[redacted]

---------- Forwarded message ---------
[redacted]
Date: Fri, 25 Apr 2025 at 09:13
Subject: Environmental Information Regulations request - Sun dimming the experiments
To: EIR requests at ARIA <info@aria.org.uk>

Dear ARIA Information Officer,

I am writing to request information under the Environmental Information Regulations 2004 (EIRs).

Please provide the following information relating to geoengineering, including but not limited to solar radiation management (SRM), stratospheric aerosol injection, marine cloud brightening, space-based reflectors, or any other research or proposals involving deliberate modification of Earth's climate through sun-dimming or related techniques.

I request:

1. Any documents, correspondence, research proposals, internal briefings, funding decisions, or commissioned work held by ARIA relating to:
    - Geoengineering
    - Solar radiation management (SRM)
    - Stratospheric aerosol injection
    - Marine cloud brightening
    - Space-based solar reflectors
    - Any other climate modification or solar dimming strategy
2. Details of any past, current or proposed funding awarded by ARIA to researchers, institutions, or consortia for work in these areas.
3. Any records of public consultation or engagement (or internal discussions about such consultation), including:
    - Public meetings, notices, surveys, or risk communication materials
    - Consideration of the need for public consultation under UK policy or international frameworks
    - Any documents reflecting concerns about the absence of public engagement on these topics
4. Any ethical assessments, environmental impact assessments, or internal risk reviews concerning the social or environmental consequences of geoengineering or solar dimming projects.
5. Records of meetings or correspondence with third parties (including government departments, international bodies, private organisations, or academic institutions) where these subjects were discussed.
6. Any legal or policy documents relating to the UK's obligations under international agreements (e.g. the Convention on Biological Diversity) regarding public transparency or consultation in relation to geoengineering.

If any part of this request exceeds statutory cost or time limits, please advise how it may be refined. I would prefer to receive the information electronically.

Kind regards,

[redacted]

[redacted]

Is info@aria.org.uk the wrong address for Environmental Information Regulations requests to Advanced Research and Invention Agency? If so, please contact us using this form:
https://www.whatdotheyknow.com/change_request/new?body=aria

Disclaimer: This message and any reply that you make will be published on the internet. Our privacy and copyright policies:
https://www.whatdotheyknow.com/help/officers

For more detailed guidance on safely disclosing information, read the latest advice from the ICO:
https://www.whatdotheyknow.com/help/ico-guidance-for-authorities
https://www.whatdotheyknow.com/help/ico-anonymisation-code

Please note that in some cases publication of requests and responses will be delayed.

If you find this service useful as an FOI officer, please ask your web manager to link to us from your organisation's FOI page.

Advanced Research + Invention Agency ARIA

[redacted]

[redacted]

9th May 2025

Dear [redacted]

Environmental Information Request

We are writing in response to your recent request for information to the Advanced Research + Invention Agency ("**ARIA**") dated 25 April 2025.

You may have seen our recent announcement in respect of the projects which we are funding as part of our Exploring Climate Cooling Programme. You can find out more information on the programme on our website. Any outdoor experiment will first be subject to an independent and publicly available environmental impact and legal assessment. Furthermore, outdoor experiments in the UK will take place at the earliest in late 2027, provided the appropriate community engagement work and the necessary assessments have taken place.

You can sign up for updates and follow us on X/Bluesky/LinkedIn.

Having carefully considered your email, we consider that the complexity and volume of the information you have requested means that it is necessary to extend the time it will take us to respond from 20 working days to 40 working days, as permitted under EIR. We will try to complete the review process as quickly as possible and endeavour to respond earlier if practicable.

In addition, having reviewed your initial request, we consider items 1, 2 and 5 of your request to be very wide in scope as currently drafted and we will need to conduct searches across a wide range of systems to locate and retrieve the information you are seeking. For example, your request for "any documents, correspondence, research proposals etc" on a wide range of specified topics will result in a high volume of documents to locate, retrieve and review. This may result in ARIA being unable to respond to your request due to the cost and burden on our resources as currently drafted.

Accordingly, and in light of the information which has already been published since your request, we would suggest that you limit the scope of sections 1,2 and 5 of your request to:

i) the 21 successful applications for funding (ie., not including the proposed applications which are not being progressed in any way), and

ii) finalised documentation detailing the research proposals - including project proposals, grant agreements and milestones,

whilst retaining sections 3, 4, and 6 of your request.

We look forward to hearing from you.

Yours faithfully,

[Digitally signed]

ARIA

[redacted]

[redacted]
Date: Fri, 9 May 2025 at 13:51
Subject: Re: Environmental Information Regulations request
To: Aria EIR <eir@aria.org.uk>

Dear Aria EIR,

Thank you for your helpful response. I'm happy to agree to the suggested narrowing of the request.

Yours sincerely,

[redacted]

-----Original Message-----

Dear [redacted]

Please find attached our response to your Information Request.
We look forward to hearing from you.
Kind regards,
ARIA

[redacted]

[redacted]

From: **Aria EIR** <eir@aria.org.uk>
Date: Mon, 23 Jun 2025 at 17:57
Subject: Information Request to ARIA
To: [redacted]

Dear [redacted]

Please find attached our letter in response to your Environmental Information Request, along with its annexes.

Kind regards,

ARIA

Advanced Research + Invention Agency ARIA

[redacted]

23 June 2025

Dear [redacted]

Environmental Information Regulations 2004 ("EIR") Request

We refer to your email dated 25 April 2025, in which you requested "*information relating to geoengineering, solar radiation management (SRM), stratospheric aerosol injection, marine cloud brightening, space-based reflectors, or any other research or proposals involving deliberate modification of Earth's climate through sun-dimming or related techniques*".

Upon our initial review of your request, we invited a clarification in relation to the scope in our email dated 9 May 2025. As a result, you agreed to narrow the scope of your request on 9 May 2025. We have set out each element of your amended request as a heading and included our response below to each.

Response to EIR request

1. **Any research proposals held by ARIA relating to the successful applications for funding under the Exploring Climate Cooling programme.**

A list of the applicants who will receive funding and an outline of their projects is contained at Annex 1 and is also available on our website - Exploring Climate Cooling Programme. We also enclose a copy of the initial proposals submitted by the applicants who will receive funding at Annex 2.

Please note that the proposals included at Annex 2 are only the initial research proposals provided by the applicants. In many cases they do not represent the final version of the project which ARIA is funding. When details of the projects have been finalised, information about their detailed scope will be available on our website as soon as possible following completion - Exploring Climate Cooling Programme. ARIA considers it important to disclose such information in the interests of transparency, and to prevent any misunderstanding as to what ARIA is funding that may be caused by reading the proposals out of context. For the avoidance of doubt, ARIA did not hold finalised funding agreements at the date of your request.

At the date of your request we were considering a further initial proposal that we did not consider would be likely to progress. However, the position has since changed and the details of that initial proposal will be made available on our website shortly. Please note that this initial proposal relates to modelling and does not relate to outdoor experiments.

We have provided the initial research proposals, subject to the following:

- In accordance with Regulation 12(3) of EIR, personal information relating to individuals has been redacted from the initial proposals provided in response to your EIR request.
- A very small amount of information has also been redacted from the initial proposals at Annex 2 pursuant to Regulations 12(5)(e) and 12(5)(f) of EIR. The applicants concerned consider that they would be adversely affected by the disclosure, which they were not legally compelled to provide. Specifically, the redacted information relates to confidential information which is commercially sensitive. In particular, the creators have developed methodology and critical research components which, if they were disclosed into the public domain, would compromise the intellectual property value and viability of the project, which in turn would affect the potential for academic publication and commercialisation. Insofar as the information relates to itemised costs, it would affect the creators' bargaining position for similar projects in the future if certain prices were known. This would cause the creators commercial detriment. ARIA would not otherwise be entitled to disclose the information, and the relevant applicants have not consented to such disclosure.
- We appreciate that the public interest is served by transparency, but it is important that applicants who seek to engage in research, can do so without the entire process being in the public domain. It would not be in the public interest to inhibit the free and frank descriptions provided by creators throughout this process and so impair ARIA's ability to allocate funding and make informed decisions on the basis of the initial proposals. Given the substantial amount of

material, which is now in the public domain, we consider that on balance, the public interest favours non-disclosure in these narrow instances.

2. **Details of any past, current or proposed funding awarded by ARIA to researchers, institutions, or consortia for work in these areas.**

Please see our answer under the heading "**1. Any research proposals, or funding decisions held by ARIA relating to the 21 successful applicants of the Exploring Climate Cooling programme**", above.

The research proposals at Annex 2 also provide more detail into the institutions who have been awarded funding and what the funded projects involve. The total funding awarded to each project is held and published on our website - Exploring Climate Cooling Programme.

3. **Any records of public consultation or engagement (or internal discussions about such consultation).**

Any outdoor experiments will first be subject to an independent and publicly available environmental impact and legal assessment, as well as a co-design process with local communities. No outdoor experiments have yet taken place. As such, no records are presently held of public consultation or engagement.

Additionally, the programme will fund projects exploring the broader societal aspects of this scientific research, including methods for public engagement, public attitudes to the field, and governance. Details of these projects can be found on our website - Exploring Climate Cooling Programme.

We note that your request also covered "*(or internal discussions about such consultation)*". In responding to "**1. Any research proposals, or funding decisions held by ARIA relating to the 21 successful applicants of the Exploring Climate Cooling programme"** above, ARIA estimates that it has spent 30 minutes per proposal locating the information and liaising with the relevant applicants to identify information covered by any exception. This amounts to 10.5 hours. In its efforts to respond to item 3 of your request, ARIA has used targeted keyword searches to identify internal correspondence where public consultations were discussed. ARIA spent 1.5 hours formulating and running the keyword searches. The targeted keyword searches produced a minimum of 381 hits which would need to be retrieved and processed. Applying a conservative estimate of 90 seconds per email to identify in-scope information and review whether information is exempt would involve a further 9.5 hours of work bringing the total time to reply to this request to 21.5 hours. Whilst we appreciate that the statutory limit of 18 hours does not directly apply to EIR, nonetheless, we consider that the cost to review the correspondence would be disproportionately burdensome solely on the ground of cost.

We appreciate that, whilst there is public interest in promoting transparency and accountability, ARIA is entitled to not incur disproportionate levels of cost relating to handling information requests. ARIA has already published a significant amount of information relating to the Exploring Climate Cooling programme. As ARIA is a small organisation, it must ensure its resources are protected and are not unnecessarily consumed. As such, on balance, we have had to refuse this aspect of your request.

4. **Any ethical assessments, environmental impact assessments or internal risk reviews concerning the social or environmental consequences of geoengineering or solar dimming projects.**

As noted in the response above, no outdoor experiments have taken place at the date of this letter. Therefore, no such assessments have yet taken place and this information is not held by ARIA. Any experiments funded by ARIA will only proceed if ARIA's stringent governance requirements are met in full. An environmental impact assessment will be performed and made publicly available before any experiment starts, and experiments will have to be developed through engagement with local communities. All funded experiments will be time-bound and limited in size, scale so their effects dissipate within 24 hours or are fully reversible.

5. **Records of meetings or correspondence with third parties (including government departments, international bodies, private organisations, or academic institutions) where the 21 successful proposals were discussed.**

We had hoped that the combination of the extension of time pursuant to Regulation 7(1) and the clarification on scope would enable us to provide a complete response. However, as set out below, the volume of material in scope of this part of your request remains very high, such that the time which would be taken to respond completely would, in our view, render the request manifestly unreasonable on the ground of the cost incurred. Accordingly, we are unable to provide a response to this part of your request.

As detailed above at "**3. Any records of public consultation or engagement (or internal discussions about such consultation)**", ARIA has spent approximately 10.5

hours responding to item 1 of your request. In its efforts to respond to item 5 of your request, ARIA has used targeted keyword searches to identify correspondence with third parties (including government departments, international bodies, private organisations, or academic institutions) where the successful proposals were discussed. ARIA spent 3 hours formulating and running the keyword searches (noting that this would also cover any correspondence with the successful applicants themselves). The targeted keyword searches produced a minimum of 7,787 hits which would need to be retrieved and processed. Applying a conservative estimate of 90 seconds per email to identify in-scope information and review whether information is exempt would involve a further 218 hours of work bringing the total time to reply to this request to 231.5 hours. Whilst we appreciate that the statutory limit of 18 hours does not directly apply to EIR, nonetheless, we consider that the cost to review the correspondence would be extremely burdensome solely on the ground of cost.

We appreciate once again that, whilst there is public interest in promoting transparency and accountability, ARIA is entitled to not incur disproportionate levels of cost relating to handling information requests. ARIA has already published a significant amount of information relating to the Exploring Climate Cooling programme. As ARIA is a small organisation, it must ensure its resources are protected and are not unnecessarily consumed. As such, on balance, we have had to refuse this aspect of your request.

By way of advice and assistance, we consider it should be possible to provide you with a response to this aspect of your request, by narrowing it to any correspondence between (i) ARIA and the Department for Science, Innovation and Technology (DSIT), (ii) ARIA and the Department for Energy Security and Net Zero (DESNZ), and (iii) ARIA and the Department for Environment, Food & Rural Affairs (DEFRA) from 15 April 2025 (the date on which project selection was completed) to 25 April 2025 (the date of your original request) relating to the successful applications for funding (i.e., not including the proposed applications which are not being progressed in any way). Please let us know if you would like ARIA to proceed with a request for this information.

6. **Any legal or policy documents relating to the UK's obligations under international agreements (e.g. the Convention on Biological Diversity) regarding public transparency or consultation in relation to geoengineering.**

ARIA does not hold legal or policy documents matching the description above. However, as detailed above, the specific protocols for transparency will be developed in consultation with the Oversight Committee and will include provisions regarding what the experiments involve, why the experiments are necessary, who is conducting the experiments and who might be impacted by the experiments. These details are also available at Annex 1.

Next steps

You can ask us to review our response. If you want us to carry out a review, please let us know within 40 working days by emailing eir@aria.org.uk.

If you are still dissatisfied after our internal review, you may complain to the Information Commissioner's Office (ICO) for further investigation who can be contacted at:

Information Commissioner's Office
Wycliffe House
Water Lane
Wilmslow, Cheshire
SK9 5AF

Yours sincerely,

ARIA

Enc.

Advanced Research + Invention Agency ARIA

Annex 1 Exploring Climate Cooling Programme

Annex 2 Initial Proposals

Annex 1 – Exploring Climate Cooling Programme

Opp space: Future Proofing Our Climate and Weather

Programme: Exploring Climate Cooling

Exploring Climate Cooling

Motivated by the possibility of encountering damaging climate tipping points, and backed by £56.8m, this programme aims to transparently explore – under rigorous oversight – whether any climate cooling approaches that have been proposed as potential options to delay or avert such tipping points could ever be feasible, scalable, and safe.

Our goal

To gather critical missing scientific data to better understand potential climate cooling approaches and their impacts.

By investing in careful research today, we can build the fundamental scientific knowledge to make wiser, better-informed decisions about our future.

Why this programme

Climate change could cause global temperatures to increase by several degrees by the end of the century, which could lead to climate tipping points – abrupt changes in the Earth system that, if crossed, could have devastating and essentially irreversible consequences.

We don't know when a tipping point might happen, or how long it would take to feel the effects if it did; significant uncertainties remain regarding the probability and potential impacts of any given tipping point.

is no substitute for decarbonisation, which is the only sustainable way to lower the chances of such tipping points and their effects from occurring.

If faced with a climate tipping point, our understanding of the options available remains limited. This knowledge gap has driven increased interest in whether there are approaches (also known as "climate interventions") that could actively reduce temperatures globally or regionally over shorter timescales.

Yet, in the absence of robust data, we currently have little understanding of whether such interventions are scientifically feasible, and what their full range of impacts might be. This programme aims to gather such data so that we can better understand these approaches and their potential effects.

How we're doing it

As a publicly funded, non-profit agency, our research efforts are grounded in transparency, responsible stewardship, and a commitment to broad public benefit.

The programme will explore more than one potential climate cooling approach in order to be comprehensive and to allow a range of potential options to be explored thoroughly and objectively.

Successful outcomes from this programme include assessing the feasibility and risks of these approaches, as well as setting the standard for how research in this field can be conducted responsibly and inclusively. The programme will not fund, and does not support, the deployment of any climate cooling approaches.

Read the programme thesis

Read the accessible version of the programme thesis

FAQs

Are you looking to deploy these technologies?

When will the outdoor experiments begin?

Are you funding activities to block the sun?

Are you funding activities that will release toxic materials into the atmosphere?

Are ARIA funding any outdoor experiments? What do they involve?

Governance

Oversight Committee

To ensure rigorous and responsible governance, this programme benefits from an independent Oversight Committee composed of international experts and chaired by Piers Forster. The committee advises ARIA leadership and plays a crucial role in scrutinising outdoor experiment plans, providing expert recommendations, and may advise against funding experiments unless certain modifications are made. While ultimate funding decisions rest with ARIA, the Oversight Committee has the authority to comment publicly and independently on experiment funding decisions and on other matters related to the programme and the wider field.

The committee focuses on:

- Supporting effective oversight of the programme's outdoor experiments and guiding transparent communication of findings.
- Shaping international norms and standards for the responsible governance of such experiments.
- Contributing constructively to the wider international discussion on potential governance mechanisms for climate cooling approaches.

Learn more about the Committee's remit, members, and work here.

Read the Oversight Committee's note on the announcement of the Exploring Climate Cooling projects, published 7 May 2025, here.

Funded projects

Our 21 funded research teams unite specialists across diverse disciplines – from atmospheric physics, chemistry, and climate modelling to chemical engineering, systems analysis, oceanography, and radiative transfer, alongside crucial expertise in governance and ethics – reflecting the programme's holistic approach. This group shares a deep commitment to objective research conducted transparently and responsibly, aiming to navigate the complex ethical dimensions and establish best practices within this field.

Projects will utilise a range of methodologies, including modelling, observations and monitoring, indoor testing and – where strictly necessary and in accordance with our oversight and governance principles – small scale, controlled outdoor experiments.

The programme will also fund projects exploring the broader societal aspects of this scientific research, including methods for public engagement, public attitudes to the field, and governance.

**All projects are subject to final contract negotiation.*

Strategic Foresight on Climate and Geopolitics: Toward governance of earth cooling approaches

Project Lead: Matthias Honegger, Centre for Future Generations

Award: £1.25 million over 15 months

Key Team Members and approximate budget breakdown: Matthias Honegger, Cynthia Scharf, Centre for Future Generations (£420k) | Trish Lavery, Australian National University Futures Hub (£150k) | Rafal Kierzenkowski, The Organisation for Economic Co-operation and Development (OECD) (£220k) | Danielle Young, University of Leeds (£460k)

Understanding if and how earth cooling approaches could be responsibly governed is critical in light of accelerating climate impacts and the risk of unwise use. This team will explore how these approaches could be responsibly governed at the global level in various future scenarios. They will start by outlining scenarios variously shaped by growing climate impacts, geopolitical challenges, the need for ongoing mitigation efforts, and the public's views. Their research will survey existing debates in both academic and policy circles, and discuss with policy makers and civil society organisations the risks, benefits and uncertainties they expect. Based on these scenarios, the project aims to develop foundational governance ideas to help ensure future decisions are socially and scientifically informed.

How to speak about climate cooling? Co-creating an engagement toolkit in the Arctic and the UK

Award: £360k over 45 months

Key Team Members and approximate budget breakdown: Ine Steenmans + Chloe Colomer, University College London (£314k) | Cody Skahan, University of Oxford (£23k) | Albert van Wijngaarden, University of Cambridge (£23k)

Emerging climate cooling approaches raise profound ethical and societal questions. Meaningful dialogues are therefore a prerequisite for ensuring that research on, and governance of, these approaches will be just and inclusive. This is especially true in the Arctic, a region where the voices of people who will be amongst the most impacted are often left out of conversations because of ongoing and historical power imbalances. This team will explore how people want to speak about climate cooling, and how they form and change their views over time. I[illegible] move beyond social opinion research by co-designing engagement programmes with local communities [illegible]ghtsholders across the Arctic and in three UK locations. Beyond the aim of empowering communities to participate more fully in governance, research, and decision-making around these new scientific approaches for cooling the earth, the learnings from these engagements will be captured in a practical, open access toolkit that can be reused for future engagement projects around climate cooling.

Evidence-based Assessments to Guide Perceptions, Governance, and Ethical Frameworks for South Asia: Comparing Marine Cloud Brightening strategies vis-à-vis carbon dioxide removal and mitigation efforts

Project Lead: Athar Hussain, COMSATS University

Award: £574k over 3 years

Key Team Members and approximate budget breakdown: Athar Hussain, COMSATS University (£532k) | Thomas Fischer, University of Liverpool (£5k) | Sajida Kousar, International Islamic University (£8k) | Hassaan Sipra, The Alliance for Just Deliberation on Solar Geoengineering (£9k) | Muhammad Mumtaz, Fatima Jinnah Women University (£20k)

This project provides a comparative analysis of potential climate response pathways – evaluating the implications in South Asia of marine cloud brightening (MCB) against carbon dioxide removal efforts and conventional mitigation approaches. This analysis combines climate science, governance research, direct stakeholder engagement, and policy analysis, deepening our understanding of potential climate cooling technologies within the ethical, governance and social context of South Asia. This work will empower decisionmakers and communities in South Asia to develop inclusive, effective, and locally-grounded climate action strategies.

