precision to detect small aerosol optical depth. The recently launched ESA-JAXA's EarthCARE, equipped with lidar and radiometer, along with NASA's forthcoming PACE (with hyperspectral polarimeters), will enhance detection capabilities through multi-sensor synergy, particularly for aerosol-cloud interactions and radiative forcing (SAPEA, 2024). Observations of background conditions, including long-term stratospheric aerosol baseline datasets such as those compiled in Kremser et al. (2016) and methodologies applied in Russian experiments (Izrael et al., 2011), are also important experimental components for isolating experimental signals from natural variability.

By targeting deployment scales, these large experiments may assess stratospheric heating, ozone depletion risks, and radiative forcing efficiency. These efforts collectively aim to constrain model uncertainties in simulating stratospheric processes, such as divergent representations of aerosol microphysics, stratospheric heating, and ozone chemistry. By validating models against empirical data, following the example of volcanic eruption modelling studies (e.g., Kloss et al., 2022; Legras et al., 2022; Baron et al., 2023; Duchamp et al., 2023), the experiments seek to inform deployment scenarios with robust observational constraints.

As with Experiment 4, Experiments 5 and 6 would likely qualify as Annex I projects under the EIA Directive (2011, 2014), requiring a full EIA. Similarly, the scale of SO_2 use would trigger REACH Regulation (2006) registration obligations for the manufacturer or importer, with research teams required to comply with the associated Chemical Safety Report and exposure scenario. Other frameworks, such as the Industrial Emissions Directive (2010), may also become relevant depending on the delivery method, emission scale, and facility type involved. At this scale, a Strategic Environmental Assessment (SEA) may also be required at the policy or programme level, under the SEA Directive 2001/42/EC (2001), particularly if the experiment is part of a broader research agenda or public funding initiative with potential significant environmental effects. While SEA does not apply to individual projects, it can be triggered during the development of overarching strategies or programmes that precede specific experiments. Depending on the structure and scope of an initiative, SEA may also be relevant for smaller-scale activities.

Beyond EU law, these larger-scale experiments would engage broader international environmental law frameworks. A transboundary EIA may be required under the Espoo Convention (1991), depending on national implementation and the likelihood of significant cross-border environmental impacts. Monitoring and reporting obligations under the Convention on Long-Range Transboundary Air Pollution (LRTAP, 1979) would also be triggered. These experiments would also likely fall outside the scope of 'small-scale' scientific research under current Convention on Biological Diversity (CBD, 1992, 2008, 2010) guidance, raising serious governance concerns in the absence of prior assessment and robust oversight.

Overall, these experiments are classified as far-term due to their technical, financial, governance, and environmental complexities – with Experiment 5 offering a relatively earlier feasibility pathway compared to the more value-laden and technically challenging Experiment 6.

No.	Material Released	Est. Cost	Primary Scientific Goal	Technological Goal	Injection Method	Exp. Types	Detect.	Environmental Considerations
1	1 kg (SO_2); single release event	$0.5–1 M	Understand early-stage aerosol formation and plume formation	Test gas-phase release system and Nozzle performance	Balloon	Process	0	No environmental impact expected
2	>1 kg ($CaCO_3$, H_2SO_4)	$0.5–1 M	Characterise properties of different aerosols	Controlled release of solid/liquid aerosol	Balloon	Process	0	EIA screening (II); REACH N/A
3	<1 tonne (SO_2)	$1 M+	Characterise plume physics	Evaluate dispersion models	Balloon	Process	0	EIA screening (II); REACH N/A
4	1-100 tonnes (SO_2, H_2SO_4, $CaCO_3$)	$1–10 M	Characterise plume physics in different conditions	Develop real-world injection scenarios	Balloon, aircraft	Process and Signal	I	EIA (I); REACH+CSR; CBD; SEA
5	1,000 tonnes (SO_2)	≥$100 M	Quantify plume tracing, large-scale radiative effect	Deployment feasibility in the relatively low altitude polar stratosphere	Aircraft	Process and Signal	II	EIA (I); REACH+CSR; CBD; SEA; ESPOO; LRTAP; IED; AARHUS;
6	1,000 tonnes (SO_2)	$0.1–1 B	Quantify plume tracing, large-scale radiative effect	Deployment feasibility in the high-altitude tropical stratosphere	Modified aircraft	Process and Signal	II	EIA (I); REACH+CSR; CBD; SEA; ESPOO; LRTAP; IED; AARHUS;

Table 2. Scientifically valuable SAI experiments identified during the technical workshop. Each experiment is characterised by the quantity and type of material released, estimated cost, objectives, injection methods, detectability, and key environmental frameworks. Box colours represent the likely timeline of the experiments: early-phase (green), intermediate-phase(orange), and distant-phase (red). Summary of potentially applicable legal and regulatory frameworks: EIA Directive (2011, 2014) Annex I, or II activity; REACH Regulation (2006) and CSR – Chemical Safety Report; CBD (1992, 2008, 2010); SEA Directive (2001); Espoo Treaty (1991); LRTAP Convention (1979); IED (2010); Aarhus Convention (1998). See Section 3.3 for further information.

5 Marine Cloud Brightening (MCB)

5.1 Scientific basis and key uncertainties

MCB aims to enhance the albedo of marine clouds by spraying fine seawater aerosol into the marine cloud boundary layer. These particles act as cloud condensation nuclei (CCN), stimulating the formation of a larger number of smaller cloud droplets, thereby increasing cloud reflectivity through the Twomey Effect (Twomey, 1974, 1977). The particles must be large enough to activate and grow within the clouds, but small enough to avoid triggering precipitation (Latham et al., 2012). The resulting increase in droplet number can trigger adjustments in the amount of water in the cloud and how long the clouds last (and therefore cloud coverage). In the right conditions, these aerosol-cloud interactions can substantially enhance cloud albedo above natural levels. MCB is primarily targeted at persistent stratocumulus cloud decks in the North Pacific, South Pacific, and South Atlantic, which are typically clean, stable, and susceptible to modification via the addition of sea salt aerosol (Jones et al., 2009; Alterskjaer et al. 2013). Other low-lying marine clouds below ~2 km altitude may also be suitable for modification (Malavelle et al., 2017; Chen et al., 2024).

Key uncertainties surrounding MCB include adjustments to clouds following injection. In particular, cloud responses to increased droplet number and reduced droplet size, as well as operational feasibility, scalability and how climate impacts would be affected by different implementations of MCB (e.g., Eastham et al., 2025). Quantifying the radiative forcing associated with aerosol-cloud interactions remains challenging due to the wide range of spatial scales involved – from sub-micron particle processes to synoptic-scale cloud systems (e.g., Boucher et al., 2013; IPCC, 2023) – and the fact that the potential for cloud brightening depends on both the meteorological conditions that produce the cloud and the background aerosol environment. The effectiveness of seeding depends on the aerosol size distribution, and varies across cloud regimes (e.g., Hoffmann & Feingold, 2021). Additional uncertainties include whether continuous deployment in a given region or targeted seeding would optimise the cooling effect, and how the point-source nature of MCB influences aerosol transport and activation above the cloud base (e.g., Jenkins et al., 2013; P. Prabhakaran et al., 2024). Like SAI, deployment-scale MCB is also expected to alter atmospheric circulation patterns, with potential downstream impacts on regional weather, precipitation, and temperature distributions (e.g., Jones et al., 2009; Feingold et al., 2024; Wan et al., 2024). These effects could disproportionately affect different human and ecological systems, resulting in 'winners' and 'losers', raising potential equity and governance implications.

5.2 Categories of proposed MCB field experiments

Following the classification framework introduced in Section 3.2 and building on the lessons from past MCB experiments, this section outlines a series of proposed ship-based MCB field experiments.