PULSE Project: Public Understanding, Leadership, and Social Ethics in the governance of earth cooling technologies in communities impacted by volcanic activity in the Philippine context

Project Lead: Lorena Sabino, University of the Philippines Los Baños, College of Forestry and Natural Resources

Award: £135k over 2 years

Key Team Members and approximate budget breakdown: Lorena Sabino, University of the Philippines Los Baños, College of Forestry and Natural Resources (UPLB-CFNR)

Communities in the Philippines living near volcanoes possess invaluable, real-world experience with atmospheric changes that share similar atmospheric processes to potential climate interventions like stratospheric aerosol injection (SAI). This project centers their unique perspectives, exploring the understanding, ethical viewpoints, and governance concerns surrounding such technologies directly within these communities through focused research. Gathering these insights is crucial for grounding abstract global discussions about SAI in lived reality, and ensuring that the voices of those most vulnerable to both climate change and potential interventions are central to the conversation. This work will help develop ethical, inclusive governance frameworks and foster informed climate leadership in the most affected regions.

Ethics and Governance of Earth Cooling Research: from concepts to implementation

~~**Project Lead:** Ignacio Mastroleo, National Scientific and Technical Research Council (CONICET)~~

Award: £453k over 2 years

Key Team Members: Ignacio Mastroleo, Timothy Daly, María Inés Carabajal, National Scientific and Technical Research Council (CONICET) + Inter-American Institute for Global Change Research (IAI)

Researching potential Earth cooling approaches raises profound ethical and societal questions that require careful consideration and robust governance frameworks, especially ensuring diverse global perspectives are included. This project focuses on building research capacity and developing ethical frameworks, particularly within the Global South. This project will build a Latin America/Caribbean-UK research network that will address fundamental questions regarding the governance of these approaches, as well as nurturing a new community of experts in the region. The work will explore societal implications, ethics frameworks for managing trade-offs and the breadth of opinions, co-production of knowledge and regional governance, particularly in the Latin America/Caribbean context.

GRID-CC: Global to Regional Impacts Downscaling for Climate Cooling

Project Lead: Andy Parker, The Degrees Initiative

Award: £2m over 3 years

Key Team Members and approximate budget breakdown: Andy Parker, The Degrees Initiative (£940k) | Babatunde Abiodun, Christopher Lennard, University of Cape Town (£770k) | Daniele Visioni, Cornell University (£290k)

Understanding the potential regional implications of earth cooling approaches is crucial, particularly for communities in the Global South which may be disproportionately affected. Yet, research capacity is often concentrated elsewhere. This project directly addresses this capacity gap by empowering researchers in the South. Through computational work, this project will build an open-access repository of detailed Global . climate data that will enable researchers to develop more accurate modelling of the global and regional impacts of these approaches. This project will create new research tools and hold expert convenings to help ensure that researchers in these regions have the evidence base to support scientifically-robust dec[illegible]n-making surrounding potential Earth cooling strategies.

Ecological Impact Assessment of Earth Cooling Experiments in the Arctic (Eco-ICE)

Project Lead: Amanda Burson, British Antarctic Survey

Award: £4.8 million over 4 years

Key Team Members and approximate budget breakdown: Amanda Burson, Jeremy Wilkinson, Louise Sime, Kate Hendry, Rhiannon Jones, Clara Manno, Florence Atherden, Rachel Cavanagh, Simeon Hill, British Antarctic Survey (£4.3m) | Neven Fučkar, University of Oxford (£270k) | Dorothee Bakker, University of East Anglia (£140k) | David Schroeder, Danny Feltham, University of Reading (£130k)

Fragile polar ecosystems are critical to the global climate system, yet the potential ecological consequences of climate interventions at the poles are poorly understood. Through laboratory experiments and computer modelling, this project will provide an independent impact assessment of potential climate interventions in the Arctic marine environment. The team will develop physical, climate and ecosystem models with direct input from bespoke biogeochemical and biological laboratory experimentation. This independent assessment by experts in modelling and ecology is critical to provide a thorough and balanced evaluation of potential climate interventions in the Arctic. The project will provide best-practice guidance for the ecological risk assessment of future proposed interventions within the polar marine environment.

Investigating the Impacts of Earth Cooling Approaches on the Variability and Wet-Dry Spell Dynamics of the West African Monsoon

Project Lead: Amadou Coulibaly, Institut Polytechnique Rural de Formation et de Recherche Appliquée (IPR-IFRA)

Award: £257k over 3 years

Key Team Members and approximate budget breakdown: Amadou Coulibaly, Abdoulaye Ballo, Institut Polytechnique Rural de Formation et de Recherche Appliquée (IPR/IFRA) | Sabina Abba Omar, University of Cape Town (at no cost to the project)

The West African Monsoon is a vital climate system supporting agriculture and water resources for millions. Understanding how potential earth cooling approaches might affect this sensitive system is crucial for regional stability and food security. This research directly addresses this need by exploring potential impacts on critical rainfall patterns, including wet and dry spells. Using advanced climate models, observational data, and scenarios from established model intercomparison platforms (such as GeoMIP), the study aims to address critical gaps in understanding how earth cooling approaches might influence regional climate systems and how they might interact with existing climate vulnerabilities. The project will provide actionable insights, helping the region understand how these approaches might mitigate adverse climate impacts while avoiding unintended consequences.

Space Reflector Baseline Survey

Project Lead: Morgan Goodwin, Planetary Sunshade Foundation

Award: £400k over 15 months

Key Team Members and approximate budget breakdown: Morgan Goodwin, Jeff Overbeek, Planetary Sunshade Foundation (£275k) | Daniele Visioni, Cornell University (£85k) | Chantal Cappelletti, University of Nottingham (£40k) | Jeff Overbeek (via Ethos Space, at no cost to the project)

To make informed choices about potential climate cooling strategies, society needs a clear understanding of possible options, including less-studied approaches like space-based reflectors. This theoretical study brings together leading space engineering teams with expert climate modellers to address a critical knowledge gap. This team will model six different conceptual designs for space reflector approaches and then use climate models to simulate their potential climate impacts (including atmospheric dynamics, chemistry, and ocean/ice feedbacks). The goal is not to deploy this technology, but to provide an initial assessment of which concepts might warrant further study based on their modelled efficiency, scalability, and potential side effects, fostering collaboration between the space engineering and climate modelling communities.

Towards Robust and Unbiased validation of SAI Simulations (TRUSS)

Project Lead: Heri Kuswanto, Institut Teknologi Sepuluh Nopember, Indonesia

Award: £345k over 3 years

Key Team Members and approximate budget breakdown: Heri Kuswanto, Kartika Fithriasari, Institut Teknologi Sepuluh Nopember

Responsible decisions about potential climate interventions like Stratospheric Aerosol Injection (SAI) depend on reliable, trusted data about their potential impacts, but current computer simulations have uncertainties. This project aims to significantly improve the accuracy and trustworthiness of the simulation outputs of these approaches. Using advanced statistical and machine learning techniques applied to climate model outputs, this project looks to ensure that impact predictions, especially crucial regional assessments, are robust and unbiased. This foundational modelling work is vital for building confidence in the science and enabling genuinely informed decision-making by policymakers and the public.

Simulating the effects of earth cooling approaches on the Dynamics and Thermodynamics of Monsoon and Precipitation Extremes

Project Lead: Byju Pookkandy, The Energy and Resources Institute

Award: £140k over 2 years

[illegible]m Members and approximate budget breakdown: Byju Pookkandy, Kaagita Venkatramana, The Energy a[illegible]esources Institute (TERI)

Stable and predictable rainfall is fundamental to societies in both India and the UK, underpinning agriculture, water security, and protecting communities from floods and droughts. This research provides essential foresight into how proposals for earth cooling could potentially disrupt these vital precipitation patterns – affecting everything from the timing of seasonal rains in India to the intensity of precipitation extremes. By analysing detailed climate simulations from established model intercomparison platforms (such as GeoMIP) specifically designed for earth cooling scenarios, the study will pinpoint why these changes might occur, disentangling the complex factors driving rainfall. This computational analysis will deliver crucial, regionally-specific evidence to help evaluate the potential risks these approaches may pose to indispensable water cycles and resources.

De-risking cirrus modification

Project Lead: Sebastian Eastham, Imperial College London

Award: £3.6m over 36 months

Key Team Members and approximate budget breakdown: Sebastian Eastham, Marc Stettler, Ed Gryspeerdt, Imperial College London (£740k) | Benjamin Murray, University of Leeds (£1.4m) | Blaž Gasparini, University of Vienna (£310k) | Takemasa Miyoshi, RIKEN (£270k)

High-altitude cirrus clouds have an overall warming effect on our climate, but how their formation is influenced by existing atmospheric particles (like dust or soot) remains a significant uncertainty in climate science. Improving our understanding of these natural processes is crucial for refining climate models and for establishing the knowledge needed to assess the potential risks and benefits of any future proposals to deliberately modify cirrus clouds. This project aims to gather vital real-world data on these natural cirrus cloud processes and how they are already being affected by the presence of aircraft engine soot.

The team will use a combination of computer modelling and analysis of existing satellite data. They will also conduct observational flights using research aircraft to directly measure how particles already present in the atmosphere, and the additional effects of aircraft engine soot, currently affect cirrus cloud properties. By observing and measuring these existing atmospheric processes, the team are looking to improve our fundamental understanding of cirrus cloud formation, providing essential baseline knowledge to help us understand if deliberately thinning cirrus clouds could ever offer a safe, predictable mechanism for cooling.

Ice-Nucleating Particles in the Upper Troposphere: Advancing Cirrus Contrc' ~nd Experimental Science Strength "INPUT:ACCESS"

Project lead: Thomas Whale, University of Leeds

Award: £1.3m over 36 months

Key Team Members and approximate budget breakdown: Thomas Whale, University of Leeds (£770k) | Alexandre Baron, Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado (£475k) | Joshua Schwarz, National Oceanic and Atmospheric Administration (NOAA) Chemical Sciences Laboratory (at no cost to the project) | Sebastian Eastham, Imperial College London (£63k)

Cirrus clouds have a significant impact on Earth's temperature, yet prediction and modelling of their formation is challenging and constitutes a key uncertainty in climate models and projections. Lack of knowledge of the concentration and nature of the tiny particles suspended in the atmosphere on which cirrus clouds form, known as ice nucleating particles (INPs), is a major contributor to this uncertainty. This project aims to address this knowledge gap by developing new methods to observe and analyse these naturally occurring INPs high in the atmosphere.

Operating out of Colorado, USA, the team will develop and operate a specialised balloon-borne collector designed to gather naturally present INPs from the upper troposphere where cirrus clouds form. These collected samples will then be brought back for detailed laboratory analysis in the UK. This focused monitoring and observation work will generate critical information about the types and concentrations of particles involved in natural cirrus formation. This data is essential for improving the accuracy of climate projections and enhancing our ability to monitor natural atmospheric processes, providing a crucial baseline for climate science.

StratoGuard - Global Monitoring of Climate Engineering using Micro High-Altitude Balloons

Project lead: Steve Tate, Voltitude

Award: £600k over 36 months

Key Team Members and approximate budget breakdown: Steve Tate, Richard Nash, Paul Stevens, Voltitude Ltd (£575k) | Chris Stopford, University of Hertfordshire (£25k)

Improving our ability to monitor the Earth's climate, particularly in remote regions, and developing the tools needed to safely observe and measure potential future climate interventions are crucial needs for both climate science and the responsible assessment of climate cooling approaches.

Project StratoGuard focuses on creating low-cost, lightweight micro-balloons (under 4kg, <5m diameter) equipped with sensors, capable of navigating the stratosphere above 55,000 feet for up to 30 days. This capability would support affordable, detailed, and sustained climate data collection across the globe. It would also enhance the capability for sophisticated and cost-effective monitoring of any future outdoor climate intervention activities. With test launches planned from 2026 and potential global launch capabilities (subject to local approvals), this project seeks to miniaturise core technologies for global sensing using small, safe balloons, operating in full compliance with existing regulatory frameworks. The overarching goal is to provide a vital new · comprehensive climate observation, as well as providing a monitoring capability essential for re, onsible research and assessment of potential climate interventions.

Monitoring Aerosol Climate Engineering (MACE)

Project lead: Matt Watson, University of Bristol

Award: £4.3m over 48 months

Key Team Members and approximate budget breakdown: Matt Watson, Arthur Richards, Tom Richardson, University of Bristol

Natural events, particularly volcanic eruptions, release tiny particles (aerosols) into the atmosphere and offer invaluable real-world opportunities to study processes relevant to climate science and potential climate interventions, such as how aerosols affect clouds and the Earth's energy balance. However, safely and rapidly collecting data from these events is challenging. This project aims to address this by developing advanced, automated drone technology specifically designed for observing and analysing emissions from active volcanoes.

The team will design, build, and test lightweight, easily operationalised drones capable of flying safely at high altitudes (10 km). Following initial test flights in the first year, the plan is to use the drones to study emissions from selected, regularly erupting volcanoes – Volcán de Fuego (Guatemala), Soufrière Hills (Montserrat), and Lascar (Chile). The team have flown in all three countries in the past under suitable permits. By analysing these natural volcanic emissions in situ, the research will investigate how tiny cloud droplets form and how natural aerosol layers affect radiation. A key goal is to develop a rapid-response capability using these drones, enabling the scientific community to safely gather crucial data from future significant volcanic eruptions, thereby improving our understanding of natural climate processes.

Re-Thickening Arctic Sea Ice (RASi)

F[illegible]t Lead: Shaun Fitzgerald, Centre for Climate Repair

Award: £9.9m over 42 months

Key Team Members and approximate budget breakdown: Shaun Fitzgerald, University of Cambridge (£1.4m) | Geoff Evatt, University of Manchester (£0.63m) | Michel Tsamados, University College London (£0.6) | Einar Ólason, Nansen Environmental and Remote Sensing Center (£0.4m) | Andrea Ceccolini, Real Ice (£3.5m) | Fonger Ypma, Arctic Reflections (£3.3m) | Edward Blanchard, University of Washington (£90k) | Steven Desch, Arizona State University (~£10k travel costs funded from Real Ice's share)

The Arctic is warming much faster than the global average, leading to dangerous sea ice loss with far-reaching consequences. This project investigates whether deliberately thickening sea ice during winter could be a viable way to slow summer melt, reduce Arctic warming, and mitigate further ice loss. The research aims to provide critical data on the feasibility, scalability, potential ecological impacts, and overall effectiveness of this approach, which involves accelerating natural freezing processes using seawater from underneath the ice.

Researchers will conduct controlled, small-scale experiments in Canada across three winter seasons (2025-26 to 2027-28). The process involves pumping seawater from beneath existing ice and spreading it on top, where the frigid air freezes it quickly, creating thicker ice patches. Over the course of the project (and if the early experiments suggest the approach is ecologically sound), later experiments will aim to cover areas up to 1 km^2 per experiment site. The key questions are whether this thicker ice lasts longer into the summer, how it might affect ice movement, and what the local ecological impacts are. These experiments will be conducted in close collaboration with local communities and under ARIA's stringent governance framework, prioritising safety and environmental monitoring. The goal is to gather essential real-world data to rigorously assess if this intervention warrants further consideration.

Marine Cloud Brightening in a Complex World

Project lead: Daniel Harrison, Southern Cross University

Award: £1m (potentially rising to £5m with matched funding) over 5 years

This project investigates Marine Cloud Brightening (MCB), a potential way to cool specific areas by enhancing cloud reflectivity using a spray of seawater. Building on their experience conducting previous small-scale outdoor experiments in partnership with local communities around the Great Barrier Reef, Australia, this team seeks to deepen our understanding of MCB. While the concept could potentially protect vulnerable ecosystems like coral reefs from heat stress, its real-world effectiveness remains uncertain. This research aims to address this critical knowledge gap by investigating the complex atmospheric dynamics and microphysical processes involved, moving beyond basic principles to assess if, and how, MCB could work safely and effectively.

The research combines advanced computer modelling with the development and indoor testing of sea salt sprayers. If these findings suggest promise, and subject to meeting ARIA's governance requirements, the project plans to conduct small-scale, controlled outdoor experiments over the Great Barrier Reef in years 3 and 4 of the 5-year project. These outdoor experiments are strictly contingent on prior results, rigorous independent safety reviews, regulatory approvals, and continued co-design and partnership with Traditional Owner groups, local stakeholders, and the broader community of the Great Barrier Reef Marine Park. If approved, these controlled experiments could involve brightening clouds within areas up to 10 km × 10 km, with seawater spraying taking place over 5-6 weeks, for 6 to 8 hours per day. All activities will fully adhere to ARIA's robust governance framework, emphasising transparency, environmental risk minimisation by design, and community engagement. The overall goal is to generate crucial real-world data to determine the effectiveness and risks of MCB, and its potential for protecting vulnerable ecosystems at a regional scale.

A REsponsible innovation Framework for assessing noveL spray tEChnology research To examine local albedo changes from marine brightening and its multi-scale impacts (REFLECT)

Project Lead: Hugh Coe, University of Manchester

Award: £6.1m over 3 years (initial phase)

Key Team Members and approximate budget breakdown: Hugh Coe, Robert Bellamy, University of Manchester (£2.1m) | Shaun Fitzgerald, University of Cambridge (£1.8m) | Dan Mace, Archipelago Technology (£0.9m) | James Haywood, University of Exeter (£1.1m) | Lindsay Bennett, University of Leeds (£22k) | Sami Romakkaniemi, Finnish Meteorological Institute* (£160k)

*Finnish Meteorological Institute are contributing to the modelling exercises in this proposal and are not involved in any outdoor experimentation

Marine Cloud Brightening (MCB) and Marine Sky Brightening (MSB) – ideas for cooling the Earth by increasing the reflectivity of clouds or the sky using tiny droplets of seawater – depend critically on having the right technology to generate sprays of these droplets effectively. However, the technical feasibility and optimal methods for doing so are poorly understood. This project aims to address this gap by developing and responsibly testing the necessary spray technologies to determine if these approaches could be viable.

Over an initial three-year period, the team will undertake computer modelling, build bespoke sprayers based on the modelling results, and conduct indoor tests. A crucial part of this phase involves beginning collaborative engagement with local communities to co-design potential future outdoor experiments. Any small-scale, controlled outdoor experiments to test sprayer performance would only occur after this initial phase, contingent on further funding, successful co-design demonstrating community engagement and support, and strict adherence to ARIA's safety and governance protocols. These potential tests are expected to be undertaken in the UK (location to be determined). Initial tests, if approved, would be very limited, lasting only a few seconds and creating small plumes of seawater spray just a few hundred metres in size. Only if these initial tests prove successful and safe might later experiments explore brightening larger cloud areas, potentially up to 10 km long and a few hundred metres wide. These tests are inherently benign, replicating natural processes that generate sea spray over the ocean developing spray systems such as those that are already employed to cool crowds with fine mists of water and dampen construction sites to suppress pollution. The overall goal is to establish a robust and responsible experimental framework to assess the technical feasibility and optimal methods for MCB and MSB.

BrightSpark – Cloud brightening with electric charge

Project Lead: Giles Harrison, University of Reading

Award: £2m over 36 months

Key Team Members and approximate budget breakdown: Giles Harrison, Maarten Ambaum, Keri Nicoll, University of Reading (£1.75m) | John Mooney, Menapia Ltd (£170k)

[illegible] ways to influence cloud reflectivity is a key research challenge. This project investigates using controlled electric charge, a natural atmospheric phenomenon, to influence water droplets in fogs and clouds as an alternative to spraying seawater. The research aims to determine if carefully managed electrical charges

could offer a safe and effective method for enhancing cloud reflectivity.

The team will investigate the fundamental science of how artificial charge release affects cloud and fog droplets. The project includes plans for very small-scale (on the order of 100 m × 100 m), controlled outdoor experiments in the UK during the third year of the project. These experiments are strictly conditional on demonstrating appropriate levels of community engagement, co-design, and adherence to ARIA's rigorous safety and ethical governance framework. The core goal is to gather foundational data to assess if this method is viable and safe enough to warrant further investigation.

Natural Materials for Stratospheric Aerosol Injection

Project Lead: Hugh Hunt, University of Cambridge

Award: £5.5m over 36 months

Key Team Members and approximate budget breakdown: Hugh Hunt, University of Cambridge (£2.5m) | Frank Keutsch, Harvard University (£2.5m) | Sebastian Eastham, Imperial College London (£0.54m)

Stratospheric Aerosol Injection (SAI) is a widely discussed potential climate cooling method, but the most commonly proposed materials (sulfates) carry significant hazards in this context, including potential ozone depletion and toxicity. Addressing whether safer, alternative materials could ever be feasible or effective for SAI is therefore a critical, unanswered scientific question. This project will undertake fundamental research to investigate the properties and behaviour of innovative, non-toxic, non-sulfate materials in a very controlled manner.