Experiment 1 is a small-scale, process-level aerosol generation study involving the release of up to 10 kilograms of sea salt particles at sea in a single-release over several hours. The primary objectives are both technical and scientific: to develop and evaluate nozzle delivery systems capable of producing aerosol within a target diameter range (30–200 nm) at the desired rate (~10^{15}–10^{16} s^{-1}) and to assess the accuracy of near-field aerosol modelling (e.g., Salter, 2012; Wood, 2021). The experiment focuses on assessing the delivery of sea salt aerosol to the marine cloud base and evaluating the stability and reproducibility of the generated plume under a variety of conditions. The stated release mass for all MCB experiments is a ballpark estimate based on assumed nozzle flow rates and target particle size distributions. Because mass scales with the cube of particle diameter, this estimate is highly sensitive to the assumed aerosol size, which is here taken to be a representative mean diameter of ~100 nm (e.g., Salter et al., 2012; Wood, 2021; Wood et al., 2024).

This pilot study is comparable to the Phase 1 MCB experiment proposed by Keith et al. (2014), the GBR prototype experiments conducted between 2020 and 2022 (Hernandez-Jaramillo et al., 2023), and the early stages of the University of Washington (UoW) 2024 Alameda experiment, which tested engineered nozzle (CARI) arrays for producing consistent sea salt aerosol (Wood et al., 2024). Monitoring would rely on in situ instrumentation, including condensation particle counters (CPCs), optical and aerodynamic particle sizers (OPS/APS), aerosol mass spectrometers, and miniaturised electrical mobility particle sizers, to characterise particle size distribution, concentration, and composition (e.g., Russell et al., 2013; Hernandez-Jaramillo et al., 2023; Wood et al., 2024). Remote sending instruments (LiDAR) could also be used for plume tracking.

The estimated cost of the experiment is \$1–5 million, covering laboratory development, at-sea deployment, and the use of advanced in situ monitoring equipment (Keith et al., 2014). Detectability of the broader microphysical signal is expected to be very low (i.e., Level 0), as the aerosol plume would likely remain imperceptible relative to background variability and undetectable using remote sensing alone. However, the generated aerosol would be readily measurable in situ using dedicated instrumentation deployed as part of the experiment. The signal would be highly localised and short-lived (hours to days) due to the small quantity of material released and rapid atmospheric dispersion.

In the European Context, such an experiment would likely fall under Annex II of the EIA Directive (2011, 2014), requiring a screening procedure to determine whether a full EIA is necessary. While MCB is not explicitly stated, it may be analogised to categories such as chemical storage, waste disposal, or project extensions; see Section 4.1 for discussion of relevant Annex II items. Since the release involves filtered but chemically unmodified, naturally occurring sea salt aerosols, the activity would likely be exempt from registration under the REACH Regulation (2006), which excludes naturally occurring substances that are not chemically modified (Annex V, Section 8). While SO_2 used in SAI is also naturally occurring and reaches the stratosphere via volcanic eruptions, its deliberate injection for experimental purposes is more likely to trigger REACH registration. In contrast, sea salt in MCB is typically released in coastal or marine environments where such aerosols are naturally introduced to the atmosphere through wave action, likely reinforcing its exemption. However, depending on particle size and exposure scenarios, additional regulatory scrutiny may be triggered under nanoform-specific provisions surrounding toxicity concerns. Given the limited scale, low environmental risk, and absence of major regulatory or financial barriers, this is considered a near-term experiment. Similar trials are already underway (e.g., GBR experiments), reinforcing both the feasibility and plausibility of such experiments under current governance conditions.

Experiment 2 is a small-scale, process-level injection test involving the continuous release of up to 200 kilograms of sea salt aerosol over several hours during a single-plume, single-day experiment. Unlike Experiment 1, which focuses on nozzles, the primary scientific aim here is to investigate how aerosol size, number concentration, and composition influence localised cloud formation, mixing processes, and potentially albedo enhancement. Cloud responses to aerosols are strongly dependent on the injected aerosol size, concentration, and prevailing background conditions – including ambient aerosol loading and meteorological structure (e.g., Wood, 2021; Hoffman and Feingold, 2021). While these dependencies are often explored using cloud-resolving and large-eddy simulation models, such studies remain limited by uncertainties in near-field plume dynamics and aerosol-cloud interaction processes. This experiment is designed to generate in situ observations that can support and constrain model development and evaluation (e.g., Feingold et al., 2024).

This experiment also serves as an opportunity to assess spray generation system performance and reliability under sustained operation, while simultaneously conducting process-level studies on aerosol-cloud interactions below, in and above the cloud base. Given the increased quantity of material released relative to Experiment 1, detectability will likely increase (Level I), with potentially observable microphysical changes – such as shifts in droplet size distribution or cloud water content – within the experiment area. While the perturbation is expected to remain localised and short-lived (a few days), such changes could, in principle, be detected using in situ measurements from light aircraft or uncrewed aerial systems flying through and around the modified cloud region. Despite the higher volume, the experiment remains a near-term experiment, with estimated cost, feasibility, monitoring, and regulatory implications consistent with Experiment 1. No significant environmental or legal thresholds would be crossed at this scale.

Experiment 3 builds on the previous single-plume trial, extending it into a 4–6-week field campaign designed to establish a long-running single-point perturbation (i.e., perturbation from a single spray source). This longer timeframe allows for investigation of aerosol-meteorology co-variability, capturing a range of meteorological, cloud, and aerosol conditions that influence plume behaviour and detectability. The experiment would release up to 10 tonnes of sea salt aerosol and aims to characterise plume generation, dispersion, and cloud interactions under varying atmospheric conditions over time, including microphysical and radiative signals observable from in situ or airborne platforms. One key modelling uncertainty is that most climate models do not resolve the point-source nature of MCB aerosol releases and assume aerosol injection from the ocean surface (Eastham et al., 2025). While Experiments 1 and 2 focus on near-field plume evolution within the first tens of metres downwind of release, this longer-duration study would provide additional insights into processes such as coagulation, particle growth, and evaporative cooling further downwind, where aerosol properties evolve in transit to the cloud base (e.g., Stuart et al., 2013; Jenkins and Forster, 2013). The resulting data would be critical for improving cloud-resolving models and help bridge model hierarchies – from large-eddy simulations to regional and global models – by providing real-world constraints on aerosol-cloud interactions (e.g., particle size distributions, entrainment, and plume subsidence effects) under real-world variability (Hernandez-Jaramillo et al., 2023).

Experiment 3 is conceptually aligned with Phase 2–3 MCB experiments proposed by Keith et al. (2014), and builds on a wider body of observational and modelling work on aerosol-cloud interactions – including both controlled injection studies such as the E-PEACE campaign and GBR experiments (Russell et al., 2013; Hernandez-Jaramillo et al., 2024) and extensive non-perturbative research examining pollution aerosol effects on cloud properties (e.g., Kaufman et al., 2005; Chen et al., 2024). Monitoring at this scale would involve coordinated measurements from in situ airborne platforms, ship-based instruments, and satellite remote sensing. Detectability of the injected aerosol plume itself would be high using in situ instrumentation, and potentially observable with airborne or satellite remote sensing. However, the detectability or radiative responses above natural variability would likely be moderate (Level I), depending on atmospheric conditions and background aerosol loading. The estimated cost of this experiment, including vessel operation and instrumentation over 4–6 weeks, is expected to be in the $10–20 million range.

From a regulatory perspective, the experiment would likely be classified as an Annex II project under the EIA Directive (2011, 2014), triggering a screening procedure to determine whether a full EIA is required. Screening decisions take into account factors such as project scale and environmental sensitivity of the location, including proximity to ecologically sensitive sites. Accordingly, if conducted near designated areas such as the Natura 2000 network sites (Habitats Directive, 1992), a full EIA may be more likely. The use of unmodified sea salt remains exempt from registration under the REACH Regulation (2006). However, the scale and duration of the experiment may approach the outer bounds of what qualifies as 'small-scale' scientific research under the Convention on Biological Diversity (CBD, 1992, 2008, 2010). While precedents such as E-PEACE and the GBR prototype experiments were not formally assessed under CBD procedures, they may have avoided scrutiny due to their limited scope, scientific intent, and low perceived risk. These cases highlight the governance ambiguity in how CBD guidance applies to small-scale atmospheric experiments. Thorough prior environmental assessment would still be essential to ensure compliance with biodiversity and ecosystem protection frameworks. Although similar-scale experiments have been conducted in recent years (e.g., GBR experiments), the increased regulatory burden, higher costs, and logistical challenges associated with sustained multi-week operations render this a mid-term experiment. Moreover, the feasibility hinges less on technological readiness than on governance approval – as highlighted by the cancellation of the UoW Alameda experiment (Burns and Talati, 2025).

Experiment 4 expands the scope of the previous study by conducting a multiple-plume field campaign over 4–6 weeks, involving up to 10 separate point sources distributed across multiple vessels and releasing a cumulative 10–100 tonnes of sea salt aerosol. This is a process and signal-level experiment, with the primary scientific aim of understanding how dynamical responses to aerosol-cloud interactions affect plume-plume interactions and clouds under varied meteorological conditions. It would assess macrophysical cloud responses to aerosol perturbations as a function of injection timing and spatial distribution (P. Prabhakaran et al., 2024; Eastham et al., 2025), while also evaluating multi-platform coordination and delivery consistency.

Existing modelling frameworks often simulate either a single point source (e.g., Erfani et al., 2022; Chun et al., 2023) or assume a uniform aerosol perturbation across broad regions (e.g., Jones and Haywood, 2012; Alterskjaer et al., 2013). However, real-world implementation would likely involve a network of overlapping plumes from multiple mobile platforms (e.g., Wood, 2021), creating a heterogeneous and evolving aerosol environment. These plumes would modify the background aerosol concentration over time, influencing the microphysical response to subsequent injections and introducing non-linear effects that are poorly captured in current cloud-resolving models. This experiment offers an opportunity to improve understanding of aerosol–cloud–boundary layer interactions under a range of real-world conditions. The resulting observational data will directly inform high-resolution modelling – including computational fluid dynamics and large-eddy simulations – and support the development of more realistic parameterisations in climate models (Rasch et al., 2024). In turn, these process-level insights are essential for improving the representation of marine cloud brightening in global climate models.

The experiment shares design elements with the Mesoscale Ocean Cloud Experiment proposed by Latham et al. (2012) and Keith et al. (2014). Detectability is expected to be high (Level II) under suitable conditions, with coordinated in situ and satellite-based remote sensing potentially enabling attribution of seeding-induced changes in cloud microphysical properties – such as droplet number concentration and cloud albedo – and associated impacts on boundary layer structure. These signals may be observable over distances of up to 1,000 km downstream. Estimated costs range from $20–100 million, depending on the number of vessels and observational platforms deployed.

From a regulatory standpoint, the experiment would likely be classified as an Annex I Project under the EIA Directive (2011, 2014), triggering a mandatory full EIA. While sea salt is a naturally occurring and chemically unmodified substance, larger-scale, repeated atmospheric release from vessels may be interpreted by national authorities as functionally analogous to Annex I(6) activities involving chemical installations. The scale, duration, and operational complexity would likely exceed the threshold of 'small-scale' scientific research under the Convention on Biological Diversity (CBD, 1992, 2008, 2010), raising significant governance concerns. Due to the potential for transboundary atmospheric effects, including aerosol transport and cloud modification beyond the exclusive economic zone (EEZ), the experiment may also fall under the notification and consultation procedures of the Espoo Convention (1991). If the experiment is deemed environmentally harmful, additional legal instruments – such as the Environmental Liability Directive (2004), the international no-harm rule, and marine pollution conventions (e.g., UNCLOS, 1982) – may also become relevant. If embedded within a national or multi-national programme, a Strategic Environmental Assessment under EU law may also be required (SEA Directive, 2001); see Section 4.1 for discussion. Given the substantial financial, logistical, and regulatory requirements, Experiment 4 is considered a far-term experiment.

Experiment 5 represents a large-scale process and signal-level study, extending the scope of Experiment 4 through continuous aerosol injection for 6–12 months. The primary objective is to assess how sustained MCB affects cloud properties under a wide range of meteorological conditions, while refining sprayer efficiency and delivery in extended operational settings. Specifically, the experiment aims to determine whether seeding persistent stratocumulus cloud decks can consistently enhance cloud albedo by increasing droplet number concentration and cloud fraction, and whether these effects can extend cloud cover westward over distances exceeding 1,000 km (e.g., Yamaguchi et al., 2015; P. Prabhakaran et al., 2024). While the experiment will not generate a measurable regional-scale climate response – such as sea surface temperature change – it would enable observation of how the cloud albedo response varies with meteorological conditions, and therefore help constrain model uncertainties and refine the representation of aerosol-cloud-radiation interactions across different atmospheric states.

Given its duration, spatial extent, and sustained radiative forcing, the detectability of cloud property changes – such as cloud droplet number concentration, optical thickness, and albedo – is expected to be high (Level II). Monitoring would utilise a combination of in situ aircraft measurements, ship-based instrumentation, sub-orbital remote sensing, and satellite-based observations. While satellite platforms such as EUMETSAT's 3MI and EarthCARE mission offer improved vertical profiling of aerosol and clouds, they are insufficient alone for resolving near-field plume structure or validating aerosol delivery to the cloud base (SAPEA, 2024). In situ and sub-orbital data are critical for characterising aerosol size distributions, cloud droplet activation, and local meteorological conditions. These data are critical for both evaluating whether injected aerosols persist in targeted regions and successfully reach cloud base, but also for evaluating the conditions under which MCB is most effective. The latter includes identifying the optimal meteorological and aerosol conditions that govern the extent of cloud albedo enhancement. Clarifying this distinction is important, as successful delivery alone is insufficient; MCB's effectiveness depends on the prevailing atmospheric environment. Large-eddy simulation models will play a central role across all MCB experiments involving aerosol-cloud interactions, particularly at smaller scales (e.g., Experiments 2–3), where they can resolve key processes such as aerosol activation and droplet formation. These processes occur at scales that are sub-grid in global and regional climate models and are challenging to observe in situ, as they exceed the capabilities of current observational networks (SAPEA, 2024). Estimated costs exceed $100 million, reflecting the complexity and duration of operations. The regulatory and governance considerations are consistent with those outlined in Experiment 4, though the scale and duration further increase the likelihood of applying international legal frameworks. In addition to obligations related to transboundary environmental harm, broader international legal duties may also apply – including those arising under the Aarhus Convention (1998) on access to information and public participation, international human rights and Indigenous rights law (where applicable), and UNCLOS (1982) if activities occur or have impacts in the high seas. As a sustained trial designed to evaluate the efficacy of MCB under deployment-like conditions, this is classified as a far-term experiment.

The feasibility of these proposed MCB field experiments hinges on governance flexibility under frameworks like the Espoo Convention (1991) and CBD Decision X/33 (CBD, 2010). Barriers to implementation are exemplified by the cancellation of the UoW Alameda experiment due to public opposition (Burns & Talati, 2025). Crucially, successful completion of Experiments (1–4) would be a necessary precondition for undertaking Experiment 5, providing essential validation of delivery systems, plume behaviour, and aerosol-cloud interactions. This larger-scale experiment would also examine the relationship between sustained aerosol injection and changes in cloud microphysics, including potential localised shifts in drizzle formation due to altered droplet size distributions. However, detecting broader hydrological cycle response – such as changes in precipitation patterns – would require a longer-term, sustained albedo change over multiple years and is not expected within the scope of this experiment (Yamaguchi et al., 2025).