The research combines laboratory studies and computational modelling with unique and contained material exposure experiments. In these experiments, tiny (milligram) amounts of materials that occur in natural mineral dust (such as limestone, dolomite, or corundum) will be secured onto supports inside the gondolas of specially adapted weather balloons. These balloons are likely to be launched from sites in the USA and/or the UK; the specific site will be determined in line with ARIA's requirements for community engagement. The balloons will carry the samples into the stratosphere for exposure periods ranging from hours to weeks before performing controlled descent for recovery. **Crucially, no materials will be released into the stratosphere**; this approach effectively brings the stratosphere to the samples. Studying the recovered samples will reveal how stratospheric conditions affect their properties over time. This foundational science is essential to advance understanding of the potential impacts of SAI and for determining if less harmful alternatives to sulfates might exist (and if they might warrant further study in the context of SAI).

Annex 2 – Initial Proposals

Please note the documents which follow in this Annex are the initial proposals which were submitted by applicants to ARIA. However, the proposals have been subject to further discussion and the finalised scope of what will be funded may differ from the initial submission. Final agreed scopes of work will be published in due course.

Index to Research Proposals

De-risking cirrus modification

[redacted]

This project will evaluate whether it is possible to intentionally modify the properties of cirrus clouds to achieve a useful (>100 mW/m^2) global cooling effect. This includes understanding (1) **how much susceptible cloud exists**, (2) **whether we can increase outgoing longwave radiation (OLR)**, and **(3) whether we can predict the circumstances under which this can be done**. We will address these questions in a two-phase experiment, starting with (P1) data mining followed by (P2) an aircraft campaign to resolve where and when cirrus modification can produce beneficial effects. We also have the ambition for a Phase 3 with dedicated cloud seeding trials, pending success of P1 & 2. The phased nature of this work is a safe and cost-effective option to produce a measurable advance towards a near-term, practical option for regional and global cooling, evaluation of which is currently unable to proceed through modelling alone[1].

1 Cirrus clouds: a potential climate dial

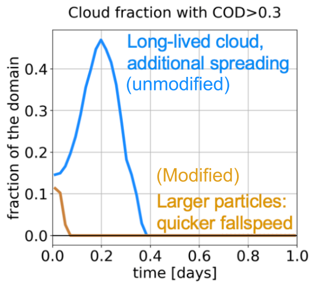

Figure 1. Homogeneous (blue) and heterogeneous (brown) cirrus lifecycles in an idealized LES model (Gasparini et al., in prep).

Globally, cirrus clouds lead to a warming effect of ~5 W/m^2. Inadvertent cirrus cloud modification by aircraft, where cirrus-forming regions are "overseeded" by ice nucleating particles (INPs) resulting in long-lived warming clouds, already causes[2] a radiative forcing of ~100 mW/m^2. By instead "underseeding" the areas, upper-tropospheric water could be made to form large crystals which rapidly sediment and sublimate – pre-empting an impending cirrus cloud (Figure 1)[3,4]. Such cirrus cloud modification (CCM) has a maximum possible global benefit[3] of 2-3 W/m^2. It is attractive from a safety and controllability perspective, given its limited temporal and spatial scope and that aircraft already modify cirrus daily; furthermore the recent CLOUDLAB project showed that it's possible to modify (less widespread and less warming) mixed-phase clouds deliberately[5], as industrial emissions do inadvertently[6]. The true efficacy of CCM is however uncertain, with some models showing negligible benefit[7] and a key uncertainty being the challenging-to-measure concentration of background ice nucleating particles (INPs) at altitude[8]. **We need to know if CCM can work so that we can either ramp up research into a potentially powerful climate tool, or confidently refocus our efforts elsewhere.**

Due to the magnitude of this uncertainty, Tully et al.[1] recommended that modelling studies be paused until observation-based evidence could be collected. To do so, we need:

A. A **safe method of testing** which doesn't creating new risks or ethical concerns;
B. Proof that the method produces **observable changes in cirrus** so that efficacy can be measured;
C. Instruments which can **measure background INPs**;
D. Models which can **accurately predict CCM-susceptible regions**; and
E. Models which can **forecast the efficacy of CCM** in light of these findings.

We propose a response to this challenge. We will test in Phase 1 whether **soot emissions from existing aircraft (A)** into soon-to-be ice supersaturated air already produce a **satellite observable change (B)** in outgoing longwave radiation. If successful, we will go to Phase 2: a dedicated flight campaign with **accurate INP measurements (C)**, using a **custom-trained saturation prediction model (D)** to verify that CCM can be achieved on demand; this will in turn allow us to determine the **potential efficacy of CCM (E).**

The key science questions are:

1. Is an observable increase in outgoing longwave radiation (OLR) produced due to the presence of aircraft aerosol during formation of an otherwise unperturbed cirrus cloud?
2. Can we predict when aircraft aerosol will yield increased OLR, verified by an aircraft experiment?
3. Can we increase the likelihood and magnitude of an increase in outgoing radiation by using dedicated ice nucleating particles, rather than relying on engine soot emissions?

These in turn define **seven project objectives**:

- **O1A:** Verify that clear-air aircraft soot produces observable changes in OLR from downwind cirrus.
- **O1B:** Establish instrument capabilities to measure ice nucleating particles (INPs) in-situ and therefore enable CCM in practice.
- **O1C:** Provide laboratory measurements of the ice nucleating properties of aircraft soot to inform O1A and Phase 2 campaign region selection.
- **O1D:** Establish modelling capabilities to predict the meteorological conditions under which aircraft soot produces an observable change in downwind cirrus.
- **O1E:** Develop a model which can translate research findings into an assessment of CCM efficacy.
- **O2A:** Execute an aircraft campaign testing our ability to achieve targeted CCM with exhaust soot.
- **O2B:** Translate findings into an assessment of the potential for at-scale CCM with optimal INPs.

1.1 Research and methodology

We propose a phased observational experiment, with three phases (two of which are included in this project budget): **data mining and trial preparation** (P1, years 1-2), **passive trial** (P2, year 3), and **active trial** (P3, not budgeted). Neither P1 nor P2 introduce novel risks nor emit anything new in any new location compared to a conventional passenger flight or aircraft-based monitoring campaign.

1.1.1 Phase 1 (P1): Identify observed changes in cirrus cloud properties due to the inclusion of aviation soot in upwind air, and prepare for an airborne experiment (years 1-2)

O1A: Data mining to study the link between aviation soot and cirrus clouds. The first phase of the trial focuses on using available data from pre-existing observations. Many of the necessary instruments (airborne, orbital, and ground based) have been in service for many years, producing potentially-relevant observations.

The basic concept is to identify times in historical data where an aircraft has passed through ice pre-saturated conditions within view of a relevant geostationary thermal infrared (TIR) instrument. We will then "follow" the affected air using wind data from reanalysis data, using Lagrangian trajectory analysis and limited plume modelling to evaluate whether air masses through which the aircraft were passing would form cirrus clouds. We will exclude any cases in which a persistent contrail would be expected to form (i.e. which are already ice supersaturated). The signal will be evaluated as a function of time since aircraft passage, but a provisional six-hour limit between aircraft passage and observation will be imposed to mitigate the effect of errors in reanalysis wind estimates. This is similar to techniques used to assess the effect of aircraft soot on existing cirrus[9,10] or the impact of ships on clouds[11].

Table 1. Data sources to be used in Phase 1.

Source	Description	Positive	Negative
Aircraft campaigns	>100 hours of measurements of upper tropospheric water vapour, temperature, and aerosol (1 Hz)[12]	Accurate measurement of initial conditions for aerosol and water vapour	Small dataset with limited coverage, instruments vary
IAGOS	Water vapour, temperature, and cloud particle count from >6,000 flights (IAGOS-CORE, 4 Hz)[13]	Large, spatially diverse dataset (vs. campaign), limited initial conditions	Limited aerosol data, capacitive water sensor less accurate
Commercial aircraft	Flight path and estimated soot from >80% of commercial flights worldwide for 2019 onwards[14]	Maximum temporal and spatial scope, good for data mining	Initial conditions must be inferred from models and reanalysis

Three different sets of aircraft will be analysed (Table 1). First, we will collect information from public databases of observations from prior aircraft campaigns[12,15–17]. These will provide a set of cases where we have a high degree of certainty in the initial conditions of the air mass based on data from the aircraft instruments and which are mostly in UK airspace (relevant for P2), but where the total data volume is limited. For example, the FAAM aircraft database for 2023 includes around 625,000 individual observations (sampling at 1 Hz), but only 22,600 of these observations are at above 5 km pressure-altitude, and most would not go on to form cirrus cloud. To augment this dataset we will include observations from IAGOS, an ongoing campaign in which commercial aircraft take high-quality scientific measurements during standard daily operations[18,19]. Although the observations are less comprehensive and of lower quality than the FAAM observations, the IAGOS observations will still provide an opportunity to observe changes to downwind cirrus while still having some data on initial conditions and providing a more global context. Finally, flight tracks for commercial aircraft from 2019 onwards[14] will be analysed (using ADS-B transponder data) for the same purpose. This will provide a much larger dataset but will rely on the temperature and estimated water vapour content at the flight locations being reasonably well estimated in meteorological data.

Observations of the pre-saturated aviation-affected air masses will be monitored in geostationary satellite data over the six-hour period following aircraft passage to assess whether outgoing radiation in satellite TIR measurements is increased – indicating a potential contribution to global cooling - relative to air masses which were upwind of (unaffected by) the flight. This will leverage the fact that, as shown by observations of contrails, an aircraft exhaust plume can spread by only 10-20 km within the first several hours such that cirrus cloud outside this region will be unaffected. Opportunistic evaluations of CCM effects from aviation soot will also be performed using both the LIDAR and TIR imager aboard the CALIPSO satellite, which was operational for 17 years until August 2023. Particular focus will be given to estimates of the ice crystal number[20]. Ice crystal number in particular has been shown to be increased in the case of aircraft flying through existing cirrus clouds, based on CALIPSO and CloudSAT observations processed using the DARDAR-Nice algorithm for the 2006-2013 period[9,20] and the CALIOP-IIR method for later periods[21]. Past work[21–23] has highlighted that mid- and high-latitude regions over or downstream of mountain ranges are key hotspots for cirrus cloud formation, often characterized by high ice crystal number concentrations. These conditions strongly favor homogeneous cirrus formation. While intense mountain waves can generate updrafts too strong for INPs to influence cirrus formation, regions with moderately elevated mountain ranges and steady large-scale flow, such as the Scottish Highlands or the Pennines, offer a unique opportunity. In these settings, cirrus clouds are more likely to respond to perturbations from additional INPs, making them ideal for targeted CCM studies.

A challenge in our proposal is that, even if CCM is theoretically possible, aviation soot may simply not be an effective enough INP[24,25]. We will therefore include in our analysis evaluation of changes in OLR associated with wildfires and lofted mineral dust[17], applying the same techniques as will be used in evaluation of changes due to commercial aircraft. This will allow us to verify whether a different strategy may be needed in Phase 2. *Key deliverables: testing of the hypothesis that aircraft passing through subsaturated air modify the properties of downwind cirrus; quantification of radiative effects; identification of meteorological conditions with a high susceptibility for cirrus modification for use in development of Phase 2. Data mining and analysis will be led by Imperial College.*

O1B: Addressing the world's inability to measure background INP relevant for cirrus clouds. The accelerated timeline of this work demands that we also begin preparation for an aircraft trial on the assumption that Phase 2 will be approved. Accordingly, we will perform the development, integration, and certification of a new instrument for measuring ice nucleating particles at altitude (PINEair) into the FAAM research aircraft (see Phase 2 description for details of intended use). PINEair is based on the established PINE instrument[26], in which parcels of ambient air are passed into a cooled chamber and then subjected to adiabatic expansion to simulate cloud formation conditions in the atmosphere. The resulting ice crystals are then counted using an optical counter, which allows us to determine the concentration of INPs active at a defined set of conditions. PINEair can make measurements of cirrus INPs down to -60°C at defined saturation ratios between ice and water saturation. It has an excellent time resolution of 2 minutes as a result of its design with three separate chambers, so while one chamber is used to make a measurement the other two are being flushed with air in preparation for a measurement. PINEair quantifies both homogeneous and heterogeneous ice nucleation. The only other online instrument capable of making measurements from an aircraft is known as a continuous flow diffusion chamber (CFDC). Existing CFDCs are limited to ~-40°C (i.e. they barely reach cirrus conditions, <-40°C)[27], and suffer from frost flake artefacts where ice falling off the walls contaminates the signal.

Work under O1B will involve purchasing a lab-based PINEtri instrument from Bilfinger Gmbh. PINEtri is the three-chamber version of PINE, with Stirling engine cooling, which allows it to be cooled to cirrus temperatures. Enviscope Gmbh will convert PINEtri into PINEair by rebuilding it in a FAAM rack in a manner consistent with the FAAM technical requirements (suitable wiring, a rack of specific dimensions, a defined centre of gravity etc), performing the necessary testing (magnetic and electromagnetic) and supply the documentation for certification. In Leeds we will then test and characterise PINEair with INP types we anticipate will be important in the upper troposphere using our aerosol chamber. These INP types will include mineral dusts mixed with varying quantities of sulphate, organic and nitrate (using samples we have used for mixed-phase cloud work) as well as proxies of soot aerosol particles (making use of experience in the existing NERC funded aircraft emission project SAFice, NE/Z503848/1). PINEair will be installed on the FAAM aircraft, connecting it to the new community inlet system that is being constructed as part of the mid-life upgrade. Work will be done to verify that aerosol losses in the cirrus INP relevant size range are minimal (<~2 µm). Once installed on FAAM PINEair will need to be certified by BAE and when we receive certification we will conduct flight tests of PINEair using flights funded by other projects.

Key deliverables: FAAM will be one of just two aircraft worldwide capable of measuring temperature, RH, cloud properties, and INP at conditions relevant for cirrus clouds; without these measurements CCM is not feasible[1]. This will put the project in an excellent position for Phases 2 and 3. Also, the UK will benefit from having an aircraft that has the capability of addressing cirrus modification, placing the UK in a world-leading position to research and execute cirrus modification. This work will be led by Leeds.

O1C: Quantifying ice nucleation by aviation soot. Given the contradiction in evidence discussed above in the role of aviation soot in defining cirrus properties[24,25,28,29] it is necessary to use our new tools to experimentally probe ice nucleation on aviation soot under well-controlled laboratory conditions. Previous work on ice nucleation on soot directly from jet engines[24] clearly shows that at most only a very small fraction (less than 1%) of soot particles typically nucleate ice. We hypothesise that it is this small fraction that may be particularly important for defining cirrus ice crystal concentrations. It has been shown previously that the gradual appearance of ice crystals as an air parcel cools can draw down the relative humidity, limiting the nucleation of further crystals[30]. Hence, materials such as soot that slowly form ice crystals will naturally prevent overseeding of a cloud. Thermal gradient diffusion chambers used in the prior research on this topic[24] are not well suited to studying very small fractions since they tend to have substantial background ice signals. In contrast, PINE has a very low background and can therefore be used to study these small activated fractions at modest supersaturations.

We will conduct a set of laboratory based PINE measurements in Leeds of the ice nucleating activity of aviation soot proxies under cirrus conditions. This will build on our current contrail formation work where we have used PINE to study the role of jet engine lubrication oil droplets[31], and will be studying soot in a new NERC funded project (SAFice - NE/Z503848/1). As well as studying the ice nucleation activity of soot under cirrus conditions, we will study the potential role of impurities from fuel additives and metal oxides from engines (known to nucleate ice under cirrus conditions[32]) on the ice nucleating activity of aviation aerosol. This will be done by adding materials to the fuels in the burner so that we produce contaminated soots. *Key deliverables: data on aviation soot ice nucleating activity, with and without impurities focused on low supersaturations where active fraction is expected to be small. This work will be led by Leeds.*

O1D: Developing modelling capabilities to predict susceptible air masses. In preparation for Phase 2, we will develop a dedicated meteorological forecast informed (where possible) by in-situ and satellite observations which is focused on the UK. The RIKEN models[33–35] can integrate live satellite data and will be run using already-available time on the Fugaku supercomputer, the 6th most powerful in the world. RIKEN's modelling approach has already proven highly capable in near-term predictions of precipitation when deployed to forecast weather during the 2020 Tokyo Olympics (see Figure 2). The model will be optimized to identify pre-saturated air masses with a one-day lead time, based on the same observations as are described above. *Key deliverables: continuous five-day forecast capability of cirrus cloud formation over the UK, developed using and validated with past observations. This work will be led by RIKEN.*

O1E: Understanding the observationally-constrained maximum potential of CCM. We will also begin preparatory work for Phase 3 of the project, incorporating the lessons being learned from Phase 1. We will conduct simulations of the potential efficacy of CCM for both soot and ideal ice nuclei, focusing on process accuracy. These will incorporate the latest information from Phase 1, using km-scale atmospheric modelling. Low-resolution climate models, the only tool used so far to estimate the cooling potential of CCM, are too coarse to explicitly simulate updrafts and cirrus lifecycle and are thus relying on uncertain parameterizations of small-scale vertical wind variability, cloud micro- and macrophysics. This has prevented a clean physical connection between dynamics, relative humidity variability, and ice formation.

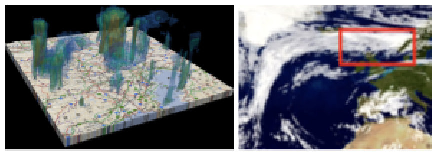

Figure 2. Left: near-term precipitation forecasts from RIKEN's SCALE model. Right: global 5 km ICON simulation, to be used in estimating CCM cooling potential of CCM (using P1&2 results) and drive regional ICON-LEM simulation.

Our modeling efforts will estimate the geophysical limits of CCT based on atmospheric modeling of INP perturbations. The potential cooling effects of CCM, constrained by Phase 1 data, will be quantified through regional 100 m-scale (LES) and global kilometer-scale (cloud-resolving) simulations using the ICON model already running at Vienna. The model currently includes only warm cloud-aerosol interactions; the first step in this work will be to extend that with a reasonable scheme to account for aerosol-cirrus interactions[36]. This will allow us to evaluate the regional sensitivities and atmospheric feedbacks of CCM, and will be crucial for understanding both the highest-potential target regions and the potential risks resulting from Phase 3. A particular focus of this work will be to increase confidence that, even if CCM is effective, the results of seeding are mostly confined to the target region. *Key deliverables: extension of ICON to include aerosol-cirrus interactions; incorporation of data analysis results into ICON; estimation of the spatial domain of influence of a potential Phase 3 trial. This work will be led by Vienna.*

1.1.2 Phase 2 (P2): demonstrate that we can predict and achieve CCM with aviation soot (year 3)

In P2 we will seek to test our ability to induce a signal based on forecast conditions. This is needed to both verify P1's findings and evaluate our ability to forecast modifiable cirrus (see Figure 3).

O2A: Target FAAM flights to deliberately modify cirrus properties. We will use the exhaust of the FAAM research aircraft to try and modify the properties of cirrus forming in UK airspace, and then to observe the changed cirrus in satellite imagery using the protocol from Phase 1. This modification is inherently low-risk, as such modification is performed inadvertently by flights worldwide every day and the FAAM routinely measures and monitors cirrus clouds. We plan for 50 flight hours across 10 sorties.

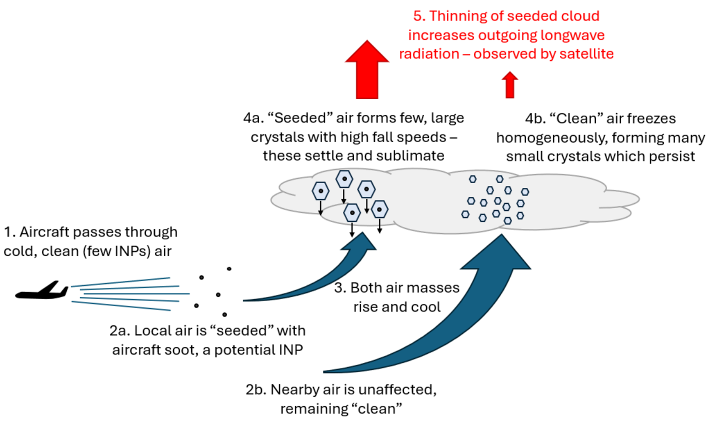

Figure 3. Target outcome of the P2 experiment.