No.	Material Released	Est. Cost	Primary Scientific Goal	Technological Goal	Injection Method	Exp. Types	Detect.	Environmental Considerations
1	<10 kg (sea Salt) particles); (single day)	$1-5 M	Pilot study focusing on delivery mechanism	Develop sprayer nozzles and infrastructure	Ship-based sprayer device	Process	0	EIA screening (II)
2	≤200 kg (single day)	$1–5 M	Characterise how different particle properties affect mixing, cloud formation and brightness	Evaluate sprayer delivery and consistency	Ship-based sprayer device	Process	I	EIA screening (II)
3	≤10 tonnes (4-6 weeks)	$5–20 M	Characterise plume generation, persistence, and cloud impacts across varying atmospheric conditions	Test sprayer reliability and delivery consistency over extended periods in a range of conditions	Ship-based sprayer device	Process	I	EIA screening (II); SEA
4	10–100 tonnes; (4-6 weeks)	$20–100+ M	Characterise plume behaviour at a larger scale across varying environmental and meteorological conditions	Test multi-platform coordination and delivery consistency under varying conditions	Multiple ship-based sprayer device	Process and Signal	II	EIA (I); CBD, SEA, ESPOO, UNCLOS, CBD
5	≥100 tonnes; (6-12 months)	$100+ M	Assess the large-scale regional impact of sustained plume release	Optimise sprayer efficiency and delivery consistency for extended seeding	Ship-based sprayer device	Process and Signal	II	EIA (I); CBD, SEA, ESPOO, UNCLOS, CBD; AARHUS

Table 3. Scientifically valuable MCB experiments identified during the technical workshop. Each experiment is characterised by the quantity of material released (i.e., sea salt) and duration of release, estimated cost, objectives, injection methods, detectability, and key environmental frameworks. Box colours represent the likely immediacy of the experiments: early-phase (green), intermediate-phase (orange), and distant-phase (red). Summary of potentially applicable legal and regulatory frameworks: EIA Directive (2011, 2014) Annex I, or II activity; REACH Regulation (2006) and CSR – Chemical Safety Report; CBD (1992, 2008, 2010); SEA Directive (2001); Espoo Treaty (1991); LRTAP Convention (1979); UNCLOS (1982); IED (2010); Aarhus Convention (1998). See Section 3.3 for further information.

6 Cirrus and Mixed-Phase Cloud Thinning (CCT/MCT)

6.1 Scientific basis and key uncertainties

CCT aims to increase the outgoing longwave radiation by reducing the optical depth and lifetime of high-altitude cirrus clouds, which tend to have a net warming effect due to their efficient absorption of longwave radiation and minimal scattering of solar radiation (e.g., Mitchell and Finnegan, 2009; Hong et al., 2016; Lohmann and Gasparini, 2017; Gasparini et al., 2017). These clouds form in the upper troposphere, at temperatures below -38°C, and are composed of small ice crystals, typically 1–100 µm in diameter (Krämer et al., 2016, 2020). CCT involves injecting ice-nucleating particles (INPs) to trigger the formation of a smaller number of larger ice crystals, which sediment faster out of the atmosphere. This leads to shorter cloud lifetime and changes cloud properties so that they are less effective in trapping longwave radiation (Storelvmo et al., 2013).

MCT operates on a similar principle, but targets low altitude mixed-phase clouds at high latitude during the winter, particularly over the oceans, which are composed primarily of supercooled liquid droplets and also contain ice crystals, forming between 0 and -38°C (Korolev and Milbrandt, 2022; Villanueva et al., 2022). In some regions, such as the Arctic winter, MCT may also target low-altitude mixed-phase clouds. MCT introduces INPs such as silver iodide (AgI) to initiate freezing of supercooled droplets, leading to precipitation and thinning of the cloud layer (Gruber et al., 2019; Villanueva et al., 2022). While the physical regimes differ, both CCT and MCT share a similar ice-nucleation-based mechanism and aim to enhance the net outgoing longwave radiation flux. Due to their shared physical basis and common intended radiative effect, CCT and MCT are considered together in this study. However, the proposed experiments focus specifically on CCT for two reasons: first, only one modelling study on MCT exists to date (Villanueva et al., 2022), and its results remain highly uncertain; second, based on that study and basic physical reasoning, the radiative cooling potential of MCT appears more limited than that of CCT. While there is still uncertainty around CCT's effectiveness, several studies suggest a possible global cooling effect of over 1–2 W m^{-2} – equivalent to ~1–2° C of global mean cooling under certain scenarios (e.g., Gasparini et al., 2020; Liu and Shi, 2021).

Relative to SAI and MCB, the uncertainties are more fundamental for CCT and MCT as these concepts are less developed. Significant observational knowledge gaps exist for INPs processes in cirrus conditions and upper tropospheric water budgets, leading to assumptions in cirrus formation modelling (e.g., Penner et al., 2015; Gasparini et al., 2020; Eastham et al., 2025). Major uncertainties also exist regarding the optimal seeding material and the potential environmental consequences of large-scale deployment, or whether a sufficient number of cirrus and mixed-phase clouds are susceptible to seeding at a scale that would generate meaningful radiative forcing and measurable cooling (e.g., Gasparini & Lohmann, 2016; Gryspeerdt et al., 2018; Liu and Shi, 2018; Gasparini et al., 2020; Mitchell and Garnier, 2025). Global climate models struggle to adequately describe these processes, necessitating advanced parameterisations informed by laboratory studies and targeted field campaigns (SAPEA, 2024). As a result, the feasibility of CCT and MCT remains highly speculative.

6.2 Categories of proposed CCT/MCT field experiments

Following the classification framework introduced in Section 3.2, this section outlines a series of proposed CCT/MCT field experiments. The experiments developed in the workshop were primarily focused on CCT, reflecting both the scientific uncertainties and the relative difficulty of conducting controlled experiments in the upper troposphere. MCT was discussed more briefly and represented here mainly through reference to existing initiatives such as CLOUDLAB and the BeyondCLOUDLAB project (ETH Zurich, 2025), which can be considered as early-phase MCT activities. Nevertheless, because of their shared physical basis and common intended radiative effect, we consider both CCT and MCT here, while recognising that the proposed experiments focus more specifically on CCT.

Experiment 1 is a small-scale, process-level injection test involving the repeated release of up to 1 kilogram of INPs (e.g., AgI, bismuth triiodide (BiI_3), or mineral dust) by drone. The primary objective is to improve understanding of ice-nucleation pathways under ambient conditions, the microphysical and optical properties of seeded ice particles, and the resulting cloud responses to seeding (e.g., Eastham et al., 2025). These in situ dynamical and microphysical observations would support process-based representations of cloud evolution and improve the performance of cloud parameterisations in climate models (e.g., Penner et al., 2015; Gasparini et al., 2020; Tully et al., 2022). Crucially, emerging techniques now allow for in situ measurements of INPs, including at cirrus temperatures (Möhler et al., 2021). Such observations are essential both for characterising background INP conditions and for interpreting the effects of seeding under different natural aerosol regimes – helping to identify the conditions under which CCT may lead to desirable or undesirable outcomes. While limited in spatial and temporal scope, the experiment may also offer targeted insights into local updraft characteristics and upper tropospheric humidity near the area of injection – factors that play a critical role in cirrus cloud formation but remain difficult to observe directly (e.g., Krämer et al., 2016; 2020; Bramberger et al., 2022).

In addition to the scientific objectives, a key technological goal is to evaluate the delivery mechanism and aerosol dispersion efficiency. Feasibility is constrained by the need for drones capable of sustained high-altitude operations at low temperatures, with costs driven by airspace coordination and instrument redundancy. The experiment is comparable to the cirrus cloud seeding process experiment proposed by Keith et al. (2014) and recent CLOUDLAB project experiments, which have examined ice nucleation in mixed-phase clouds using AgI flares releasing ~20 grams of material each (Henneberger et al., 2023; Fuchs et al., 2025). While CLOUDLAB operates in low-level mixed-phase clouds over Switzerland, this experiment would be conducted in high-latitude cirrus clouds, which are thought to yield the maximum cooling effect (e.g., Storelvmo and Herger, 2014).