Experimental design: Prior to each sortie UK airspace will be analysed using the RIKEN model which was tested during Phase 1 to find locations where a) pre-saturated air exists, b) the aircraft is expected (based on P1) to cause an observable change downstream, and (if possible) c) higher-resolution observations will be available from a ground station or overpassing low Earth orbit (LEO) satellite. During the one-month FAAM campaign period, we expect to make continuous 5-day forecasts to support this effort. Flight days will be chosen based on identification of a cirrus-forming region which is within the FAAM flight envelope, within range of the FAAM home base (Cranfield), and large enough that we can expect to see both modified and unmodified areas. A high-potential target is the Scottish Highlands, where orographic uplift often produces mountain waves with updraft velocities large enough to support homogeneous cirrus nucleation in conditions with low background INP concentrations. These conditions make this region a promising area for testing CCM strategies. Aircraft campaign management will be led by Leeds, with the following strategy:

- *Before each flight*: Five-day meteorological forecasts will be produced for all UK airspace continuously over the one-month trial period. Candidate dates and locations will be chosen based on a daily review of the expected likelihood of cirrus formation from air which will be within the flight envelope of the FAAM aircraft, the visibility of the region for MTG-I1, and the possibility of coincident measurements from a LEO satellite overpass (ideally from the EarthCARE satellite, but also considering others such as Sentinel 3's VIIRS and SLSTR depending on local time and orbital parameters) or from a relevant ground station. A go/no-go decision will be made 18 hours ahead of each flight to permit flight planning. *Forecasting and meteorological modelling will be led by RIKEN.*
- *During each flight:* In-situ measurements will be taken of three crucial parameters in order to provide high-quality initial conditions for trajectory analysis. We will need to measure (with high accuracy) **(1) the water vapour mixing ratio** and **(2) the ambient temperature**. These, along with pressure, aerosol concentrations, and aerosol properties, will be determined by existing FAAM core instruments. PINEair, integrated into the FAAM in P1 (O1B), will be used to determine **(3) the number of background INPs** present in the air as a function of temperature and saturation ratio. This is necessary to understand the baseline which is being modified by the passage of the aircraft, and therefore the change in the number of potential INPs as a result of the soot produced in the aircraft exhaust. *Instrument data collection and coordination will be led by Leeds.*
- *After each flight*: Satellite measurements from MTG-I1 and static/LEO instruments identified during pre-flight planning will be gathered and analysed for the air downstream of the flight, using the protocols developed during P1. We will seek to establish whether the properties of the cirrus cloud were measurably changed by the passage of the research aircraft. *Satellite data analysis will be led by Imperial.*

When predicting the effect of emissions, we will need not only the background INP (from PINEair) but also the aircraft soot emissions. These will be estimated based on ground testing which has already been performed with the FAAM research aircraft to characterize its exhaust in terms of the number of particulates produced per unit of fuel burned (manuscript currently in preparation; personal communication from [redacted]), translated to cruise conditions using existing empirical relations[37]. *Emissions estimation will be performed by Imperial.*

O2B: Translate findings into an estimate of potential CCM efficacy. Simultaneous to this phase, we will conduct an observation system simulation experiment (OSSE) to identify INP characteristics which would maximize the expected observationally-verifiable negative radiative forcing (climate benefit) resulting from CCM. This work, conducted with the ICON model will be directly informed by the results of the campaign (where we are using soot as an INP), taking advantage of the large-scale modelling capabilities developed during P1. *The OSSE will be led by Vienna.*

Phase 2 will be deemed complete once all flights are complete and analysed. The key metric of success will be the total outgoing longwave radiation integrated along the trajectory from initial cirrus formation to 24 hours subsequently, calculated using geostationary satellite measurements and compared to outgoing longwave radiation from nearby (upstream) cirrus.

1.1.3 Phase 3 (P3): extend beyond aircraft soot to support INP-optimal CCM (year 4 onwards, not budgeted)

If CCM using aircraft engine soot can be proven to both modify the cloud properties and increase the trajectory-integrated outgoing longwave radiation, and if the conditions for this can be predicted using weather forecast data, then P3 will proceed. This phase, shown in Figure 4, will expand the project to include artificial seeding and will constitute the first step towards a full CCM trial.

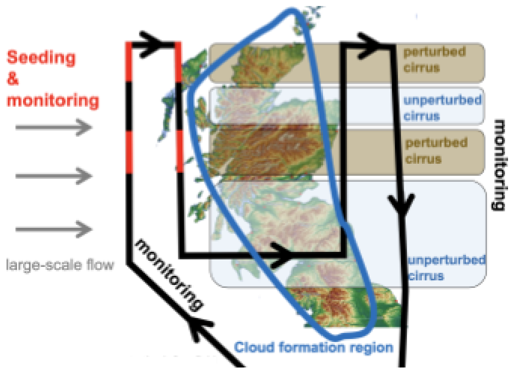

Figure 4. Schematic of the P3 seeding approach.

These trials are again expected to take place over the northern British Isles during wintertime, possibly based in Stornoway (where FAAM has operated in the past). This location and season is particularly well suited due to the likelihood of homogeneous ice nucleation (HOM) events as described for P2.

The seeding strategy will involve the release of custom seeding particles over a defined part of the Highlands, followed by a downstream measurement campaign to assess the effects on cloud properties. The research aircraft will attempt to sample the same air parcels - identified through operational trajectory analysis and flow calculations - both before and after seeding to provide a robust comparison.

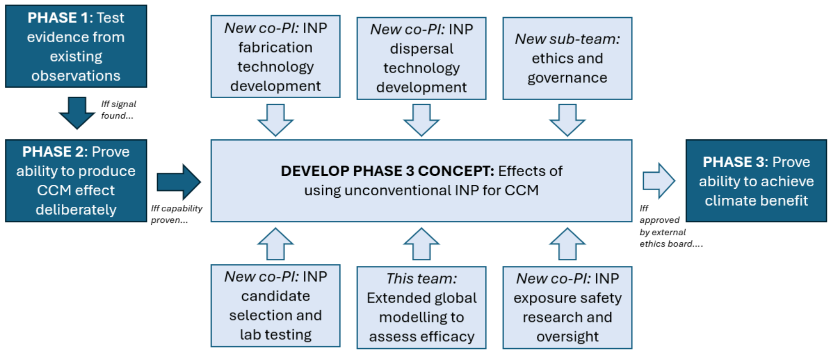

Figure 5. Requirements for success in Phase 3. Dark blue boxes indicate project phases. Light blue boxes indicate stages which must be completed between Phases 2 & 3, including entrainment of new team members.

Key objectives of Phase 3 would be:

1. **Baseline sampling**: Verify that the dynamical and aerosol conditions are sufficiently uniform across the trial region. This will ensure that any subsequent changes can be attributed to the seeding intervention.
2. **Seeding experiment:** Verify that a seeding experiment can be conducted in regions where homogeneous cirrus formation is expected.
3. **Post-seeding observations:** Monitor and sample seeded and unseeded air parcels downstream to determine if measurable differences in cloud properties and radiative effects occur, and to verify that these differences are of the expected magnitude.

The decision on the seeding agent and the design of the device for producing the seed aerosol will be part of Phase 3. We envisage the choice being between: **silver iodide**, already used[5] for cloud seeding but may cause overseeding as it is so effective; **glassy sugar solutions**, found to nucleate ice under cirrus conditions with very gradual nucleation onset (perfect for cirrus cloud seeding[38]), can be nebulised into the atmosphere, and would not have a detrimental effect on lower altitude mixed-phased cloud (unlike silver iodide); or a **designed nucleator** as described in an ARIA proposal by [redacted] to create designer ice nucleating materials with ideal properties for cirrus modification.

Before progressing to Phase 3, the team would need to be expanded (Figure 5). Of particular importance would be a dedicated ethics and governance team, an ethics review board, and a safety assessment team to ensure there would not be unintended side effects from the deployment of artificial seeding materials.

1.2 Why has this not been done before?

As previously stated, CCM research is in a deadlock which pure modelling studies cannot break[1]. Resolving this with observations has been challenging because cirrus clouds are hard to reach, monitor, and model. The advent of high-resolution geostationary imagers and improved LEO capabilities, alongside a large and growing archive of in-situ upper-tropospheric observations, heralds an unprecedented opportunity to test the hypothesis of CCM. The launch of the GOES-R satellites means we have an archive of 6 years of continuous US observations coincident with LIDAR data from the (now-defunct) CALIOP orbital LIDAR, which can be merged with copious upper-tropospheric observational data from aircraft campaigns to inform P1. We can now observe in real time over the UK/Europe at a resolution of ~2-5 km using the MTG-I1 satellite at 0° longitude, which has now been declared fully operational. With the new EarthCARE low Earth orbit satellite we also have access to a top-down view of cirrus properties, including high-resolution imaging and LIDAR. The availability of these instruments means that we can learn from experience (as described above) and translate this knowledge into a trial over the UK. Finally, we have lacked the ability to make measurements of INP under cirrus conditions in the mid-upper troposphere, which has limited our ability to assess the efficacy of cirrus cloud modification. With PINEair and this project, we can break the deadlock.

1.3 Project plan and staging

Our project is staged to facilitate project expansion, extension, merging, or termination depending on results. If the P1 null hypothesis is not rejected at the end of year 2, then P2 will not be justified without significant revision. Similarly if P2 is unable to produce a statistically-significant signal, then P3 (not budgeted) will not be justified without significant revision. A full timeline is given in Figure 6.

1.3.1 Risk to the public

We have deliberately split this project into three phases to minimize risk to the public. P1 carries essentially zero physical risk, as it involves no outdoor experiments and is mostly concerned with data analysis, model development, instrument construction and laboratory measurements. P2, although it does involve outdoor flights, emits nothing into the atmosphere other than the engine emissions which would be associated with any flight by the FAAM. As such it carries the same minimal risk as any conventional aircraft campaign. P3 will require a deeper evaluation of potential risk, and for this reason is not budgeted under this project. Its execution would require, at the very minimum, entrainment of an internal ethics and governance team, evaluation of any potential for human health risks resulting from exposure to the candidate ice nucleating particles, and establishment of an integrated ethics team to assist with trial design and an external ethics review board tasked with the power to halt the project (see Figure 5).

1.3.2 Risk mitigation

Our stage gates also minimize project risk. At the end of P1 there is a go/no-go decision predicated on whether a statistically significant signal could be found in the analysed satellite data. If it cannot, P{2 will not proceed. All activities planned in P1 are nonetheless expected to yield longer-term benefits including improved modelling of humidity and enhanced UK instrument capabilities.

Possible external risks include the possibility that the PINEair instrument cannot be built, integrated, or certified in time, or the possibility that the FAAM mid-life upgrade is delayed. The former risk is considered low, as the PINE instrument is already commercially available from Bilfinger such that only integration and certification is necessary, and PINEair integration was already provisionally approved for the FAAM. The latter risk is also considered low, as the FAAM mid-life upgrade has been subject to thorough planning and review for several years. However, if these events do occur it will result in a delay of the project only.

With regards to meteorological forecasting, RIKEN is highly experienced in short-term forecasting and will be collaborating with Vienna to advance the representation of cirrus formation in their models. ECMWF forecasts will be used as a fallback if we cannot improve formation prediction during P1.

Finally, this proposal will require a substantial hiring push. Given the short timeline, it may not be possible to hire all of the necessary postdoctoral researchers in time for the April 2025 start date. This may delay parts of the project by up to 3 months; if so we may need to seek a no-cost extension, to ensure that data produced from the P2 experiments can still be processed.

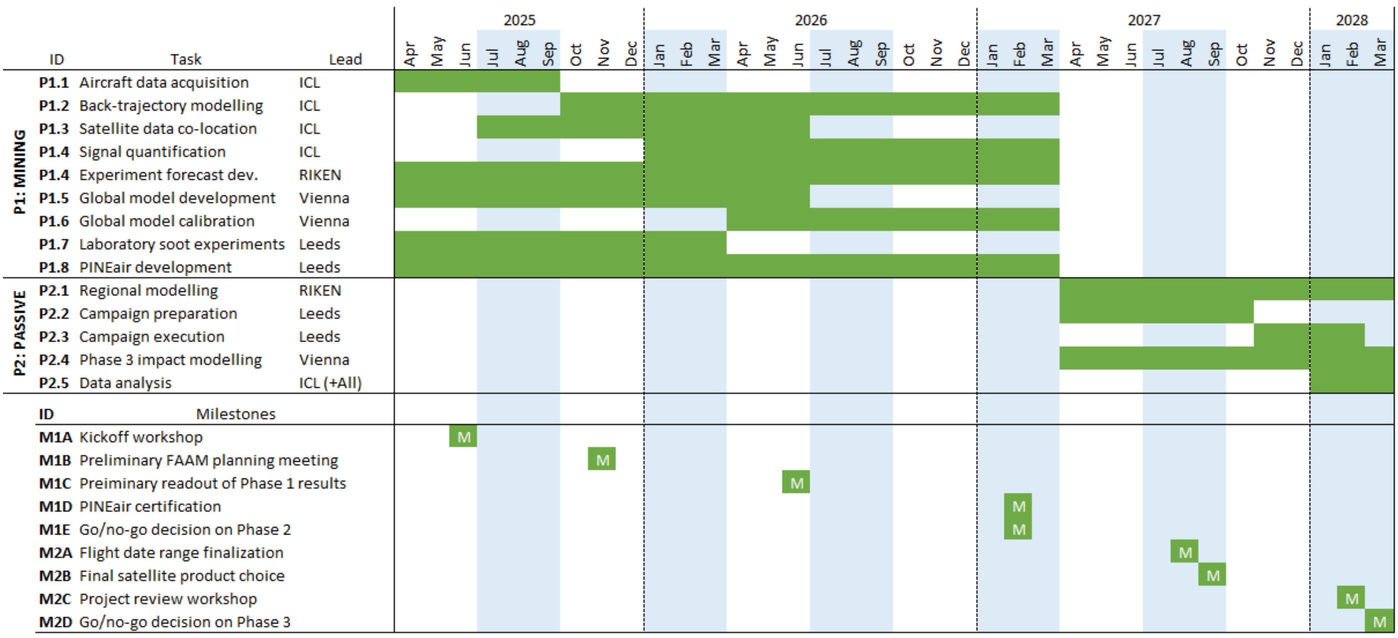

Figure 6. Gantt chart for the project. Phase 3 is not shown as it is not budgeted in this proposal.

2 The Team

We are a team of six investigators, motivated by concern over the combination of a lack of reliable data on the robustness and safety of climate interventions and the urgency of the climate crisis. This team has the necessary skills to evaluate, soberly and objectively, whether cirrus modification is a promising avenue for climate cooling, an artifact of model assumptions, or even counterproductive. The entire team will be engaged throughout both P1 and P2, with further team expansion anticipated if P3 goes ahead.

[redacted] and will dedicate 10% of [redacted] time to this project while supervising a PDRA for 3 years.

[redacted] will dedicate 20% of [redacted] time to this project while supervising a PDRA for 3 years.

[redacted] will be supervising a junior researcher (100%) and senior researcher (50%) at [redacted] in the development of a specialized model to predict sub-saturation conditions which are likely to result in later cirrus cloud formation.

B[redacted] will commit 15% of [redacted] time, supervising 1 PDRA (years 1-3) to work with the instrument, and another PDRA (year 3) to coordinate flight planning, trial execution, and campaign measurements.

[redacted] will commit 5% of [redacted] time to co-supervise the Imperial College PDRA, focusing on satellite data acquisition and interpretation.

[redacted] will commit 5% of [redacted] time to co-supervise the Imperial College PDRA, focusing on characterization of commercial aircraft soot emissions for Phase 1 and of the FAAM in particular for Phase 2.

Project management will be conducted at Imperial College through a dedicated Project Manager, due to the size of the project. This is a staff position, with 50% of their time dedicated to the project throughout the full 3-year duration.

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Planetary Sunshade Baseline Survey

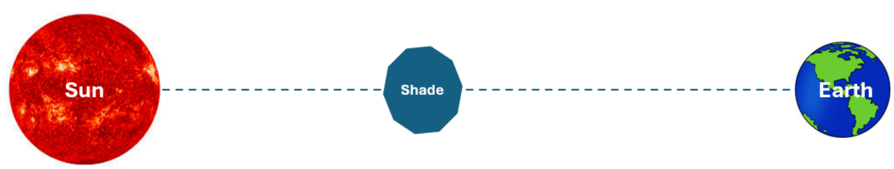
Section 1: Programme & Technical

The Planetary Sunshade Project aims to advance our understanding of space-based Solar Radiation Modification (SRM) architectures. Our work will involve developing and comparing various SRM options, assessing key factors, and conducting climate modeling. While conducting an outdoor experiment—specifically a spacecraft-based test—is beyond the scope of ARIA's funding, there is an urgent need to advance space-based SRM to a level of understanding comparable to existing in-atmosphere SRM interventions. At the conclusion of our project, we will propose a space-based experiment, deliver a rigorously modeled set of potential space interventions, and establish a comprehensive baseline for ARIA and the global community.

Section 1.1 Proposed Project

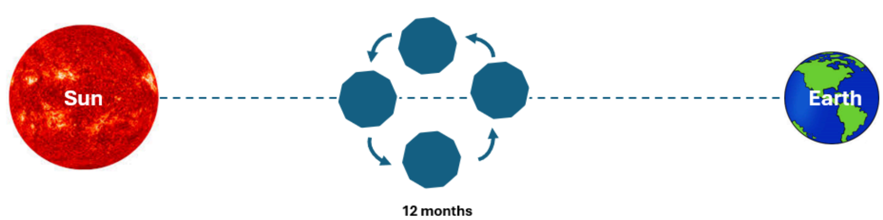
This project will study the practical feasibility and predicted climate impacts of the set of all plausible space based SRM solutions. Previous climate modeling efforts have looked at general Solar Dimming (SD) in the abstract from feasible space architectures, and until now, specific space architectures have not been modeled by climate scientists. To understand a plausible intervention, we need to consider the full range of possible architectures from both engineering and climate modeling perspectives. The representative architectures we will use for our study are:

A: Reflective spacecraft at Sun Earth Lagrange 1 (SEL1) with minimal preferential seasonal hemisphere shading



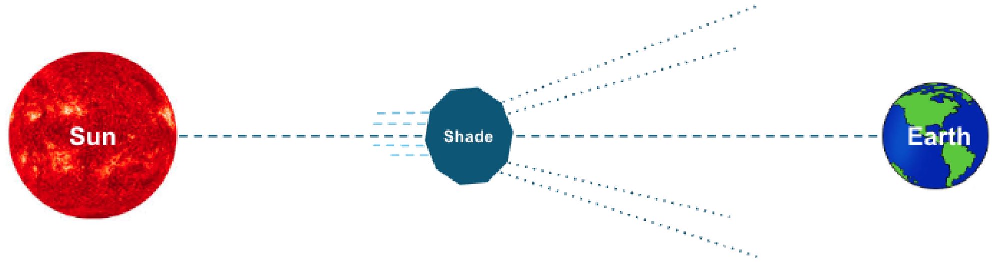
This intervention is a constellation of spacecraft, with a total area of the magnitude of 2 M km^2 stationed the SEL1. This location is, by definition, constantly in line with the Earth and Sun, providing constant shading that is diffused evenly across the globe.

B: Reflective spacecraft at SEL1 in an orbit with preferential seasonal hemisphere shading



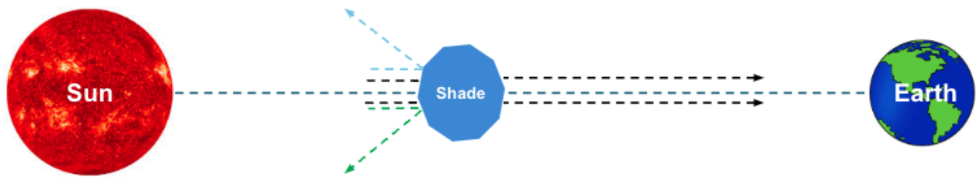
This intervention is a constellation of spacecraft, with a total area larger than the 2 M km^2 in architecture A, orbiting the SEL1 point in a 12 month period such that the northern hemisphere is shaded more in the northern summer and the southern hemisphere is shaded more in the southern summer. This intervention studies the engineering and orbital mechanics feasibility of Visioni et. el's 2021 work [1]. The goal of this intervention is to achieve solar dimming in three independently adjusted patterns (globally uniform, linear with sine of latitude, and quadratic with sine of latitude) to maintain global mean temperature, the interhemispheric temperature gradient.

C: Diffractive spacecraft at SEL1



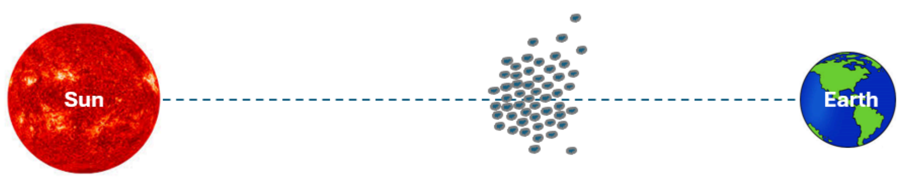
This intervention is similar to A and B, but instead of reflecting or blocking all wavelengths of light, this diffracts that light away from the Earth. Prismatic materials can be created to alter the trajectory of solar radiation. Diffraction could result in a smaller sunshade mass for similar cooling benefits.

D: Selective Wavelength blocking spacecraft at SEL1



This intervention is similar to C, but only blocks selective wavelengths. This intervention uses materials that filter some wavelengths while blocking others. The ability to specify wavelengths could be an advantage to achieving specific cooling outcomes. Specifically, infrared wavelengths most directly linked to the earth's warming could be blocked with spectrally selective coatings or low-emissivity coatings commonly used in architecture.

E: A dust cloud made from asteroids at SEL1



This intervention is a dust cloud made of pulverized regolith sourced from asteroids or the moon which diffuses across the SEL1 area, providing constant and even shading across the earth. Work on this architecture builds on the JPL team's work on the DimSun concept [2]. This studies the construction and climate properties of a dust cloud composed of ≈ 4.52 × 10^23 particles of 1.6 μm-radius at SEL1. Since most of the Sun's energy is in wavelengths smaller than 2.5 μm, these particles will block the Sun's rays along specific wavelengths.

F: Reflective spacecraft in Low Earth orbit

This intervention is a constellation of spacecraft in low earth orbit, which shade the earth as they pass between it and the sun. While not typically considered viable due to the small amount of time that an object is shading the earth on any orbit, this is included in the study because of the need for a comprehensive look at the options. Unique challenges include a distinct increase in orbital debris and collision risks as well as the chemical impact of so much metallic mass re-entering the atmosphere.

Climate Modeling Work

The impacts of the different space based constellations on the Earth System will be studied with the NCAR Community Earth System Model (CESM). The model includes comprehensive processes in the atmosphere that are coupled to land, ocean, and cryosphere and can be run in more or less complex configurations, reaching from more simplified simulations for climate impact studies, to very comprehensive configurations that include interactive aerosols microphysics, chemistry, radiation, and transport, well suited to assess effects on the whole atmosphere, the ozone layer, including climate feedbacks.

Modeling approach

Different space based constellations will potentially differ in details of solar dimming reaching Earth. This may be a simple dimming of incoming solar radiation globally and through the solar spectrum or it may vary depending on the sophistication of the ability to modulate latitudinal gradients of dimming as well as wavelength specific dimming. The more degrees of freedom a solar shield may offer in terms of modulating location and strength of the dimming the more it is possible to adjust climate impacts towards more optimal deployments in terms of climate impacts as well as impacts on societies and ecosystems.

Climate model simulations are a useful tool to explore possibilities that may be offered by the different space based constellations and help to assess most beneficial options. We'll first run general sensitivity analysis on all the architectures. We will increase the complexity of models run, pursuing interesting discrepancies and surprising results, leading to more in depth modeling work. More simplified (single column runs) will be used for assessing details of changes in incoming radiation on chemistry, while more comprehensive CESM model configurations will be used to look at the complicated feedbacks between the whole atmosphere, land, ocean and cryosphere. The interventions will be applied to a couple of future scenarios (potentially a high forcing scenario and a more optimistic scenario), in order to assess unintended consequences for stronger and weaker applications. With this work, will develop a set of GeoMIP experiments proposed to run in a multi-model setting.

In addition to intended impacts, we must also study unintended climate impacts. The GHG emissions from rocket launches will be considered alongside the chemical and heating impacts of spacecraft re-entry. Re-entry impacts are potentially significant for both reusable rockets and spacecraft intentionally burning up in the atmosphere. This discussion will reference the Montreal Protocol on the Ozone layer.

Section 1.2 Technical and Non-Technical Risks

Each architecture will be modeled to better understand its value as a possible SRM option. The modeling work can help map out potential impacts of out-door test cases and assess potentially measurable impacts depending on the scale and type of SD intervention. In addition, we must compare the challenges and risks of each of these approaches. Our work will compare the following factors for each of the architectures:

- Technological Readiness Levels (TRLs): what we know about the technologies needed for construction?
- Total mass to achieve the specified level of cooling, and a discussion of the possibility of sourcing mass from space resources.
- Cost is perhaps the least accurate factor that we can assess, given the wide unknowns of economies of scale of building space infrastructure, but we will offer general cost parameters.
- Orbital considerations: What orbits are physically possible, and for each architecture, what amount of energy to reach and maintain the desired orbit?

- Ongoing maintenance. How often do spacecraft or debris need to be replaced and what sort of work is required to do so?
- System reversibility. How might the system be reversed assuming a correctly functioning spacecraft constellation, and what would happen if there is a general loss of control of the constellation?
- Other key risk factors include the system durability to meteor impacts, the risk of collisions among spacecraft in the constellation, the possibility of damaging solar storms and degradation caused by long term radiation.
- We will calculate the visual impacts for the general public and for scientists observing the sun and sky.

Section 1.3 Differentiation From Other Approaches

Our project is the first sunshade effort to bring leading researchers on the aerospace and climate science fields into the same project. Here is a brief overview of the significant advances to date from the respective fields:

Aerospace Engineering Concept Development

Aerospace engineers have studied the planetary sunshade concept for decades, laying the groundwork for current explorations of space-based solar geoengineering. The concept first gained traction in the 1980s with James Early's (1989) proposal of a large reflective shield positioned at the Sun-Earth Lagrange Point 1 (L1). [3] Early's work emphasized the feasibility of mitigating global warming by reducing incoming solar radiation, introducing the idea of a single, monolithic structure. This early design, while visionary, faced substantial challenges due to the immense mass required for deployment and the associated launch costs.

Subsequent research sought to address these engineering obstacles. In the 1990s, Lowell Wood and colleagues at Lawrence Livermore National Laboratory expanded on Early's ideas, proposing the use of multiple smaller, lightweight reflectors instead of a single monolithic structure. [4] This shift toward modular designs was a significant innovation, as it reduced the overall system weight and increased redundancy, making the concept more practical for implementation.

Sanchez and MacInnis (2015) advanced the planetary sunshade concept by investigating optimal configurations designed not only to offset global temperature increases but also to address regional and seasonal variations in temperature. [5] Using a globally resolved energy balance model, they demonstrated how the motion of sunshades could be dynamically coupled to the Earth's climate to mitigate latitudinal and seasonal temperature disparities. Their work revised earlier studies by identifying families of forced orbits near SEL1 which required only minimal adjustments to the sunshade orientation to maintain their desired trajectories. This innovation marked a breakthrough in integrating orbital mechanics with geoengineering goals, offering a more efficient and nuanced approach to mitigating climate change on both global and regional scales. However, Sanchez and Macinnis used the GREB, a simple climate modeling tool which does not incorporate many of the elements used by state-of-the-art climate models.

Other noteworthy studies include a group at MIT who developed a concept to build a sunshade out of bubbles. [6] Scientists have proposed dust clouds, which could even be 'anchored' by a larger asteroid towed into place. A physicist proposed using an asteroid to anchor a very light-weight sail. These studies contribute to our understanding of the range of options.

Sunshade Development Prototype Efforts

With the increased urgency of the climate crisis and the dramatically falling cost of access to space, a number of private initiatives have emerged in recent years to launch prototype missions. While actual launches are far from certain, it is worth noting here the efforts underway.

The private company Earthguard.space is developing a diffractive film deployment technology and making plans to launch test missions. They are privately funded, and they have done their own in-house climate modeling. Our proposal will study their technology as architecture C. Cool Earth is a demonstration sunshade effort led by Israel's Asher Space Research Institute. While their project has not made notable advances in the past year, they have developed a simple demonstration concept of Architecture A. A group organized around the Cosmos Club in DC is working with a Rocket Lab engineer to develop very small sunshade elements which they plan to fly in a test mission soon. Ethos-space.com has a sunshade as the goal, and is focused on the more immediate aims of building a spaceport and developing industrial capacity to use lunar resources.

NASA has developed and partially built the Solar Cruiser mission. While not described as a space SRM prototype, the spacecraft is an exact demonstration of a sunshade element. The 1600m^2 solar sail is designed to fly at SEL1. The project's funding was cut and it is not currently scheduled to fly. [7]

Climate Modeling Existing Work

The climate modeling community has long relied on Solar Dimming (SD) as a baseline scenario to compare the impacts of solar radiation management (SRM) interventions. GeoMIP (Geoengineering Model Intercomparison Project) has played a critical role in advancing this research, standardizing SD scenarios to facilitate cross-model comparisons. The GeoMIP framework has enabled researchers to evaluate the climatic and hydrological effects of SD across various regions, but its simplicity may obscure the complex dynamics of feasible space architectures. For instance, Kravitz et al. (2013) noted that while SD offers a convenient reference point, it falls short in capturing the intricate, spatially heterogeneous outcomes that more targeted interventions might achieve. [1]

Recent research examines whether SD is as uniform of a comparison as previously thought. In 2021, Visioni, MacMartin and Kravitz published a paper asking "Is turning down the sun a good proxy for stratospheric sulfate geoengineering", and found that a uniform dimming across all latitudes has drawbacks with regard to equatorial vs. polar cooling. They further also considered a hypothetical SD with a latitudinal dependence determined by a combination of the first three Legendre Polynomials in order to, together with reducing global temperatures, maintain the equator-to-pole and interhemispheric temperature gradient. They found this preferential shading to produce more even effects over the earth than a general SD, or then even more sophisticated forms of SAI using various injection locations. [8] However, the purpose of that research was to develop a better baseline for comparing stratospheric aerosol injection methods. The team did not discuss what sort of architecture could actually achieve such preferential shading.

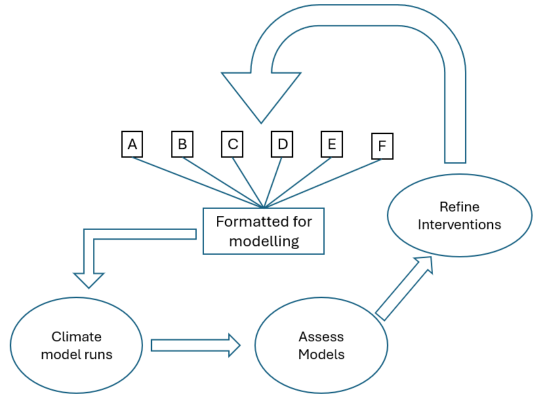
ARIA Sunshade Project Proposal

Our project will bridge the gap between these two bodies of work. We will bring realism and technical capability to SD models used by climate modelers. One result of this would ideally be developing a GeoMIP experiment for realistic SD could be an outcome of this proposal. By creating a standard experiment, other researchers can compare and study the sunshade concept in a repeatable way.

Finally, our project will consider the minimum measurable impact for a test sunshade. We will describe what sized test shield would have a measurable effect. To answer this we'll consider the solar cycle fluctuations and the measuring tools that could determine that. This will set out a definition of 'test' vs. 'pilot' vs. 'implementation' and inform demonstration missions. This should establish a framework for governance and policy discussions.

Section 1.4 Activity of Work, Key metrics and Milestones

As a multidisciplinary project, we are seeking to create parallel but interacting workstreams. Our work is split generally into the engineering and modeling teams. Each architecture will be scaled to match the same level of cooling, and described in terms of latitudes, ramp-up time, wavelengths and other factors relevant to modeling. While the engineering teams continue to develop their concepts at higher levels of engineering detail, the climate modeling team will run analysis.



Key Milestones:

1. Week 1: Project kickoff. Team aligns on standardized parameters to compare different space based options, and align on what we mean by hardware capabilities. Climate Modeling team clarifies formats and definitions of data and inputs.
2. Week 10: Engineering teams present basic conceptual design reviews of interventions. First guess at ramp-up times, how many watts/sq M would be achieved over time, and in what orbit, what wavelengths.
3. Week 12: Alignment between engineering and modeling teams to clarify understandings
4. Week 20: Modeling team completes investigation of climate impacts of proposed options
5. Week 30: Engineering teams have refined proposals. Conceptual Design Review, including assessment of risks, mitigation strategies, costs, timelines.
6. Week 40: Modeling team completes second round of modeling and produces results for final publication
7. Week 45: Report drafted and published, including space based experiment recommendation. This includes buffer time to complete project and work with the ARIA team on final forms and presentations.

Dependencies and assumptions:

As with all geoengineering research, we assume that climate models are an effective way to study proposed interventions. We assume that different architectures can be compared by the models in a meaningful way. We are depending on the climate modeling expertise to adapt existing models to the unique characteristics of space based architectures.

We are assuming that the architectures we have selected are representative of desirable and feasible possible constructions, and that we have assembled a team of researchers who are the best in their fields and can provide accurate details. We are depending on this expertise being informed by the history of study as well as ongoing developments.

Collaboration across disciplines assumes that we have sufficient understanding, language, trust and time to be effective, and allow each group to make meaningful contributions. We are dependent on that willingness to collaborate toward a holistic common goal.

Section 2: The Team

The Planetary Sunshade Foundation (PSF) is a newly established, US-based 501(c)3 nonprofit dedicated to advancing space based SRM. Our organization is a global network of researchers which has developed out of a shared belief that space can contribute to climate solutions. We committed to bridging the gap between geoengineering climate scientists and aerospace engineers, and over the past 4 years have worked hard to build trust. We have also worked hard to find collaborators with a rigorous approach and far-ranging curiosity. Our contributors are intrinsically motivated, as evidenced by so much willingness to donate time. This proposal seeks funding to enable key PSF staff to focus full time on developing the sunshade concept by deepening collaboration across disciplines.

Core PSF Leadership: [redacted]

Engineering Expertise from Ethos Space: [redacted]

Climate Modeling Leadership: [redacted]

Sub-contracted in-kind engineering specialty contributions: Due to institutional constraints around grant funding, the following individuals are excited to contribute their time in-kind for this project. [redacted]

2.1 Coordination and Management

To coordinate and manage the teams, we will facilitate regular meetings focused on identifying gaps in understanding, aligning on key milestones, and ensuring accountability. The climate modeling team operates as a tightly-knit unit and has the capability to work independently. Our approach will include structured check-ins and a consistent format for the exchange of information to maintain alignment and progress.

The core engineering team, anchored by Ethos Space, is able to meet in person in Los Angeles on a frequent basis for brainstorming sessions. We will leverage the Ethos shop space, equipped with collaboration tools, to foster innovation and streamline communication. [redacted] will be responsible for collaborating with specialized engineers to define work milestones and rigorously assess underlying assumptions.

As project coordinator, [redacted] role will involve establishing and maintaining systems that ensure effective collaboration and timely progress. [redacted] will also be responsible for communicating with both internal and external stakeholders, providing regular updates and ensuring transparency throughout the project lifecycle.

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Investigating the Impacts of Solar Geoengineering on the Variability and Wet-Dry Spell Dynamics of the West African Monsoon

Section 1:

1. Programme and Technical

1.1 Introduction

The West African Monsoon (WAM) is a pivotal climatic system that profoundly influences the livelihoods of millions in the West African region. Characterized by its variability and the occurrence of wet and dry spells, the WAM governs agricultural productivity, water resources, and ecosystem services, making it a critical element for regional sustainability (Abiodun et al., 2021). Climate change threatens to exacerbate WAM variability, posing risks to food security, water availability, and economic stability. The IPCC 5th report provides evidence with high confidence that dryness will continue to increase in West Africa as the climate is forced by increasing anthropogenic warming. To mitigate these adverse effects, solar radiation management (SRM) has been proposed as a potential approach to counteract the warming influence of human activities and help avert the worst impacts of climate change.

SRM is a proposed method of reducing the adverse effects on weather and climate associated with climate change in order to temporarily counteract some of the imbalance produced by the increase in atmospheric greenhouse gases (GHGs) and to avoid the worst consequences of climate change (Visioni et al., 2021). Some of the widely proposed approach of SRM include marine cloud brightening, space shading, stratospheric aerosol injection, and cirrus cloud thinning (Abiodun et al., 2021; Stjern et al., 2018). To date, the most common suggested approach is via injection of SO2 into the stratosphere in order to produce a layer of sulfate aerosols capable of partially reflecting incoming solar radiation; this is usually defined as stratospheric aerosol intervention (SAI) or sulfate geoengineering (Pinto et al., 2020). Previous studies have shown that SRM could alter global as well as regional climate scales, mostly reduce the intensity of extreme precipitation and associated impacts (Muthyala, R., Bala, G., & Nalam, 2018), significantly reduces temperature means and extremes (Pinto et al., 2020), decrease surface ocean hydrogen ion concentration and attenuates the seasonal amplitude of [H+] (Jin et al., 2022). However, its regional impacts, particularly on complex systems like the WAM, remain poorly understood.

This research focuses on exploring the implications of SRM on WAM variability, with a specific emphasis on wet and dry spell dynamics. By employing advanced climate models, observational data, and scenarios from the Geoengineering Model Intercomparison Project (GeoMIP), the study aims to address critical gaps in understanding how SRM interventions might influence the WAM system. Furthermore, the project seeks to provide actionable insights into how SRM might be leveraged to mitigate adverse climate impacts while avoiding unintended consequences, thereby supporting the overarching goals of the ARIA Exploring Climate Cooling programme.

1.2 Scientific Rationale and Objectives

The ARIA Exploring Climate Cooling programme seeks to advance innovative solutions for mitigating climate change impacts, with a particular focus on avoiding tipping points in global and regional systems. This project aligns closely with these objectives by:

a) Investigating the effects of SRM on a critical regional climate system, the WAM.

b) Exploring the potential for SRM to reduce extreme weather variability, including prolonged wet and dry spells, which are significant drivers of socio-economic vulnerability in West Africa.

c) Generating high-resolution projections of WAM behavior under SRM scenarios to inform policy and adaptation strategies.

Key Objectives:

- Assess how SRM modifies rainfall variability and the occurrence of extreme wet and dry spells.
- Evaluate the implications of these changes for water resources, agriculture, and regional sustainability.
- Examine the performance of high-resolution climate models in capturing the dynamics of WAM under SRM scenarios.
- Assess the predictability of WAM onset and cessation through dynamical modeling.

- Compare the outcomes with baseline scenarios (SSP2-4.5 and SSP5-8.5) to determine the distinct impacts of SRM.

1.3 <u>Methodology</u>

a) Study Area

The study focuses on the West African region, spanning latitudes 5°N to 20°N and longitudes 15°W to 20°E. This area encompasses diverse climatic zones, ranging from arid Sahelian to humid Guinean, making it an ideal natural laboratory for studying monsoon dynamics and their response to external forcings.

b) Data Sources

This research will utilize a diverse array of data sources, including long-term meteorological and hydrological datasets as follow:

i) Regional climate models

CORDEX-CORE: CCLM5-0-15, REMO2015, RegCM5 forced with ERA5 reanalysis data, spatial resolution of 0.25°,1981-2009/2010

ii) Reference data

- CHIRPS V2.0, 1981 to present, spatial resolution of 0.25° (~28 km) (Funk et al. 2014, 2015)
- GPCC V2020, 1891 to 2019, spatial resolution of 1.0° (Schneider et al. 2020)
- TAMSAT V3.1, 1983 to present, spatial resolution of 0.25° (Maidment et al., 2017)
- CRU TS V4.06, 1901 to present, spatial resolution of 0.5° (Harris et al., 2020)
- ERA5 reanalysis data, 1979 to present, spatial resolution of 0.25°, the Copernicus Climate Change Service (C3S) (2019) (Hersbach et al., 2020).
- Alongside outputs from Geoengineering Model Intercomparison Project (GeoMIP) simulations. Four distinct simulation sets will be analyzed: two baseline scenarios without geoengineering interventions and two geoengineering scenarios.

The baseline scenarios correspond to the Shared Socioeconomic Pathways (SSPs) SSP2-4.5 and SSP5-8.5 (Meinshausen et al., 2020). SSP2-4.5 represents a moderate emissions trajectory with balanced challenges for mitigation and adaptation, while SSP5-8.5 reflects a high-emissions pathway associated with limited climate change mitigation efforts and a fossil-fueled development scenario (Burgess et al., 2020).

The geoengineering scenarios include G6solar and G6sulfur, which are part of the GeoMIP framework. The G6solar scenario involves a reduction in solar constant to offset radiative forcing associated with a high-emissions scenario like SSP5-8.5. Conversely, the G6sulfur scenario simulates the injection of sulfur dioxide into the stratosphere to increase sunlight reflection and reduce surface warming (Kravitz et al., 2015). These scenarios will be instrumental in evaluating the potential impacts of Solar Radiation Management (SRM) on regional climate systems, particularly the West African Monsoon (WAM).

Additionally, high-resolution simulations using the Regional Climate Model (RegCM5) will be conducted, tailored specifically to the study region. RegCM5 is chosen for its demonstrated ability to accurately simulate WAM dynamics, including monsoon onset, spatial rainfall patterns, and extreme weather events. To ensure robust and reliable results, the performance of RegCM5 will be thoroughly evaluated against observational datasets.

c) Methods

The simulations will be performed using regional climate models highlighted in *section i)*, configured with high spatial and temporal resolution to accurately capture key monsoon processes. A comprehensive evaluation of the model's performance will compare its outputs with observational datasets and other models within the GeoMIP ensemble, focusing on its capacity to simulate monsoon onset, intensity, and spatial variability.

To achieve a holistic understanding of WAM variability under SRM scenarios, this study will integrate observational data with model outputs. Multi-model ensemble simulations, based on CORDEX regional climate models, will also be employed to address uncertainties, leveraging high-performance computing facilities for computationally intensive tasks.

Several indices will be applied for monsoon analysis, including the Standardized Precipitation Evapotranspiration Index (SPEI), Precipitation Concentration Index (PCI), Precipitation Concentration Degree (PCD), and Precipitation Concentration Period (PCP). These indices will facilitate detailed assessments of monsoon variability and its broader implications.

Statistical methods such as trend analysis, correlation analysis, and anomaly detection will be employed to uncover patterns and relationships within the data. This comprehensive approach will ensure that the study provides robust and actionable insights into the impacts of SRM on WAM dynamics.

1.4 Technical and Non-Technical challenges, and Mitigation Strategies

One of the primary technical challenges of this project is establishing and maintaining the computational infrastructure required for high-resolution climate modeling. These tasks demand substantial computing power, efficient storage systems, and expertise in managing large datasets. Key technical challenges include:

- Running high-resolution Regional Climate Models simulations and performing multi-model ensemble analyses, which require access to high-performance computing (HPC) systems. These simulations are computationally intensive, necessitating not only advanced hardware but also skilled personnel to manage and maintain these systems. In West Africa, where resources for climate modeling are often limited, establishing such infrastructure presents a considerable challenge.
- Dynamical downscaling of global datasets to the regional scale involves complex modeling techniques and precise data processing tools to ensure accurate and regionally relevant results for studying the West African Monsoon (WAM).