Monitoring would involve a mixture of ground-based LiDAR and radar, as well as balloon- or drone-based in situ instruments for Lagrangian sampling of aerosols and cloud particles. Techniques would include aerosol mass spectrometry and optical particle spectrometry of evaporated cloud residuals – the particles that remain after sublimating – to characterise their composition and size distribution (e.g., Cziczo et al., 2004; Ramelli et al., 2024; Fuchs et al., 2025). Monitoring of the aerosol plume would extend up to 10 km downwind of the release. Despite its scientific value, the microphysical and radiative impacts are expected to have very low remote detectability (Level 0) relative to natural variability, due to both the small injection mass and short aerosol residence times of 1–2 days.

Given the use of advanced but existing in situ instrumentation, estimated costs are in the range of $0.5–1 million. Environmental impact is expected to be negligible, and the experiment would likely be classified as an Annex II project under the EIA Directive (2011, 2014), with screening required only if conducted in environmentally sensitive areas. The use of AgI or BiI_3 in this experiment would not trigger REACH registration, provided the quantities fall below the relevant thresholds and qualify under the scientific research exemption. See Section 4.1 for discussion of relevant Annex II (EIA Directive, 2011, 2014) and REACH Registration (2006) information. Given its small scale, scientific value, and comparability to ongoing mixed-phase cloud experiments, Experiment 1 is classified as a near-term experiment, with a high degree of technical and regulatory feasibility.

Experiment 2 is a larger, mid-term, process-level injection test involving the release of up to 100 kg of INPs. The primary aim is to quantify cloud response and radiative effects from a relatively large-scale single release (or set of releases), evaluate model performance, demonstrate the feasibility of mesoscale aerosol delivery with consistent cloud perturbation, and detect the microphysical signal of overseeding. This scale of experiment would support investigations into heterogeneous ice nucleation in unperturbed cirrus and help identify overseeding thresholds, advancing understanding of where CCT may yield the most effective cooling benefit (e.g., Storelvmo and Herger, 2014; Gasparini et al., 2017; Gryspeerdt et al., 2018; Tully et al., 2023; Mitchell and Garnier, 2025).

Monitoring would include ground-based LiDAR and airborne in situ detectors to track seeding impacts within ~10–20 km downwind of release. While the direct perturbation from a single injection would likely dissipate within 1–2 days due to particle sedimentation and cloud evolution, it is expected to be detectable (Level I) in terms of changes to local ice crystal number concentration, cloud optical properties, and potentially cloud coverage within the local sampling region – exceeding the signal strength of smaller-scale trials. The experiment is classified as mid-term, given its current theoretical status, limited precedent (e.g., CLOUDLAB), and the lack of established protocols for releasing this quantity of material into the upper troposphere in high-latitude environments. Estimated costs are in the range of $1–10 million, primarily driven by aerosol delivery and monitoring logistics.

Although the total mass released would remain below one tonne, the use of chemically active substances such as or BiI_3 may invite greater regulatory scrutiny than inert substances like AgI or sea salt aerosol used in other cloud seeding or SRM activities. Under the EIA Directive (2011, 2014), the experiment would likely be classified as an Annex II project, requiring screening to determine whether a full EIA is necessary. While CCT/MCT is not explicitly listed, it may be analogised to Annex I categories such as chemical storage (10(f)), disposal of waste (10(h)), or extensions of existing projects (13); see Section 4.1 for discussion. Provided the substances are not manufactured or imported by the research team in quantities exceeding one tonne per annum, and the activity qualifies as scientific research and development under REACH Article 56, registration would not be required (REACH Regulation, 2006). However, due to the hazard classification of the materials involved, notification, risk assessment, or consultation with national authorities may still be required.

Experiment 3 is a far-term, process- and signal-level deployment-scale test involving the release of up to 100 tonnes of INPs. The aim is to assess cloud-radiation interactions and associated feedbacks across varying meteorological conditions, while demonstrating the operational consistency of large-scale seeding. The experiment would be sustained over an extended period of time (e.g., 6–12 months), with the seeding site situated adjacent to a control region for comparative analysis. Experiments of this scale could serve as a benchmark for process-based model evaluation and complement large-eddy model simulations used to study mixed-phase (Ahola et al., 2020) or cirrus microphysics and aerosol interactions (e.g., Sölch and Kärcher, 2011; Unterstrasser, 2014).

Extended observations would clarify the macroscale radiative effects of CCT, including the role of atmospheric ageing in altering aerosol optical properties relevant to cloud interactions, how overseeding influences cloud reflectivity, and the overall efficacy of the technique in producing a net cooling effect. At this scale, aircraft-based injection may be the optimal seeding method, offering additional opportunities to study in-contrail aerosol processing if aircraft are flown through seeded regions (Eastham et al., 2025). This is particularly relevant given substantial uncertainties surrounding INPs and cirrus-aerosol interactions (Kärcher, 2018; Lee et al., 2021). Monitoring would rely predominantly on remote sensing, with the signal likely detectable by lidar 100–1000 km downwind of release. Current radars (e.g., CloudSat) lack vertical resolution for multi-layered clouds, but the recently launched EarthCARE mission's radar-lidar suite (Mason et al., 2023) on board a polar orbiting satellite (Wehr et al., 2023) could address these gaps – particularly through lidar-based detection of optically thin cirrus, complemented by radar where appropriate (SAPEA, 2024). Detectability would be high (Level II), with clearly distinguishable changes in aerosol concentrations, cloud optical properties, and cloud extent relative to the unseeded control site. However, if the experiment was terminated, the atmospheric lifetime of the injected material would remain relatively short – on the order of 1–2 days – limiting the persistence of these signals. The estimated cost of such an experiment ranges from $10–100 million, reflecting the significant technical uncertainties and the requirement for sustained monitoring and coordination.

From a regulatory perspective, Experiment 3 would likely be classified as an Annex I project under the EIA Directive (2011, 2014), requiring a full EIA. While not explicitly listed, larger-scale and sustained atmospheric release of aerosols may be interpreted by national authorities as functionally analogous to AnnexI(6) activities involving chemical installations, particularly given the operational scale and specialised delivery infrastructure involved. The release of up to 100 tonnes of chemically active INPs would exceed the REACH registration threshold, requiring a formal registration with the ECHA and submission of a Chemical Safety Report assessing risks to human health and the environment (REACH Regulation, 2006).

While the experiment itself would not trigger a Strategic Environmental Assessment Directive, the broader research programme or policy under which it is developed may do so under the (SEA Directive, 2001), particularly given its potential scale, duration, and policy relevance; see Section 4.1 for discussion. Given the potential for transboundary atmospheric transport in the upper troposphere, the experiment would fall within the scope of the Espoo Convention (1991), requiring notification and consultation with affected countries via a transboundary EIA. Ongoing obligations under the Convention on Long-Range Transboundary Air Pollution (LRTAP, 1979) would also apply. Given the potential for transboundary atmospheric transport and effects, the experiment may also fall under the notification and consultation requirements of the Espoo Convention (1991). Additionally, public access to information, participation, international human rights and Indigenous rights law (dependent on location) would be governed by the Aarhus Convention (1998). Furthermore, this sustained, deployment-scale test would likely exceed the limits of 'small-scale scientific research' outlined under current guidance from the Convention on Biological Diversity (CBD, 1992, 2008, 2010). While no international legal framework currently exists that is specific to SRM, such an experiment would nonetheless be subject to a range of binding international and domestic legal obligations, depending on its characteristics and impacts. Consequently, Experiment 3 is considered a far-term experiment, given its high cost, operation and technical complexity, and considerable regulatory and governance challenges.