Mitigating these challenges, the project will utilize regional climate centers equipped with HPC facilities, such as the West African Climate Science Service Centre on Climate Change and Adapted Land Use (WASCAL) HPC in Ouagadougou, Burkina Faso. The WASCAL HPC infrastructure includes 20 nodes, 320 cores, 1TB of RAM per node, 2 Mgnt , 2 Object, 2 Metadata servers, and over 250TB of storage, supported by a 10G network system based on SFP. This robust infrastructure will provide the necessary computational capacity for the project's simulations.

Additionally, the project will benefit from collaboration with the Climate Systems Analysis Group (CSAG) at the University of Cape Town (UCT). CSAG has extensive experience in managing computational resources and offers technical support for climate research through its local data center, which is staffed by skilled software and hardware engineers. Their expertise will help ensure smooth execution of computationally demanding tasks.

The project will also engage with the Degrees Initiatives team, supported by ARIA, to enhance access to critical data and computational resources. Furthermore, collaboration with initiatives such as the **Global to Local Impacts of SRM Project (GLISP) project teams** will provide access to global expertise in climate modeling and downscaling. GLISP's commitment to maintaining accessible repositories of high-quality climate data will help address existing gaps in data availability for the Global South, providing significant benefits to this project.

A major non-technical challenge involves selecting the most appropriate downscaling methods for precipitation and other key climatic variables.

In mitigating this, the **Global to Local Impacts of SRM Project (GLISP) project teams** from UCT have capacity for both statistical and dynamical downscaling. Collaborations in conjunction with ARIA's support, connected this project to the UCT, **GLISP** project aims to make downscaled global climate data accessible to researchers in the global south.

1.5 Description of the proposed activity of work

WP 1 – Data Collection and Preprocessing

This work package involves assembling meteorological, hydrological, and climate model dataset necessary for understanding the variability of the WAM under baseline and geoengineering scenarios. This phase forms the foundation for subsequent modeling and analysis by ensuring high-quality and consistent data inputs. Therefore, the activities include:

a) Collection of observational datasets, including precipitation and temperature, from GPCC, TAMSAT, CRU, and CHIRPS.

b) Acquire reanalysis datasets such as ERA5, which provide a comprehensive historical record of atmospheric conditions.
c) Model outputs from Shared Socioeconomic Pathways (SSPs) SSP2-4.5 and SSP5-8.5 to establish baseline scenarios, offering insights into climate variability without SRM interventions.
d) Collect outputs from Geoengineering Model Intercomparison Project (GeoMIP) simulations under G6solar and G6sulfur scenarios for the evaluation of SRM's potential impacts on WAM dynamics.
e) Perform quality control and preprocessing to standardize datasets, ensuring compatibility across different data sources. This includes regridding data to a uniform resolution, addressing missing values, and correcting biases.

WP 2 - Climate Modeling and Simulations

This work package focuses on leveraging the capabilities of the Regional Climate Model (RegCM5) to simulate WAM dynamics under baseline and SRM scenarios. The WP include:

f) Configure RegCM5 with region-specific parameters to ensure accurate representation of WAM features, such as monsoon onset, spatial variability, and extreme weather events.
g) Use of high-resolution grids to enhance the model's ability to capture fine-scale processes critical to WAM dynamics.
h) Conduct simulations for SSP2-4.5 and SSP5-8.5 scenarios to provide a reference for understanding the natural variability of WAM under moderate and high-emission pathways.
i) Perform simulations for G6solar and G6sulfur scenarios, assessing the impacts of SRM interventions on WAM variability and wet-dry spell dynamics.
j) Compare simulated outputs with observational datasets to evaluate the model's performance in capturing key climatic features. Iteratively refine the model configuration to improve accuracy.

WP3 - Analysis of Wet-Dry Spell Dynamics

This work package utilizes statistical indices (SPEI, PCI, PCD, PCP) to analyze WAM variability.

This work package focuses on applying statistical methods to analyze the variability of WAM under the simulated scenarios. The statistical methods include:

k) The use of indices such as the Standardized Precipitation Evapotranspiration Index (SPEI), Precipitation Concentration Index (PCI), Precipitation Concentration Degree (PCD), and Precipitation Concentration Period (PCP) to quantify the characteristics of wet and dry spells.
l) Assess changes in the frequency, duration, and intensity of extreme wet and dry spells under baseline and SRM scenarios.
m) Trend analysis to identify long-term changes in WAM variability.
n) The use of correlation analysis to explore relationships between climatic variables and WAM behavior.
o) Examination of spatial patterns of rainfall distribution and their temporal evolution across the West African region. Highlight potential hotspots of vulnerability to SRM-induced changes.

WP4 - Evaluation of Model Performance

The final work package evaluates the reliability and robustness of RegCM5 simulations by benchmarking them against observational and ensemble datasets. The activity will consist to:

p) Evaluate the accuracy of RegCM5 outputs by comparing them with observational datasets (GPCC, TAMSAT, CRU, CHIRPS) and reanalysis data (ERA5).
q) Compare RegCM5 results with other models in the GeoMIP ensemble to assess consistency and identify sources of uncertainty.
r) Use statistical metrics such as bias, root mean square error (RMSE), and correlation coefficients to quantify model performance.
s) Conduct sensitivity analyses to determine how model outputs respond to variations in key parameters, ensuring robust interpretations of the results.

1.6 Estimated Timelines and Project Plan

Activities	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Data collection and preprocessing (WP1)	■	■	■	■																																
Data quality control and standardization (WP1)					■	■	■	■																												
Configuration of RegCM5 for simulations (WP2)									■	■	■	■																								
High-resolution simulations for baseline scenarios (WP2)													■	■	■	■																				
Simulations for geoengineering scenarios (WP2)																	■	■	■	■																
Initial statistical analysis of WAM variability (WP3)																					■	■	■	■												
Detailed analysis of wet-dry spells (WP3)																									■	■	■	■								
Model performance benchmarking and sensitivity analysis (WP4)																													■	■	■	■				
Final reporting, policy recommendations, and dissemination (All WPs)																																	■	■	■	■

1.7 Milestones and Stage Gates

The project will adopt a stage-gated approach to funding and implementation, with each phase tied to specific deliverables:

Gate 1 (Year 1, Q1- Q2): Successful completion of WP1 with a curated dataset collection and quality control and initial model configuration.

- Deliverables: Quality-controlled datasets, interim report on data preparation.
- Funding Tranche: **£50,000**

Gate 2 (Year 2, Q3-Q5): Completion of WP2, including high-resolution simulations for all scenarios.

- Deliverables: Scientific publication on simulation results, on WAM variability under SRM.
- Funding Tranche: **£100,000**

Gate 3 (Year 3, Q6-Q7): Finalization of WP3 and WP4, ensuring robust analysis of WAM dynamics and model performance.

- Deliverables: second scientific article publication based on comprehensive analysis on validated model outputs.
- Funding Tranche: **£75,000**

Gate 4 (Year 3, Q8-Q9): Integration of results and dissemination.

- Deliverables: Final report, policy briefs, peer-reviewed publications.
- Funding Tranche: **£25,000**

Section 2:

2 Details of the Project Team

The project will be implemented by an interdisciplinary team of experienced researchers and professionals, each bringing unique expertise in climate modeling, monsoon dynamics, and solar radiation management (SRM). The team members are carefully selected to ensure a balanced blend of technical, scientific, and policy-oriented skills, creating a robust framework to address the complex challenges posed by SRM and its impacts on the West African Monsoon (WAM). Below is a detailed description of each team member's role, expertise, and time commitment to the project.

[redacted]

[redacted]

Role and Contribution: [redacted] will oversee all aspects of the project, ensuring seamless integration of activities across work packages. [redacted] will dedicate 100% of his time to managing the project, supervising the modeling efforts, coordinating data acquisition, and leading the analysis of WAM variability under SRM scenarios and report writing (publications article).

[redacted]

Role and Contribution: [redacted] will lead the project, dedicating 70% of [redacted] time to supervising the climate modeling and dynamical downscaling tasks. [redacted] primary focus will be on configuring RegCM5 and analyzing its performance in simulating monsoon features under SRM scenarios. [redacted] will also provide expertise in evaluating the physical processes influencing WAM variability and contribute to capacity-building activities for junior researchers. [redacted] will also act as the primary liaison with external collaborators such as the Climate Systems Analysis Group (CSAG), **Global to Local Impacts of SRM Project (GLISP) project teams under ARIA funding** and WASCAL Competence Centre for HPC access.

[redacted]

Role and Contribution: [redacted] will dedicate 30% of [redacted] time to statistical analysis and quality control of the datasets. [redacted] will be responsible for preprocessing observational and reanalysis data, applying indices like SPEI, PCI, PCD, and PCP, and conducting trend and correlation analyses. [redacted] role is critical in deriving actionable insights from the modeled data and ensuring its alignment with the project's objectives.

[redacted]

Expertise and Role: [redacted] Working closely with [redacted] will be responsible for data preprocessing, quality control, and the organization of large datasets for analysis. [redacted] will also contribute to the calculation of statistical indices and assist in developing visualization tools for presenting the results.

Time Dedication: [redacted] will dedicate 30% of [redacted] time to the project, focusing on data management, statistical analysis, and model validation tasks.

[redacted]

Role and Contribution: [redacted] will dedicate 20% of [redacted] time to analyzing the impacts of SRM scenarios on water resources and agricultural systems in West Africa. [redacted] will collaborate on the evaluation of rainfall variability and extreme weather events, ensuring that the results are directly applicable to agricultural planning and water management. [redacted] insights will enhance the relevance of the findings for policy and adaptation strategies.

- [redacted] **Role: Technical guidance and model refinement.**
- [redacted] **Role:** Support in downscaling techniques and analysis of SRM impacts.

2.1 Collective Contribution and Integration

The project team will adopt a collaborative approach, leveraging their diverse expertise to address the multi-faceted challenges of SRM and WAM variability. Each team member will contribute to multiple work packages while maintaining clear delineation of roles and responsibilities:

a) **Data Collection and Preprocessing (WP1):** [redacted] and [redacted] will lead the quality control and standardization of datasets, with support from [redacted] and [redacted] will oversee the integration of data from various sources, ensuring compatibility and consistency.

b) **Climate Modeling and Simulations (WP2):** [redacted] and [redacted] will co-lead the configuration and execution of RegCM5 simulations, with technical input from [redacted] and [redacted] on data integration. [redacted] will provide domain-specific expertise on interpreting simulation outputs.

c) **Wet-Dry Spell Dynamics Analysis (WP3):** [redacted] and [redacted] will take the lead in applying statistical indices and conducting trend analyses. [redacted] and [redacted] will guide the interpretation of findings in the context of WAM dynamics and SRM impacts.

d) **Model Performance Evaluation (WP4):** [redacted] will lead the benchmarking of RegCM5 outputs, collaborating with [redacted] to compare model performance against observational and ensemble datasets.

2.2 Time Allocation and Commitment

- [redacted]**:** 100% time commitment.
- [redacted]**l):** 70% time commitment.
- [redacted] 30% time commitment.
- [redacted] 30% time commitment.
- [redacted]**:** 20% time commitment.

2.3 Team Coordination and Management

The project team will adopt a collaborative management structure, emphasizing efficient communication, clear role delineation, and task integration. [redacted] as the Lead Principal Investigator, will spearhead project coordination, ensuring seamless collaboration among team members and external partners.

e) **Internal Coordination:**

- Bi-Weekly virtual meetings will be held during the first 6 months of project to review progress, address challenges, and allocate tasks for the upcoming week. After 6 months the virtual meetings will be held monthly.
- Each work package will have a designated lead (e.g., [redacted] for WP2, [redacted] for WP3), ensuring accountability and clarity.
- Shared digital platforms like Google Drive and project management tools will be used for document sharing and task tracking.

f) **Collaboration with Third Parties:**

- Monthly consultations with UCT collaborators ([redacted]) will provide technical input and ensure alignment with project objectives.
- Periodic check-ins with GLISP project representatives will address challenges in data acquisition and downscaling methods.

2.4 Addressing Potential Gaps in Core Competencies

The team's interdisciplinary expertise covers most areas required for the project. However, some gaps may arise, particularly in:

- Advanced computational expertise**:** While the WASCAL HPC infrastructure is robust, technical support may be required for optimizing model performance and troubleshooting.
- Specialized SRM knowledge: Collaborations with GLISP and ARIA experts will provide additional insights into the nuanced impacts of SRM.
- Policy translation: While the team is scientifically strong, translating findings into actionable policy recommendations may require additional support from policy specialists.

Mitigation Strategies:

- Engage technical experts from CSAG for computational troubleshooting and system optimization.
- Leverage GLISP's knowledge-sharing platforms to fill gaps in SRM expertise.
- Collaborate with regional policy institutes to bridge the gap between scientific findings and policy formulation.

2.5 Motivation and Suitability

The team's motivation is driven by a shared commitment to addressing the pressing challenges posed by climate variability and change in West Africa. The profound impacts of WAM on regional livelihoods highlight the urgency of this research, which seeks to inform sustainable development and climate resilience strategies. Additionally, the team is motivated to contribute to the scientific exploration of SRM and its impacts on the West African climate. This includes analyzing both the potential positive and negative implications for climate tipping points across different subregions and regions of West Africa.

Another key motivation is to actively support and build a well-connected community of African SRM researchers. Strengthening this network is crucial to enhancing Africa's capacity to engage in the global discourse on SRM. By contributing in placing Sub-Saharan Africa – the continent most vulnerable to climate change and its impacts at the forefront of scientific and policy discussions, the team seeks to contribute addressing the historical dominance of the Global North in climate research and policy development, ensuring a more inclusive and equitable approach to addressing climate challenges.

Why This Team is the Right Fit:

- The team's collective experience in climate modeling, SRM, and monsoon dynamics ensures the scientific rigor required for the project.
- **Regional Focus:** With team members rooted in West Africa, the project is well-positioned to address context-specific challenges and engage local stakeholders effectively.
- Existing partnerships with institutions like CSAG - UCT, The Degrees Initiative and WASCAL highlight the team's ability to work collaboratively across disciplines.
- By involving junior researchers like [redacted] and [redacted] the project contributes to building local expertise, ensuring long-term benefits beyond the project's lifecycle.

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Ice-Nucleating Particles in the Upper Troposphere: Advancing Cirrus Control and Experimental Science Strength "INPUT:ACCESS"

[redacted]

Abstract: We will advance process-level understanding of three climate cooling approaches focused on cirrus clouds and water vapor controls at high altitudes. Cirrus processes are one of the largest sources of uncertainty in surface temperature response to climate change, and central to several intervention ideas. Hence, in situ measurements are needed to assess specific drivers of ice nucleation. We will address this need by combining our respective expertise in 1) balloon-borne measurements, 2) ice nucleating particle measurements, and 3) cirrus modeling. Our proposed efforts will enable us to advance both the measurement technology and the understanding of ice processes and parameters relevant to cirrus interventions. We will launch small weather balloons with novel instrumentation to collect ice nucleating particles from the cirrus regime, analyze them under laboratory recreations of cirrus conditions, and port our findings to improve model assessment of cirrus intervention impacts. These capabilities, which have never previously been achieved, will dramatically change the landscape of cirrus-relevant research. If large-scale outdoor testing – or deployment – ever occurs in regards to related climate interventions, then the balloon payload and analysis techniques developed in this proposal will be essential for monitoring. Climate intervention via manipulating upper troposphere cirrus may provide significant surface cooling with minimal environmental effects; this study will strengthen confidence in evaluating cirrus cloud related interventions, as well as identifying the most efficient ways to apply them.

I. Background: Water vapor (WV) and cirrus ice clouds in the upper troposphere (UT) strongly affect Earth's radiation balance by trapping long-wave radiation. Three climate intervention (CI) approaches focus specifically on manipulating UT/lower stratospheric water vapor and/or cirrus thickness/lifetime to reduce global climate forcing. They are: **cirrus cloud thinning** (CCT, focused on reducing homogeneous nucleation of UT cirrus(*1*)), **contrail management** (CM, focused on diverting civilian aircraft to influence cirrus cloud formation for climate benefits (*2*)), and **intentional stratospheric dehydration** (ISD, focused on reducing WV at the tropical tropopause layer (TTL) entry to the stratosphere by seeding short-lived cirrus (*3*)). However, these approaches rely upon manipulation of some of the least well understood phenomena in the climate system. As models do not represent cirrus cloud formation well, confidence in the effectiveness of these approaches to cool our climate is low. Currently available measurements are inadequate to constrain the models. This is due to the fact that:

1) Small variations in water vapor (WV) concentrations, which can only be measured in situ, can have large impacts on relative humidity and thereby cloud formation. Direct in situ measurements are not widely available for model initialization, and global model resolution is too coarse for realistic representation. Consequently, models have poor skill in predicting ice-super-saturated airmasses in the UT; however this is a necessary capability on which all three interventions depend.

2) Measurements of ice nucleating particles (INP) composition and concentration in the UT are critically rare, and development of off-line analysis abilities is an ambitious paradigm changer for such research. Presently, our understanding of the most relevant sources of INP depend on extremely limited determinations primarily from high altitude aircraft campaigns that, by nature, are not global in representation. Laboratory determinations of INP nucleating properties at temperatures in the cirrus regime below ~240K depend on equipment available at only a few institutions, and are not suitable for routine measurement or for samples collected in situ.

3) Direct measurements even of cirrus cloud spatial and crystal size distributions are rare and usually only associated with research aircraft campaigns. Without these data, the connections between INP, WV, ambient temperature and actual cloud and radiative impact are very tenuous. In sum, these limitations severely hinder confident assessment of the potential of cirrus/WV controls as effective climate interventions. We propose to develop and apply technologies that will provide unprecedented data on ambient INP to assess applicability and to guide implementation of high-altitude cirrus climate interventions. Specifically, we will enhance our knowledge of UT WV and ice supersaturation distributions, and their dependence on INP type and concentration through new measurements.

II. Concept: We will simultaneously measure UT WV, INP, and cirrus crystal vertical profiles using balloon-borne instruments. Providing INP characteristics and concentrations within the context of the larger aerosol population and air mass humidity and temperature in the cirrus regime is a new and innovative approach to evaluating cirrus-relevant interventions. This effort will address the critical issues relevant to all three of the cirrus cloud related climate cooling approaches and to natural cirrus and UT WV controls more generally. First, we will advance measurement technology by developing balloon-borne INP collectors and cirrus crystal measurements. We will extend UK capabilities to provide routine cirrus-regime INP measurements in a laboratory setting (which will also support evaluation of synthetic INP for other ARIA efforts). These advances will provide critically needed constraints for models on the actual background UT INP available to influence cirrus formation and dehydration. Second, we will correlate our observations with air mass history and evolution focusing on cirrus formation/evaporation, convective anvil injections, and possible air-traffic corridor radiative processes. Third, we will document actual cirrus ice crystal size distributions and frequencies, elucidating formation and aging processes. Finally, we will integrate our findings into regional and global models to ensure that these efforts translate into usable information relevant to CM, CCT and ISD.

III. Research methodology:

III.1 Develop ability to collect INP from cirrus regions:

Large uncertainties about the sources, distribution, and ice nucleating ability of INP relevant to cirrus persist. Methods to measure them are extremely limited. For example, ice crystal residuals have been measured from a specialized high-altitude aircraft with Particle Ablation by Laser Mass Spectrometry PALMS (4), but these measurements are spatially limited, and, as they were performed on residuals, include additional uncertainties associated with potential post-nucleation coagulation.

Our first goal is to develop the technology necessary to collect INP from cirrus regimes onto substrates for off-line analysis. Although INP collection for offline sampling has been carried out routinely at the surface and even in the lower-mid troposphere with high-volume samplers (e.g. Sanchez-Marroquin et al. 2019 (5), the challenges of collection in the low pressures of the upper troposphere have not yet been overcome. These challenges include 1) low concentrations of INP (1/liter marks the minimum concentration that we have identified as necessary to constrain) 2) cold temperatures and dry conditions, and 3) Reaching cirrus altitudes. INP at the surface can activate at temperatures as high as 270 K. However, cirrus conditions are much more extreme, with temperatures of 210 K (~10-12 km) in the midlatitudes to as low as 185 K (~ 17 km) in the tropics. Hence sampling of INP under cirrus conditions is much more difficult than those relevant to low altitudes. Deploying INP collectors at cirrus regime altitudes can only be done with balloons or aircraft. As balloons are cheaper, more versatile, and provide an excellent testbed to develop and test new instrumentation, they are the proposed for this work.

Hence, we will develop collectors for use on small balloons that are potentially extendable to aircraft deployment. The proposal team has long expertise in balloon-borne observations for rapid-deployments in response to specific events and long-term monitoring of aerosol, ozone, and WV vertical profiles (Balloon Baseline Stratospheric Aerosol Profiles, B^2SAP, csl.noaa.gov/projects/b2sap/). We are very well positioned to apply this expertise to INP collection and are currently building an aerosol collector for balloon deployment. This development effort is underway, funded via NOAA/U. Colorado, and first flights are expected in Spring, 2025. This collector may be appropriate for INP, providing the ability to collect multiple samples in different altitude ranges. For this proposal, we will also explore an alternate design using an electrostatic precipitator. This approach stems from a proven design applied to INP collection and analysis (*6*). The electrostatic precipitator has excellent collection efficiency at even 5 lpm, a very high flow rate we believe is achievable even in the extremely thin air of the UT. At this rate, and a standard balloon climb/descent rate of 5 m s^{-1}, we will be able to sample aerosol from ~60 liters of air in a two-kilometer deep layer at the top of the troposphere. The minimum INP concentration of interest for cirrus is a few per liter. At this concentration, we would expect to collect on order 200 INP on a filter, which would then provide an uncertainty in the concentration of less than 10%. This provides a very reasonable expectation for success, assuming that we can port this design to balloon use. Our expectation is that the collector will gain efficiency in aerosol collection at high altitude relative to lower altitudes, but we will test this in an environmental chamber at NOAA.

III.2 Develop off-line analyses of INP relevant to cirrus formation and controls:
Our team includes experts from the UK whose research focuses on ice nucleation research in a variety of atmospheric conditions. UT ice formation is a particularly challenging area of research that will require extending existing techniques to colder and drier conditions. We will begin our effort by designing an ice nucleation chamber based on the FRIDGE isothermal diffusion chamber (IDC) (*6,7*) constructed at Goethe University Frankfurt. FRIDGE has been used for INP analysis on collected filters down to 238 K, but is not suitable for mid-latitude cirrus temperatures (down to ~210 K) or TTL conditions (ideally down to 185 K) as unwanted ice tends to form in the silicon substrate used. Studies using quartz substrates coated with silanising agents are known to resist ice formation in the conditions we need to access. The new IDC will be built at UoL and tested using relevant concentrations of known INPs sampled from the Leeds Aerosol Chamber (LAC) to establish that we can make the types of measurements needed for both this proposal, and those of Phase 2 of the MAD-INC: Machine learning Assisted Design of Ice Nucleators for Climate Engineering ARIA proposal led by [redacted]

We anticipate using a liquid nitrogen cooling system to achieve temperatures, along with high-vacuum equipment produced by the School of Earth and Environment mechanical workshop. The Leeds team has very extensive experience of building ice nucleation equipment ranging from simple droplet freezing assays to cloud chambers. The existing FRIDGE design uses a rather large substrate, to enable good statistics on INP measurements without the problem of nucleation on substrate imperfections at lower temperatures. Our new design will reduce the size of the substrate, allowing a more optimal balance between INP detection and influences from the substrate. We will apply the new IDC to evaluating our experimental procedure for preparing, loading, transporting and analyzing INP collection substrates for cirrus study. Ultimately, this system will provide INP activity and concentration for the collected samples. The approach also allows individual INPs to be localized after which Scanning Electron Microscopy (SEM) and Energy-dispersive X-ray spectroscopy (EDX) analysis will be used to generate compositional information for the INP, constraining future focus to specific sources of cirrus INP.

III.3 Develop in situ measurements of cirrus crystals
Cirrus ice crystal concentration and size distributions are critical measurements necessary to evaluate impacts of injected INP in CCT and ISD, and relevant to perturbed cirrus from some CM approaches. Crystal size affects cirrus lifetime and radiative impacts. At NOAA, we are developing an In situ Balloon-borne Ice Spectrometer (IBIS). This is a new, provisionally patented instrument, designed for deployment on small free-release balloons. First test flights of the prototype are expected in Spring, 2025. IBIS has been shown to resolve particles to below 3 µm diameter, a requirement for detecting TTL cirrus and more than adequate in the mid-latitudes. IBIS samples a cross-section of 0.5 × 0.5 cm, corresponding to a sample volume of 25 $cm^3 s^{-1}$, approximately 8 times higher than used for total particle measurements with the POPS instrument.

III.4 Apply these technological advances to measurements in the mid-latitudes
We will perform a measurement campaign using the technical capabilities developed above. At least 10 balloon launches from Boulder, CO, USA will be carried out in year two. Boulder, CO is the longest-standing site for B^2SAP, with more than 100 successfully launched and recovered balloon payloads. Hence it is the ideal location to allow easy operations and scientific evaluation of the observations in the context of a multi-year climatology of aerosol, ozone, and WV. Launch timing will be optimized based on transport model forecasting coupled with initialization via GPS-radio occultation temperature measurements. Modeling work from Imperial College London (see below) will help with these forecasts, with potential further improvement if results are available from the “De-risking cirrus modification” project proposed by Dr Eastham. This measurement series will provide first determinations of INP concentration, composition, and relevance to mid-latitude cirrus formation and controls. We have optimized our plans for the balloon payloads to minimize complexity and maximize value. We will deploy IBIS, the INP sampler, and a suitable WV measurement with balloon telemetry and position information only. WV concentration is extremely relevant to cirrus, and can be used as an indicator of stratospheric influence in the mid-latitudes (hence dispensing with the need for inclusion of an ozone measurement). A low-cost, very lightweight WV measurement that we have determined is as good as that from a frost-point hygrometer in the mid-latitudes upper troposphere can be provided by a Vaisala RS41 radiosonde. The

use of the RS41 radiosonde requires the use of a proprietary ground receiver (NOAA operates one in Boulder, CO).

III. 5 Apply our observations to advance modeling of cirrus-relevant climate cooling strategies:
Finally, we propose a period of analysis to ensure that the measurements will be fully QA/QC'd, publicly archived, integrated into models, and assessed for relevance to potential climate interventions and cirrus science more broadly. As part of this work, we will compare our observations to model output and infer potential model improvements which could support CM, CCT, and ISD trials. Of particular relevance is the Community Earth System Model Version 2 (CESM2) climate model, already established at Imperial College London. Global cirrus frequency and properties will be generated using an ensemble of conventional model runs (Year 1), which will in turn be used to inform launch timing (Year 2). The output from these runs will be compared to the INPUT:ACCESS observations, with the goal of generating statistical corrections (Year 3). These will in turn be used to assess the degree to which efficacy of different climate cooling approaches might have been historically over- or under-estimated. If funded, results from the "De-risking Cirrus Modification" ARIA proposal will also be incorporated into this effort.
Conclusions will be disseminated to the community via conference presentations and peer-reviewed publications.

IV. Budget Narrative, Timelines with work packages

Budget narrative: The budget will support coordinated efforts at three different institutions, two in the UK, and one in the USA. The University of Leeds (UoL) is the primary applicant, with NOAA in the USA and the Imperial College London as subcontractors.

The work at UoL will focus on the INP analyses, including substantial effort on developing the new IDC for measurement of INP concentrations in cirrus conditions. A dedicated postdoctoral research fellow will be hired for the duration the project, tasked with constructing and testing the IDC, developing methods for safely transporting slides carrying cirrus INPs, conducting measurements on INPs collected from balloon launches in Colorado and performing SEM analysis on test and collected INPs. We have budgeted £88,000 to cover workshop costs, materials and equipment needed to construct and test the IDC. This includes high-vacuum equipment, a high-end turbopump, chillers capable of cooling the equipment to below 180 K and instrument PCs. We have also requested £12,000 to cover SEM measurements and other consumables that will be needed for the project. [redacted] will devote 0.2 FTE for the three years of the project allowing him to work hands-on with postdoc and the instrument to ensure success. [redacted] will contribute his extensive experience in INP measurements and help coordinate efforts with other ARIA projects and the wider atmospheric science community.

The work in the USA will be focused on the balloon-instrument development, testing, and deployment. ARIA will support a full time scientist, hired through the cooperative agreement between NOAA and the University of Colorado, and a part time scientist to support ARIA specific balloon flight forecasting, balloon operations, and post flight analysis (0.2 FTE during year 1, 0.4 FTE during year 2) NOAA will provide very substantial in-kind funding in the form of additional scientist support (including the efforts of [redacted]), engineering and software support, cover materials and instrument costs (i.e. IBIS, the INP collector, balloons, the water vapour measurement, helium, etc., publications, and travel.

The efforts at Imperial College London will support [redacted] contributions to directing optimal deployment of the balloons and using data collected to improve process understanding of cirrus formation, and consist of labor (1 month/year support for [redacted] and travel costs.

Timeline and work packages: We envision three years of support, with the following support level (funding tranches) and deliverables:

Year 1: Scientist at UoL focused on instrument development incurring materials and equipment costs. Scientist at NOAA focused on balloon instrument development. 0.2 Scientist equivalents of effort at NOAA supporting balloon launches for testing. 1 month support for engagement of [redacted] to establish baseline model runs at ICL.. (Material/deployment costs for the balloon instruments will be borne by NOAA). *Deliverables:* Anticipated start of efforts to hire is February 2025. Hire at Leeds within 3 months; hire at NOAA within 3 month, making month zero May 2025. By end of year 1 new IDC will be functional; testflight(s) of IBIS conducted; INP collector designed and constructed.

Year 2: Scientist at UoL focused on developing methods for off INP analysis and analysis of INP on slides. PostScientist at NOAA focused on balloon instrument deployment/collaborative testing of collected INP assays. 0.4 Scientist equivalents at NOAA supporting balloon launches for deployment, data archiving, etc. 1 month support for engagement of [redacted] on model support for launch timing. *Deliverables*: Finalization of INP chamber build and testing; successful balloon deployment in mid latitudes; first successful INP measurements on resulting slides

Year 3: Scientist at UoL focused on the INP analysis findings, manuscript preparation. Scientist at NOAA focused on balloon instrument manuscript writings and analyses relevant to cirrus interventions. 1 month support for [redacted] on modelling incorporating observational findings. *Deliverables:* IBIS and INP collector established and available for launch as part of B2SAP launches from the tropics. Analysis of year 2 findings, incorporation of findings into cirrus model. Manuscript preparation relevant to: a) INP chamber performance and design, b) IBIS, c) INP collector, D) INP findings, relevance to cooling strategies and impacts on model performance. In year 3, all INP measurements will be made publicly available after quality assurance evaluations.

Workplan:

Month	Year 1				Year 2				Year 3			
NOAA activities – WP1												
Ballon instrument development (electrostatic precipitator, In situ Balloon-borne Ice Spectrometer (IBIS)).	■	■	■	■								
Balloon instrument deployments in Colorado with associated measurements and INP collections					■	■	■	■				
Support deployment of IBIS and INP collector for other balloon launches							■	■	■	■		
Joint analysis of data from balloon flights									■	■	■	■
University of Leeds activities – WP2												
Design and construction of new isothermal diffusion chamber (IDC) for INP measurements	■	■	■	■								
Development of transport methods for slide carrying cirrus INPs			■	■								
Development of scanning electron microscope techniques for characterisation of cirrus INPs				■	■							
Testing of IDC using aerosol sampled from the Leeds Aerosol Chamber			■	■	■	■						
Measurement of balloon-collected INP samples using IDC and SEM					■	■	■	■	■	■		
Joint analysis of data from balloon flights									■	■	■	■
Imperial College activities – WP3												
Establishment of baseline model runs	■	■	■	■								
Modelling support for timing balloon launches					■	■	■	■				
Model runs incorporating findings from balloon flights									■	■	■	■

Budget options: There are possibilities to reduce the cost and scope of effort proposed here. We believe that the proposal presented provides the strongest and most synergistic support to addressing CM, CCT, and ISD possibilities. However, isolated efforts for example to 1) develop a cirrus-relevant ice nucleation chamber for routine measurements, 2) develop an INP collector for the cirrus regime, or 3) develop the IBIS instrument for cirrus crystal measurements, would all independently provide significant strengthening of the technical infrastructure needed to evaluate cirrus interventions. Each of these isolated efforts could be supported by a single dedicated scientist/technician at the appropriate institution for ~ 1 year, with associated materials costs.

Technical and Non-technical challenges: The balloon payloads and flight trains will comply with local airspace regulations and each flight is coordinated with local aviation authorities for safety. An important advantage of using weather balloons and instrument packages of the size we propose is that they fall outside of rigid requirements for coordination in aircraft airspace, and thus enable flexible deployment. Although forecasts of balloon trajectories are generally reliable, recovery of balloon packages can be complicated by issues such as access to private land and terrain. We have successfully launched balloon payloads from multiple international locations including New Zealand, Réunion Island, Antarctica, and

Costa Rica. Here we propose a set of measurements from Colorado, USA, where we have a superb record of recovery. In future deployments, our international connections will be critical for ensuring high recovery rates, smooth interactions with international communities hosting launches, and sufficient infrastructure to support launches. So long as we incorporate INP collection, we will only operate from locations where we anticipate reasonable chances to recover the payloads. For example, in the tropics we have had good success recovering launches from San Jose, Costa Rica.

V. Program Alignment, Synergies with other ARIA proposal: CCT, CM, and ISD are highly uncertain but potentially useful climate cooling approaches, strongly relevant to the call. By developing the ability to acquire concurrent measurements of WV, RHi, and INP, we will advance the technology necessary to understand these approaches, as well as extend understanding of the fundamental processes that they hope to manipulate. In a world where interventions are being actively tested or deployed, our highly flexible and low-cost balloon-borne approach will be a critical tool for assessing impacts.

The technical developments proposed here (airborne INP collector, demonstrated balloon-borne ice crystal detector, extended-range ice nucleation chamber) will form the basis for future deployments on other platforms. Hence, they are synergistic with several other ARIA proposals.

The “De-risking cirrus modification” effort led by [redacted] which proposes to track changes in cirrus caused by passage of the FAAM BAe-146 research aircraft, will benefit from our work on developing the INP collection approach that will inform designs for airborne platforms. Presently, that aircraft has an INP collection system that is only effective below 20,000’ (too low to address cirrus issues). The prognostic modeling needed to plan FAAM flights for “De-risking cirrus modification” will also serve to enhance selection of balloon launch times, and will gain validation data from our launches for the following aircraft mission. Similarly, phase 2 of the ‘MAD-INC’ proposal led by PI Whale will benefit from the cirrus-regime INP evaluations enabled by the IDC chamber development.

Further, the longer-duration balloon approaches of the Voltitude ARIA proposal could support multi-filter collections and longer-term tracking of air parcel evolution and cirrus formation. Finally, our proposal is relevant to large-scale questions of WV controls and cirrus generation/radiative impacts, and the possibility that WV/CIRRUS forcing will change in future climate or under other, non-cirrus focused CI efforts.

VII. Future consequences of the proposed work:

The efforts funded by this proposal will result in long-term value for cirrus and cirrus-intervention relevant science. Briefly:
1) The development of the technology and experimental methodology for post-collection analysis of cirrus relevant INP will enable studies from all relevant platforms (long and short term balloons, UAVs, manned aircraft), as well as in future studies such as those proposed for ARIA exploring synthetic INP.
2) The balloon-borne instrumentation for collecting INP and measuring cirrus in situ will transition from development stage to operational. They will be able to support fast science deployments (for example, as were done by B2SAP for the Hunga Volcano Response), as well as long-term measurements (for example as an extension of B2SAP). NOAA anticipates pursuing a tropical deployment once the payload is fully operational; as B2SAP supports regular (but low frequency) launches from the tropics, this is a likely early opportunity for deployment.
3) We anticipate that the work on developing the INP collector for balloon deployment as described here will also apply to design development for research aircraft and alternate platforms. This would enable the collection of INP referred to in point 1, above.
4) Long-term monitoring of cirrus and UT INP properties in a changing atmosphere.

Overview of Proposal Team: Our multinational team is uniquely suited to carry out the proposed measurements and apply them to assessing and steering relevant climate cooling interventions. We include senior, mid-career, and early-career scientists with specific expertise in the topics we explore:

Cirrus processes, UT and stratospheric water vapor measurements and modeling: [redacted].

Balloon-borne observations: [redacted]

Ice nucleation measurements [redacted]

Regional-to-global modeling relevant to aviation emissions and impacts: [redacted]

Proposal Facilties:

*NOAA Chemical Sciences Laborator*y: provides a highly supportive environment for the finalization, testing, and mid-latitude deployment of the balloon packages. We are equipped with environmental chambers for low-pressure testing, design and manufacturing facilities, and aerosol testing equipment. This US Federal facility will house all the US scientists and technicians supporting the effort (consisting of both federal and cooperative institute employees).

University of Leeds: [redacted]

Imperial College London has world-class high-performance computing capabilities, already configured to support meteorological simulations across scales and used regularly in simulations of contrails and UT WV.

VIII. Response to Proposal Encouragement Feedback – Why ARIA?

We have addressed most review feedback from the NOI within the proposal body above. One question we did not address was: *"Please expound on why ARIA is the best (or only) funder of such work. Why is no one else funding this already?"*

Firstly, the questions we seek to address in this proposal are most specifically relevant to climate intervention proposals. While uncertainties surrounding upper tropospheric conditions are significant, there are many knowledge gaps that create similar-or-larger uncertainty in current understanding of the climate system, notably around the effects of mixed-phase clouds (e.g. ref 10). As such, proposals looking at cirrus conditions would have to compete with important research on many other uncertain processes for general climate-focused funding. Only ARIA is providing resources to quickly advance intervention-relevant research and development. Without this support, no clear timeline or pathway to its completion can be anticipated. For example, the aerosol filter collection work, envisioned as a possible extension to B^2SAP was not inspired by climate cooling interventions, but rather by the recent findings from our laboratory of meteoric and space debris impacts on stratospheric aerosol composition (*11*). This effort found limited external funding (<$30,000) only sufficient for material costs and is being supported only fractionally as a potential extension from a team supported for B2SAP base operations. NOAA doesn't have the resources to expand efforts directed to this or the IBIS development (which has been a side project of a semi-retired scientist and a group leader). On the side of the UK INP measurement team, cirrus-relevant measurements have received relatively little attention because collecting INPs in cirrus conditions is so challenging, meaning proposals have mostly been directed at lower-hanging fruit in other areas.

Secondly, the ARIA call catalyzed interactions between the NOAA team developing the balloon-borne instrumentation with the UK teams with foci on ice nucleation measurements and cirrus intervention modeling. Previously, the balloon effort did not consider INP, and UK measurement efforts were not appropriate for cirrus conditions. Further, opportunities for multinational teams to collaborate are very rare, especially in the context of national government support. Here, the unique strengths that enable this proposal are dispersed on either side of the Atlantic. ARIA funding is the only route that will directly harness these existing strengths in a cost effective, rapid manner.

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Section 1: Programme & Technical

1.1 The idea

Climate Engineering can be defined as deliberate intervention into the Earth's climate system in order to reduce the risks from anthropogenic climate change. Technologies that might achieve that aim fall broadly into two categories, those that focus on removing warming gases from the atmosphere, and those that focus on altering the Earth's radiation budget, typically by increasing scattering of incoming solar radiation. Known as Greenhouse Gas Removal (GGR) and Solar Radiation Management (SRM) respectively, the two categories have different challenges around efficacy, speed, scalability and, critically for this proposal, risk. SRM technologies focus mostly upon either injection of aerosols into the stratosphere or brightening of clouds in marine environments in the troposphere, and are generally considered to be effective, fast, scalable and risky opposite GGR technologies. One important pathway to quantify and reduce risk, particularly for SRM technologies, is through the study of natural analogues.

Large episodic volcanic eruptions regularly inject millions of tons of sulfur-bearing species into the stratosphere which form sulfate aerosols and subsequently reflect sunlight back into space, cooling the Earth's surface. Persistent passive degassing of volcanoes into the troposphere has been observed to alter cloud microphysics, brightening clouds and also altering the Earth's radiation balance. Volcanoes have taught us much about the atmosphere, cloud microphysics and climate[1]. Their study has also informed the efficacy of climate engineering technologies, as both of these natural processes (Figure 1) have SRM climate engineering analogues – Stratospheric Aerosol Injection (SAI) and Marine Cloud Brightening (MCB) respectively. SAI and MCB could both be used to create albedo altering effects as a deliberate intervention to create cooling in the climate system. If SAI or MCB were ever to be tested or deployed the dispersion, chemical evolution and radiative impacts of injections would need to be understood and carefully monitored.