No.	Material Released	Est. Cost	Primary Scientific Goal	Technological Goal	Injection Method	Exp. Types	Detect.	Environmental Considerations
1	1–5 kg (BiI_3; AgI; Mineral Dust); multiple release events	\$0.5–1 M	Improve understanding of nucleation pathways, microphysical properties, and cloud response to seeding	Evaluate the delivery mechanism and aerosol distribution efficiency for small-scale perturbation	Drones	Process	0	EIA screening (II)
2	≤100 kg (BiI3; AgI; Mineral Dust); several release events likely	\$1–10 M	Quantify cloud response and radiative effects from larger-scale cloud thinning and assess model accuracy	Demonstrate consistent delivery and cloud perturbation at mesoscale	Drones	Process	I	EIA screening (II)
3	≤100 tonnes (BiI3; AgI; Mineral Dust)	\$10+ M	Assess cloud-radiation and other feedbacks from cirrus or mixed-phase cloud thinning across varying atmospheric and cloud conditions	Demonstrate operational consistency and efficiency of large-scale seeding over varying atmospheric conditions	Aircraft	Process and Signal	II	EIA (I); REACH+CSR; CBD; SEA; ESPOO; LRTAP; AARHUS

Table 4. Scientifically valuable CCT and MCT experiments identified during the technical workshop. Each experiment is characterised by the quantity and type of material released, estimated cost, objectives, injection methods, detectability, and key environmental frameworks. Box colours represent the likely immediacy of the experiments: near-phase (green), intermediate-phase (orange), and distant-phase (red). Summary of potentially applicable legal and regulatory frameworks: EIA Directive (2011, 2014) Annex I, or II activity; REACH Regulation (2006) and CSR – Chemical Safety Report; CBD (1992, 2008, 2010); SEA Directive (2001); Espoo Treaty (1991); LRTAP Convention (1979); Aarhus Convention (1998). See Section 3.3 for further information.

7 Procedural governance and design safeguards

Effective governance of SRM field experiments requires not only legal compliance but also procedural safeguards that allow experiments to be paused, altered, or terminated. Two complementary tools serve this role: *Exit ramps*, which specify conditions under which an experiment must stop, and *stage-gates*, which set criteria that must be met before research progresses. Taken together, these mechanisms help ensure that SRM field experiments remain accountable, adaptable, and responsive to emerging risks (e.g., MacNaghten and Owen, 2011; Pidgeon et al., 2013).

Responsible experimental design also requires attention to broader ethical commitments. The AGU Ethical Framework (2024) outlines five guiding commitments: responsible research, climate justice, inclusive participation, transparency, and informed governance. In practice, this means including Indigenous perspectives and ensuring intergenerational justice, since today's decision on SRM research may constrain future options (Hansen et al., 2025). Approaches such as '*two-eyed seeing*' have already been applied in sensitive research contexts, for example in sustainable development initiatives in Small Island Developing States (Roche et al., 2020) and Indigenous-led monitoring in the Canadian Arctic (SIKUTTIAQ, 2024).

Exit ramps and stage-gates can help operationalise these principles. Reversibility is one element: the ability to halt an experiment and return conditions to baseline with minimal lasting impact (Diamond et al., 2022). The Arctic Ice Project's decision to halt its sea ice albedo trials in response to toxicity concerns, public scepticism, and funding constraints (Turner, 2025) illustrates how evolving ethical and social considerations can prompt responsible closure. Similarly, the University of the Arctic's two-track review of Arctic interventions (Climate Interventions, 2025) demonstrates how inclusive processes combining Indigenous and academic perspectives can strengthen oversight in contested domains.

For SAI, exit ramps and stage gates would need to account for uncertainties in plume behaviour and detectability. For near-phase experiments (1–3), reversibility is high: releases are rapidly diluted and environmental impacts are negligible. Yet evidence from the Hunga Tonga-Hunga Ha'apai eruption shows that stratospheric plumes can remain coherent for extended periods due to limited turbulence (Legras et al., 2022), highlighting the need for contingency protocols such as operational shutdowns for instrument failure or unexpected plume advection, ideally under independent oversight, like the SCoPEx advisory model (e.g., Jinnah et al. 2014; Burns and Talati, 2025). For intermediate-phase experiments (4), reversibility extends over weeks as particles sediment (e.g., Vattioni et al., 2019), making early detection of anomalies more critical. For the larger-scale, distant-phase experiments (5–6), predefined triggers such as ecological impacts under the EIA Directive (2011, 2014) would be central, but detecting radiative anomalies is fundamentally limited by signal-to-noise constraints. For example, Seidel et al (2014) show that even a 0.002 increase in global albedo (~0.7 W m^{-2} forcing) would require up to a year of observations and a five-year baseline to achieve confident detection. This is over a thousand times larger than the radiative forcing expected from the largest-scale SAI experiments considered here (see Table 3, Experiment No. 6 in Keith et al., 2014).

For MCB, the central uncertainty is whether models can reliably predict how injected sea salt aerosol influences cloud properties. Near-phase experiments (1–2) act as stage-gates, testing model accuracy in aerosol activation and hygroscopic growth before progressing further (Russell et al., 2013). Operational pauses may be needed, for example in response to wind shifts or adverse forecasts, as outlined in the GBR experiments governance framework (Hernandez-Jaramillo et al., 2024). For intermediate- to distant-phase experiments (3–5), risks include overlapping plumes and unintended precipitation, which require coordinated multivessel operations and advanced monitoring. Current satellite sensors like MODIS and SEVIRI provide columnar cloud properties but lack vertical resolution to resolve aerosol activation processes (SAPEA, 2024), necessitating complementary in-situ measurements or remote sensing from the surface. Consequently, uncertainties around point-source aerosol transport and coagulation near injection sites underscore the need for smaller-scale studies, which serve as stage-gates to identify and resolve such issues before advancing to larger-scale experiments. Exit ramps at this stage could include particle overconcentration leading to precipitation anomalies, as observed in coastal MCB simulations (Hoffman and Feingold, 2021) or ecological breaches identified under the EIA Directive (2011, 2014). Precedents such as the UoW Alameda experiment show that sustained public opposition can also act as a practical termination trigger (Burns & Talati, 2025). More broadly, State Parties may invoke CBD Decision X/33 if experiments deviate from biodiversity safeguards.

For CCT and MCT, the short atmospheric lifetime of INPs – typically 1–2 days in mixed-phase cloud altitudes, and slightly longer at cirrus cloud altitudes – means that persistent cloud thinning is unrealistic (Tang et al., 2018). The main risk is overseeding, where excessive particle concentrations generate unnecessarily large impacts. Because such effects would be detectable in near real-time, stage-gates should require demonstration of modelled predictability at small scales before progressing, while exit ramps could mandate pauses in response to shifting atmospheric conditions, drone failures, or signs of overseeding. These operational safeguards should be aligned with existing biodiversity protections (CBD, 2010).

Taken together, these examples underscore the importance of incorporating exit ramps and stage-gates into SRM experiment design. These internal safeguards provide contingency planning at early phases, but they must also align with legal frameworks. Instruments such as the EIA Directive (2011, 2014), the SEA Directive (2001), and the Espoo Convention (1991) can provide procedural triggers for halting or reassessing projects where socio-economic or environmental risks emerge. However, these instruments were not designed with SRM in mind, and their applicability to climate experiments remains uncertain. If larger-scale experiments were to proceed, they would likely need to be preceded or accompanied by new SRM-specific governance arrangements. As experiments increase in scale and complexity, exit ramps and stage-gates therefore become both safeguards for individual projects and critical design principles for a responsible, and accountable research programme (e.g., MacNaghten and Owen, 2011; Pidgeon et al., 2013).

8 Discussion

8.1 Regulatory and Governance Implications of Plausible SRM Field Experiments

The proposed field experiments described in this study span several orders of magnitude in both quantity of material released and the geographic scale of their potential effects, as shown in Figure 2. While previous classifications of SRM experiments have focused on broad technical categories (i.e., laboratory studies, technology development, process studies, scaling tests, and climate response tests) (Keith et al., 2014), this study takes a different approach. We propose a set of illustrative field experiments, describe their characteristics, and assess them using parameters such as material mass, detectability, and governance exposure. On this basis, we classify experiments into early-, intermediate-, and distant-phase activities, and discuss their regulatory and governance implications.

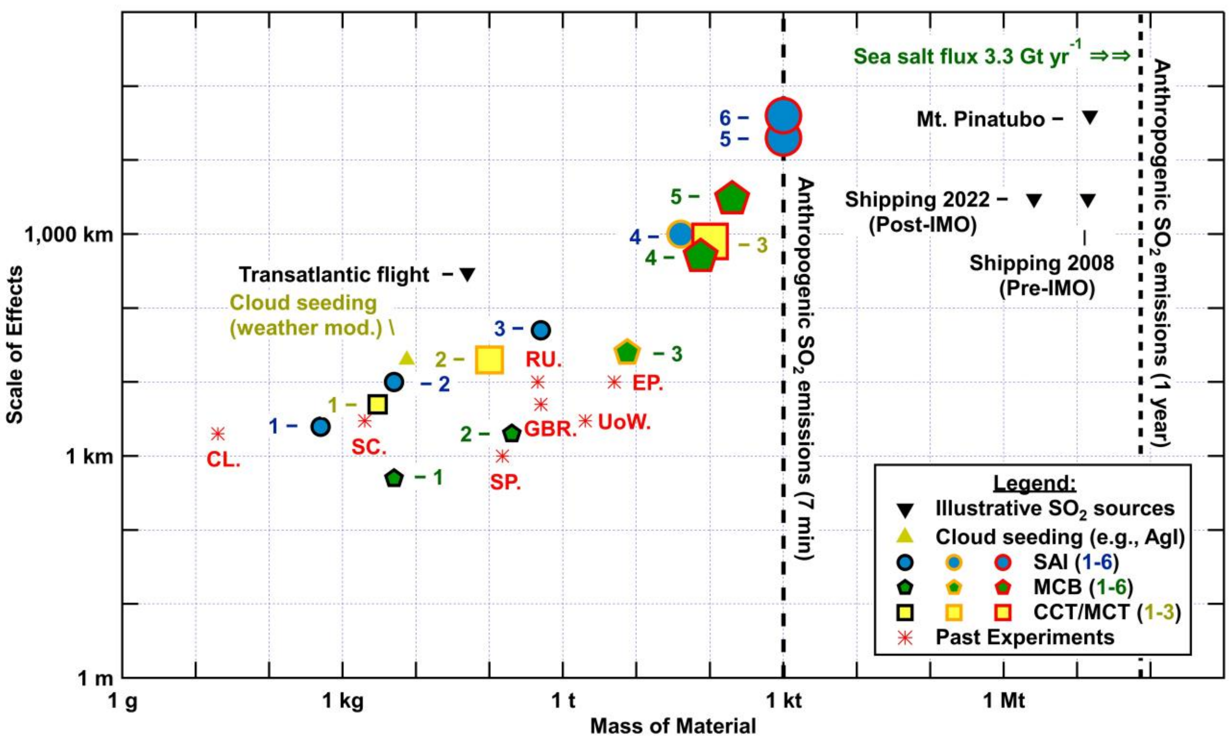

Figure 2. The logged scale of the scientifically valuable SRM experiments proposed in this study shows the scale of the proposed SRM field experiments compared to some relevant analogues and thresholds. Numbers correspond to the experiments described in Sections 3, 4, and 5, for SAI, MCB, and CCT/MCT, respectively. Symbol size and rim colour indicate characteristic experiment scale and timing: small with black rim (near-term), medium with orange rim (mid-term), and large with red rim (far-term). The gold icon is representative of the typical amount of material released in a cloud seeding event; the black icons represent the amount of SO_2 released by different phenomena: annual shipping emissions before and after the 2020 IMO ruling, the 1991 Mt. Pinatubo eruption, and anthropogenic emissions over approximately 7 minutes and

one year. Past SRM field experiments are included using approximate estimates of mass and downwind perturbation scales based on available literature, including for cancelled or proposed trials (CL. – CLOUDLAB; SC. – SCoPEx; SP. – SPICE; RU. – Russian Experiments; GBR. – Great Barrier Reef MCB; UoW. – Alameda MCB project; EP. – E-PEACE).

The precautionary principle remains central to debates over the legitimacy of SRM research. As Davies and Vinders (2025) argue, the application of precaution in Article 191(2) of the Treaty on the Functioning of the European Union (TEFU, 2016) requires a proportional, balanced appraisal of both the risks of action and inaction. Not researching SRM, particularly at small scales, may foreclose future response options or delay critical advances in risk governance. Importantly, this reading reframes precaution not as a barrier, but as a procedural framework for responsible experimentation. This balanced, procedural view of precaution is echoed in recent guidance from the Group of Chief Scientific Advisors to the European Commission (2024), which supports an EU-wide moratorium on SRM deployment while cautiously allowing for 'small-scale', controlled experimentation – although it does not explicitly address the potential risks associated with not pursuing knowledge that could be gained through well-designed field experiments. However, as interest in experimental SRM grows – including through the UK's £56.8 million *Exploring Climate Cooling* programme launched by the Advanced Research and Invention Agency (ARIA, 2024) – legal and policy definitions of 'small-scale' remain vague and inconsistently applied. The Convention on Biological Diversity (CBD, 1992, 2008, 2010) permits 'small-scale' scientific research under strict conditions but offers no clear threshold for scale or impact. Similarly, both the SAPEA report and ARIA programme support the use of small, controlled, and reversible outdoor experiments, but do not define 'small' experiments in quantitative or spatial terms. This ambiguity underscores the need for consistent, cross-cutting criteria to evaluate the acceptability of SRM experiments across different techniques and jurisdictions.

This study focuses on the European legal framework as a representative example, offering a structured lens through which to assess the regulatory implications of SRM field experiments. While not globally encompassing, this regional focus enables analysis that may inform governance approaches elsewhere as experimental scales increase. Within the EU, the Environmental Impact Assessment Directive (EIA Directive, 2011, 2014) and the REACH Regulation (2006) provide two of the most robust procedural frameworks for regulating SRM field experiments. However, a broader range of legal instruments may also apply depending on the nature and context of the activity – including those relating to public participation (e.g., Aarhus Convention, 1998), planning and permitting, liability, and environmental consent.

The typology developed in this study enables proposed experiments – across techniques including SAI, MCB, and CCT/MCT – to be mapped onto these frameworks, with many near-to-mid-term experiments (e.g., SAI Experiments 1–3, MCB Experiments 1–3, CCT/MCT Experiments 1–2) likely falling under Annex II of the EIA Directive (2011, 2014), requiring only screening. By contrast, mid-to-far-term experiments, such as SAI Experiment 4, would likely exceed key regulatory thresholds and invoke more intensive oversight mechanisms under EU and international law (see Section 4.1 and 6 for detailed discussion of Annex I and other applicable regimes). The most ambitious experiments considered here in this study (e.g., SAI Experiments

5–6, MCB Experiments 4–5, CCT/MCT Experiment 3), despite being orders of magnitude smaller than full-scale deployment, may nonetheless invoke more comprehensive regulatory oversight. This includes transboundary impact protocols such as the Espoo Convention (1991) and the LRTAP Convention (1979), and – where such experiments are embedded within broader policies or funding programmes – strategic assessment under the SEA Directive (2001). In addition to regulatory challenges, estimated costs scale accordingly with experimental size, technical complexity, and legal burdens, ranging from less than \$1 million for early-phase studies to more than \$100 million for extended, multisite trials.

A further consideration is the EU Taxonomy Regulation for Sustainable Activities (EU Taxonomy Regulation, 2020; Climate Delegated Act, 2021), which sets criteria for classifying economic activities as environmentally sustainable. Although SRM is not currently addressed, its core principles – (i) substantial contribution to environmental objectives, (ii) do no significant harm to other environmental objectives, and (iii) minimal social safeguards – align closely with the legal thresholds described above. The Taxonomy may therefore become increasingly important at the policy level, particularly in shaping eligibility for public or green finance, in parallel with strategic assessment processes such as those under the SEA Directive (2001).

8.2 Scale Considerations for Plausible SRM Field Experiments

Beyond regulatory detail, SRM field experiments raise broader issues of scale. Proposed activities span many orders of magnitude in size and detectability, yet often attract heightened scrutiny compared with natural or industrial analogues of much larger scale. As shown in Figure 2, many proposed experiments involve material releases far smaller than those associated with commonly tolerated activities: AgI in routine cloud seeding (1–10 kg), SO_2 emissions from a single transatlantic flight (<100 kg), or approximately seven minutes of global anthropogenic SO_2 emissions (~1,000 tonnes) (e.g., Forster et al., 2023; T. Prabhakaran et al., 2024; Hoesly et al., 2024; Hansen et al., 2025) (for scale estimates see Supplementary Information S1). Yet their classification as intentional geoengineering subjects them to added public scrutiny. This contrast underscores the importance of aligning governance with the physical scale and potential environmental signal of experiments, and also how they are socially and politically framed.

A final complexity lies in defining who qualifies as a stakeholder in atmospheric SRM experiments. In cases such as MCB Experiments 4–5, perturbations may occur thousands of kilometres downstream from the injection point, while in SAI Experiments 5–6 and CCT/MCT Experiment 3, particles released into the upper troposphere or stratosphere may disperse hemispherically. Although environmental regulations are typically grounded in national jurisdiction, the geographical reach of high-altitude experiments complicates assumptions about localised impact and consent, raising the need for adaptable international governance frameworks. One often-cited precedent is the Montreal Protocol, the only environmental treaty with universal ratification (Montreal Protocol, 1987). It has been proposed as a potential instrument and forum for SRM governance, given its existing institutional capacity and jurisdiction over ozone-depleting activities (e.g., Bhasin et al., 2022). Indeed, Decision XXXV/4 (Montreal Protocol, 2023) explicitly acknowledges the potential risks of SAI to stratospheric ozone and highlights the need for further scientific assessment and international collaboration.

While the Montreal Protocol does not currently govern SRM, its framework, scientific rigour, and political legitimacy make it a plausible foundation for future multilateral governance structures.

Our analysis highlights the importance of recognising a distinct intermediate phase of SRM field experiments. These activities occupy a grey zone: many orders of magnitude smaller than deployment or even climate-response trials (Keith et al., 2014), yet large enough to cross regulatory thresholds and raise governance sensitivities that early-phase, localised studies largely avoid. Current debates often hinge on a binary distinction between small-scale scientific research and large-scale experiments, with the latter frequently perceived as blurring the line between research and early deployment. However, our typology and Figure 3 show that experiments advance in discrete, non-sequential steps – a steep staircase rather than a slippery slope – with each phase introducing qualitatively new governance challenges. Like other experimental domains such as carbon capture and storage (Argüello and Bokareva, 2024), these expansions can be treated legally as changes or extensions of existing projects, meaning each step may trigger fresh review under instruments such as Annex II(13) of the EIA Directive (2011, 2014).

Intermediate-phase experiments illustrate this clearly. SAI Experiment 3 may exceed thresholds under the EIA Directive (2011, 2014), REACH Regulation (2006), CBD (1992, 2008, 2010), or SEA Directive (2001). MCB Experiment 3 could challenge the definition of 'small-scale', and as the UoW Alameda experiment shows (Burns and Talati, 2025), it may depend as much on social approval as on technical feasibility. CCT/MCT Experiment 2 remains largely theoretical, with limited precedent (e.g., CLOUDLAB) and no established protocols for releasing material into the upper troposphere at high latitudes. This is where governance challenges are most acute: legal triggers are likely to be activated, but consistent policy guidance and procedural norms remain underdeveloped. By explicitly identifying the intermediate phase, we move beyond the small-/large-scale binary and underscore the need for proportionate, context-specific governance at this stage.

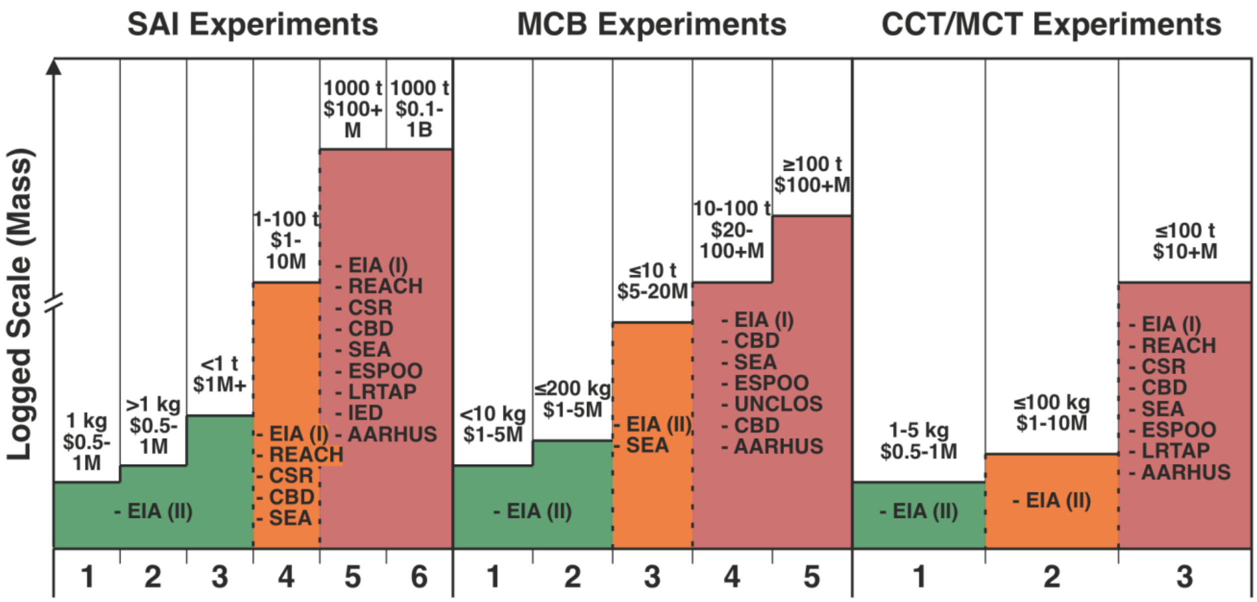

Figure 3. The staircase of phased SRM experiments illustrates the stepwise increase in applicable legal and governance frameworks. Regulatory mechanisms listed are indicative, not exhaustive, and their applicability varies by context, material, and jurisdiction. Box colours represent the likely immediacy of the experiments: near-phase (green), intermediate-phase (orange), and distant-phase (red). Summary of potentially applicable legal and regulatory frameworks: EIA Directive (2011, 2014) Annex I, or II activity; REACH Regulation (2006) and CSR – Chemical Safety Report; CBD (1992, 2008, 2010); SEA Directive (2001); Espoo Treaty (1991); LRTAP Convention (1979); UNCLOS (1982); IED (2010); Aarhus Convention (1998). See Section 3.3 and Supplementary Table S28 for descriptions of each framework/acronym.

9 Conclusion

This study outlines a diverse set of scientifically credible field experiments targeting the most technically and logistically feasible solar radiation modification (SRM) approaches: stratospheric aerosol injection (SAI), marine cloud brightening (MCB), and cirrus and mixed-phase cloud thinning (CCT/MCT). By presenting a cross-technique typology, developed through a technical expert-led workshop, we show how plausible field experiments span several orders of magnitude in scale and cost, yet remain distinct from operational deployment. Our analysis highlights that SRM field experiments advance in discrete phases, or steep steps, not along a smooth continuum or slippery slope. Early-phase activities are technically and legally feasible under existing rules. Distant-phase activities are technically plausible but would almost certainly trigger full legal review and require new multilateral governance frameworks. We note, however, that some of the thresholds identified here remain approximate and would benefit from further research to refine and quantify them.

The critical focus lies in the intermediate phase: experiments many orders of magnitude smaller than deployment, but large enough to cross regulatory thresholds and raise societal concerns. Our analysis shows that while most small-scale experiments to date have remained below regulatory thresholds, several intermediate-phase experiments would likely trigger environmental regulations within the EU and challenge prevailing interpretations of 'small-scale' under international frameworks such as the Convention on Biological Diversity. This underscores the need for proportionate, context-specific governance to provide consistent policy guidance on the scope, limits, and conditions under which SRM experiments may be responsibly undertaken.

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