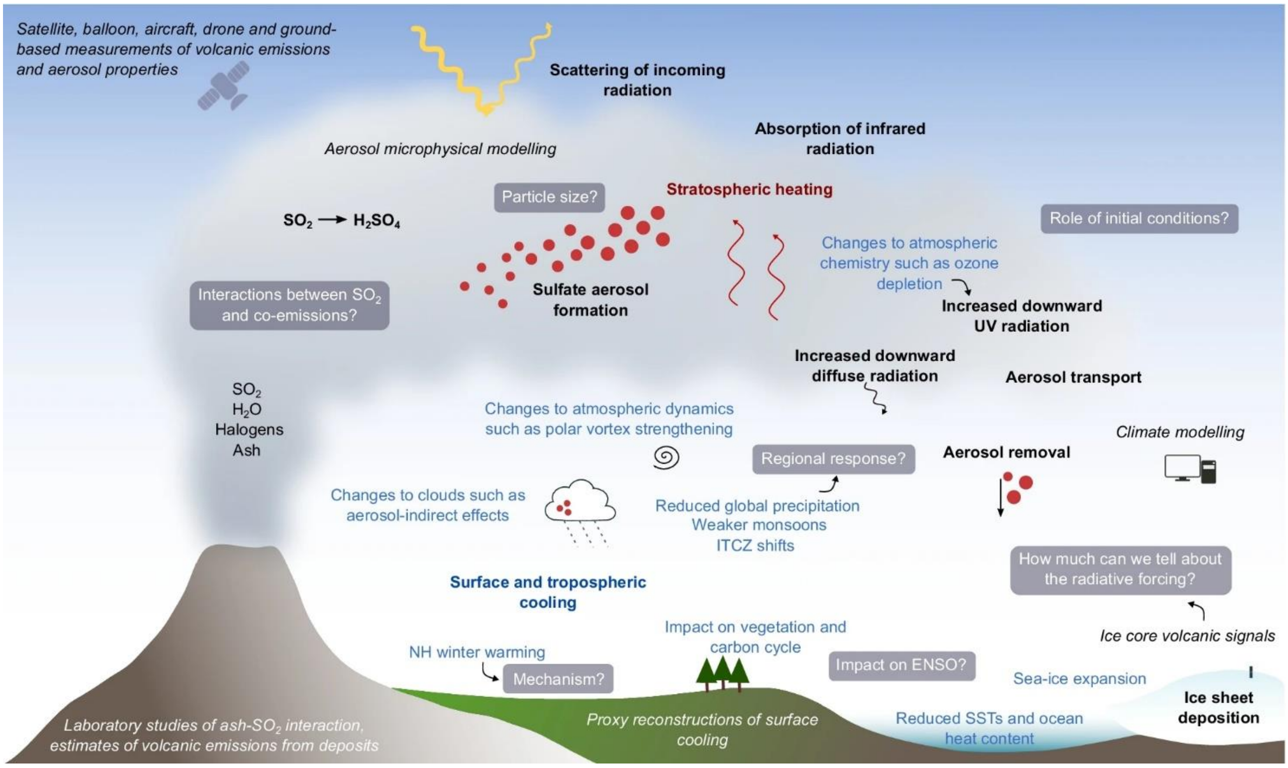

Figure 1. From Marshall et al., 2022[1]. Figure showing volcanic influence on climate include aerosol and cloud albedo effects.

Active volcanoes can be used as an analogue to develop and test the systems required to observe and monitor the injection, evolution and impacts of SRM technologies whilst also providing vital observations of how aerosols and clouds form and evolve. Volcanoes are frequent emitters of gases and producers of aerosols, and have already informed research into albedo modifying climate engineering[2,3]. However, that knowledge is incomplete - much can be learned from the next eruptions that impinge on the stratosphere or strongly alter cloud microphysics. The last eruption with a strong cooling was Pinatubo in 1991[4], over thirty years ago. However our knowledge of the climatological impacts of volcanic eruptions continues to expand with, for example, unexpected climatic responses from the recent Hunga Tonga-Hunga Ha'apia eruption[5]. Studying climate impact of eruptions at this scale presents unique measurement challenges, requiring precise 4D sampling in evolving hazardous conditions, rapid deployment, and zero emissions. This demonstrates a clear need for new aerial robotic systems (also known as uncrewed aerial systems (UAS) or drones) that can monitor and learn from smaller eruptions whilst also being ready to be deployed in the event of large-scale events[6].

We propose to develop and test aerial robotics that will quantify droplet and aerosol behaviour at injection altitudes from the lower troposphere to the lower stratosphere. The system, a modular, fully automated monitoring-focused UAS will be developed using volcanoes as analogues for SRM, in order to both better understand natural processes and prepare for outdoor experiments that aim to emulate them. Specifically, this system will be developed to (a) investigate natural analogues for both MCB and SAI and learn from frequent, smaller scale eruptions (injection altitudes up to 10 km AMSL) and passive volcanism, with a focus on aerosol and cloud formation and associated changes in radiative forcing, (b) standby aerial systems and expertise in UAS based volcanic monitoring ready for deployment during the next significant global volcanic eruption and (c) monitor and measure outdoor SRM experiments within this programme and beyond.

Our investigation will first focus on three volcanic systems, Soufriere Hills Volcano, Montserrat (1,050 m AMSL (above mean sea level), which degases into the marine boundary layer, Fuego Volcano, Guatemala (3,768 m AMSL) a persistent emitter of volcanic gas and ash into the free troposphere, and Lascar, Chile (5,592 m AMSL) a passive emitter of SO_2 into the high dry troposphere of the Atacama desert. The team have gathered data at active volcanoes in all three countries and regularly at Soufriere Hills and Fuego. Cloud formation and the importance of cloud condensation nuclei (CCN) will be investigated at Soufriere Hills and will act as an analogue for MCB, whereas at Lascar the focus will be on the conversion of SO_2 and the production of aerosol as an analogue for SAI. Fuego, where the team have deployed various UAS over a decade will act as a final-stage test bed for aircraft and instrument development. The team has a strong relationship with the relevant authorities in Guatemala where Fuego's frequent eruptions has necessitated the closure of airspace to cruise altitude (~10 km AMSL). Before this stage aircraft and instruments will be tested in the laboratory (e.g. wind tunnels), at the university's outdoor flight testing facility, and at selected test sites in the UK.

We propose to develop the capability to monitor subsequent testing for both SAI and MCB technologies, whilst also investigating the natural processes that make volcanism important analogues for SAI and MCB. The outcomes of this research project will be a system ready to be deployed quickly in the event of a significant volcanic eruption, a framework for monitoring, a capability demonstrator for higher altitude sampling and more complete understanding of volcanoes as analogues for SAI and MCB. We will build a system that can (a) be used during the project to quantity physical processes that relate to climate engineering, (b) prepares the community for a more significant event (in the troposphere or the stratosphere) that would have a regional-global scale climate perturbation and (c) be deployed as part of the broader programme to assess the efficacy and impacts of small scale outdoor experiments.

1.2 <u>The Risks</u>

<u>Technical Risks.</u>

Technical risks focus on the limits of current technologies. It is not trivial, at the intersection of technology and cost proposed here, to remotely lift the necessary instrumentation to 10 km AMSL and keep it there for several hours. Specific technical risks include failure to (i) design and assemble a capable aircraft system (ii) adequately test the aircraft at altitude working within technical and regulatory constraints (iii) plan for a change in volcanic activity and (iv) failure to gain permission to fly at target sites. Technical risks are ameliorated by the team's previous expertise and a robust annual stage-gating process. The Bristol Flight Lab has successfully designed and build many UAVs for different purposes including radiation monitoring in Ukraine, high altitude meteorological sampling over the Ascension Islands, volcanic plume sampling worldwide and conservation biology in Africa. The team have flown beyond visual line of sight (BVLOS) to 18,000ft AMSL with aerosol sampling instrumentation over volcanoes (Figure 2). We have local (university owned) testing facilities, access to UK testing facilities (e.g. Llanbedr) and have already secured flight BVLOS (beyond visual line of sight) permissions on multiple occasions in multiple countries. Fuego, Soufriere Hills and Lascar are significant emitters of SO_2 and have been for several decades, but fieldwork could be refocused on other active systems if needed / desired. For example, if there were a significant eruption in Iceland or there was a requirement to deploy during a programme experiment the MACE project could support it. One previous Bristol Flight Lab example of this was the deployment of UAS to help monitor the Cumbre Vieja volcano eruption on the island of La Palma, Canary Islands in 2021.

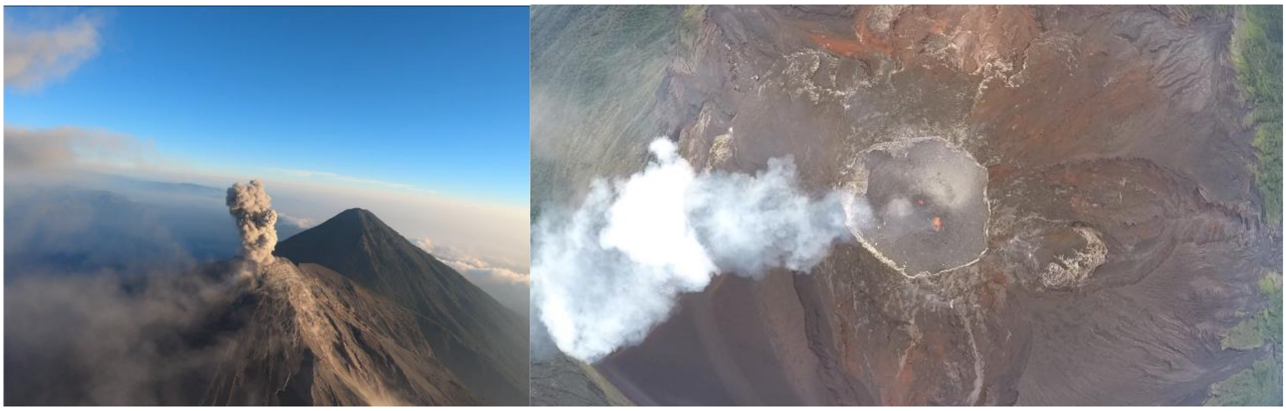

Figure 2. Images captured by the University of Bristol in 2019 from drones over Fuego, Guatemala: (a) eruption monitoring prior to in-plume ash sampling and (b) crater overflight for imagery between eruptions.

Non-technical Risks.

Other risks would include (a) political opposition to climate engineering research, in the UK and elsewhere, (b) objection to the research by the University's ethics committee and (c) general unsettling of research staff working in a controversial field. Climate engineering is a challenging field which solicits strong responses from government, scientists and the public. Our mitigation strategies will be formed of previous experience. We have chosen to focus upon learning from natural analogues and monitoring deployment, not deployment itself, based around the idea of preparedness. We will operate with absolute transparency and have a PI that is uniquely experienced in this challenge, having led SPICE[8] (Stratospheric Particle Injection for Climate Engineering), a more controversial project that included a deployment technology field test[13]. Transparency will be required by the University's ethics committee (who also oversaw SPICE) and will reassure all researchers that, albeit in a controversial field, the work will be undertaken in good faith. Absolute clarity will be provided to new staff upon application about the ethos of the research (described below).

1.3 How is this different from commercial or emerging technologies

This is an end-to-end solution that is designed to give UK researchers a new capability. It requires the adaptation and integration of commercially available lightweight sensors with a newly designed aircraft system, capable of flying in challenging environments up to an altitude of 10 km AMSL. The aircraft will operate autonomously with smart flight systems and control based upon machine learning recognition of volcanic emissions[8] with on-the-fly route planning for multiple intercepts within a predetermined geofence. The new platform will have a flight envelope not easily achieved with a COTS solution. No such integration of an uncrewed (UAS) high altitude platform, AI-based automated real-time route planning and particle and radiation detection capability currently exists in the commercial world, with a very limited number of research groups worldwide having the capability to deliver and operate such a system.

1.4 Proposed Activity of Work (see also Figure 3).

WP1 *Development of platform capable of operating in the troposphere and lower stratosphere.* WP1 is made up of three sub-tasks. (**T1.1**) MCB typically operates in the boundary layer whereas SAI efficacy broadly increases, per delivered volume of material, as a function of altitude. The aircraft will be modular in terms of the onboard sensor systems, and capable of undertaking measurements that pertain to both target technologies. The nominal design brief is to have an electric fixed-wing aircraft, capable of lifting the required sensor payload from WP2, plus the associated avionics for autonomous operation, to 10 km AMSL. The team has extensive experience with both modifying existing COTS airframes and original new designs to meet stringent mission requirements. (**T1.2**) Software development will deliver an integrated simulation environment for the aircraft system and its controlling AI in digital representations of the target environments, including plume models. Autonomous guidance will permit dynamic re-sampling in 4D to measure evolution of the same air 'parcel' over time, exploiting machine learning and dynamic replanning to track and revisit the plume. On-ground, in-air and remote automation will support pilot and science situational awareness with manageable workloads. (**T1.3**) Initial flight tests of the MACE aircraft will be carried out at the university field site in Bristol, moving to Llanbedr as the required airspace increases. An agile approach will be used for UAS development with regular flight tests throughout the project. The data collected during these UK tests will lead to rapid airframe iteration and code development, as well as performance analysis for AI based mission optimization and preparation for field deployments. **Stage-gate deliverables: D1.1 (Year 1)** Development, performance testing and flight demonstration of a viable prototype aircraft system.

WP2 ***Payload selection, integration and field testing.*** With a functional prototype aircraft, the aircraft systems and operations will also be developed iteratively during the payload integration phase. WP2 is made up of three subsections. (**T2.1**) We will down select from a larger suite of instrumentation capable of quantifying two critical types of coupled observations. Firstly, we will consider in-situ measurement of gas, aerosol and droplet properties such as concentration, shape, number density and particle size distribution[7]. There are a wide variety of lightweight electrochemical gas sensors (e.g. H_2O, SO_2) and laser-based optical particle counters designed to measure CCN at submicron scale, coarse mode sulphate aerosols (0.5-10 μm) and cloud droplets at a range of 5-50 μm that will be reviewed according to scientific and engineering requirements. Radiative transfer observations constitute the second suite of observations from which we will delimit radiative forcing. Pyronometers will measure diffuse and direct upwelling and downwelling SW radiation across the visible and near-infrared spectrum (~0.4-2.7 μm wavelength). This will be coupled with LW radiation (5-100 μm) measurement using pyrgeometers capable of quantifying broad spectrum upwelling and downwelling thermal radiative fluxes (Table 2).

Target parameter	Science question (?)	Example instrument	Mass(g)
[SO_2]	What is the conversion rate of SO_2 > SO_4^{2-}	DD Scientific 4 Series	20
CCN size and #density	How quickly do CCN evolve	Naneos Partector 2	483
Cloud droplet size	What rate do cloud droplets form/evolve	DMT CDP-2	1670*
Aerosol size distribution	What is the aerosol size distribution	Met One 212	1200*
Up/down SW radiation	How is SW radiation altered by species	AT SPN-1	786
Up/down LW radiation	How is LW radiation altered by species	Apogee SL510/610	190
T, P, Rh	What are ambient atmospheric conditions	Trisonic Mini	50

Table 1. Example instrument suite (not all instruments need to be flown simultaneously) *mass with housing

(**T2.2**) Laboratory and field testing of the onboard sensors will be carried out at selected sites in the UK including Llanbedr in Wales, and at Fuego volcano, Guatemala. During a careful programme of flight tests, we will increase flight altitudes whilst working within regulatory frameworks. Active volcanoes present significant opportunities as airspace above them is often closed to above cruise altitudes, as has been the case at Fuego since 2015. (**T2.3**) Preparation for rapid deployment. By the end of year 1 the MACE team will assemble an initial UAS capability for rapid (48hr) deployment in response to a large scale volcanic eruptive event. This will develop annually with the project, incorporating step changes in sensing, processing, aircraft and expertise. **Stage-gate deliverables: D2.1** (Year 2) An integrated aircraft and payload with onboard computer for data processing, ground control station, real-time route planning with AI-based optical sensors. The system will include equipment for in-field support. Instrument suite selected, tested and integrated into aircraft from WP1. Repeatable successful flights to target 10 km AMSL altitudes with active payloads by the end of year two. **D2.2** (Year 3) Fully automated flights with onboard AI and on-the-fly route planning for multiple intercepts that have successfully achieved science goals.

WP3 ***Volcanic plume and secondary aerosol sampling across a range of altitudes***. (**T3.1**) We will conduct a two-phase campaign at reliable producers of SO_2. Our first target is Fuego, Guatemala (3,780 m AMSL) where the team have flown UAS extensively to > 5,000 m AMSL. We have a longstanding relationship with both the national institute for atmospheric, geophysical and hydrological hazards (INSIVUMEH) and the Guatemalan civil aviation authority (DGAC) and have hundreds of hours of experience flying beyond visual line of sight[8,9] (BVLOS). Here we will fly within established flight envelopes, and gather preliminary data from within, above and below the plume. We will use machine learning[10] to train the system to repeatedly intersect the same section of the plume at Fuego and investigate SO_2 loss, aerosol formation and radiative transfer across the vertical profile of the plume. (**T3.2**) Following two Fuego campaigns, two other sites, the Soufriere Hills Volcano, Montserrat (1,050 m AMSL and British Overseas Territory) and Lascar in Chile, will become the focus of the project. The Soufriere Hills Volcano, Montserrat, is an MCB analogue, where SO_2 is rapidly converted into sulphate aerosol[11], an effective source of cloud condensation nuclei observed at volcanoes during passive degassing[12]. Lower plume altitudes mean potential heavier payloads and/or longer flight times and, given the rapid conversion of SO_2, allows us to investigate a series of physico-chemical reactions from heterogenous nucleation of aerosols though to cloud formation and brightening. We will observe radiative transfer processes as a function of time, potentially through coordinated multi-aircraft campaigns. In contrast, Lascar is one of the highest persistent emitters in the world at ~5,600 m AMSL, which emits into the dry free troposphere of the Atacama desert. Here we will undertake plume characterisation experiments in conditions as close to those of the stratosphere as is possible from a passive degasser, again looking at aerosol microphysics and radiative transfer through the plume. (**T3.3**) If other funded projects require monitoring support the team will assist in co-designing observational capabilities, and provide support around logistics and regulations. **Stage-gate deliverables: D3.1** (1st quarter, Year 3) Successful deployment of aerosol measurement instrumentation on the MACE UAS at Fuego volcano, Guatemala and radiative profiling above, in and below the volcanic plume. **D3.2** (3rd quarter, Year 4) Successful deployment into volcanic plumes and downstream clouds during years three and four across a range of altitudes and environmental conditions, leading to an improved understanding of the relationship between aerosol physico-chemical processes and radiative properties across a range of altitudes and atmospheric conditions using MACE UAS.

WP4 ***Readiness planning, monitoring deployment strategies and targets of opportunity.*** This WP is dedicated to putting in place the processes, protocols, software and paperwork required to operate at short notice internationally. Due to technological and regulatory challenges, relatively few in-situ measurements of sulfur-bearing species have been made, particularly in the stratosphere. The next volcanic eruption and/or small-scale experiment will require monitoring, and small scale SRM deployments are highly likely to operate at scales below those easily detected from orbital platforms. In addition to the hardware preparations for rapid deployment identified in WP2, we will prepare for targets of opportunity, including, but not limited to volcanic eruptions, noting that kgs of SO_2 are already being released by companies, such as Make Sunsets, in the US. The MACE team at Bristol have extensive experience operating UAS internationally including Papua New Guinea, Cameroon, Chile, Italy and Kenya. (**T4.1**) We will develop the capacity for rapid response deployment to targets of opportunity such as a significant volcanic eruption, leveraging simulation capability and automated planning from WP1 to design, train and verify missions in advance, as far as possible, and during the 48-hour response window. (**T4.2**) The required permissions can often be just as challenging as the hardware and software. The team will be building on previous research in the automation of UAS safety cases and in-flight operations around regulation planning. Selected potential operational vignettes will be used as test cases. (**T4.3**) A 20 km altitude safety case will be developed to facilitate further development of UAS monitoring at likely SAI injection altitudes. **Stage-gate deliverables: D4.1** (3rd Quarter, Year 2)**.** An initial safety case for deploying UAS above cruise altitude during the next large (20 km injection height) volcanic eruption. Note we have pulled this effort forward in response to feedback. **D4.2** (1st Quarter, Year 4) Successful discussions and future planning with relevant authorities in volcanically active regions (Caribbean, Central and South America, Indonesia, Japan) for rapid response during periods of high sulfate aerosol load at altitude. If requested by national authorities the team will carry out demonstration flights at selected sites.

WP5. ***Project Management, Impact and Outreach.*** (**T5.1**) We will have regular project meetings involving teams members on at least a weekly basis and (**T5.2**) in person, all hands quarterly review meetings (**T5.3**) Outreach materials and publications (**T5.4**) We will conduct six monthly project progress reviews and annual reporting, including deliverables for stage-gates at year end 1,2 and 3. **Stage-gate deliverables: D5.1** (End of years 1,2,3 and Final Year 4) Demonstration of deliverables and project reporting to inform stage-gate decision making **D5.2** (End of years 1,2 and 3, 3rd Quarter, Year 4) We will develop outreach videos, as part of a broader suite of materials to inform stakeholders, academics and the public of our work and our findings.

Previous research has generated significant interest, and outreach has allowed us to connect with a wide array of people, an outcome that can be argued to be particularly important in the field of climate engineering.

Work Package #	Work Packages (WP)	WP Leads	Task & Deliverable #	Task	Year 1				Year 2				Year 3				Year 4			
WP1	Platform Development			Work Package Tasks and Deliverables	1	2	3	12	1	2	11	12	1	10	11	12	1	10	11	12
	Development and flight testing of platform capable of operating in the troposphere and lower stratosphere.	Professor Richardson	T1.1	Platform and System Design																
			T1.2	Hardware and Code Development																
			T1.3	Flight and Performance Testing																
			D1.2	**Flight Test MACE UAS Prototype**				X												
WP2	Instrument Down-selection and Integration	Professor Watson		Work Package Tasks and Deliverables																
	Payload selection, integration and field testing.		T2.1	SAI and MCB instruments selection																
			T2.2	Integration and field testing																
			T2.3	Hardware for rapid deployment																
			D2.1	**MACE UASs ready for field**								X								
			D2.2	**Succesful field trial review**												X				
WP3	Field Testing at Representative Volcanoes	Professor Watson		Work Package Tasks and Deliverables																
	Volcanic plume and secondary aerosol sampling across a range of altitudes.		T3.1	Field testing at Fuego volcano																
			T3.2	Plume and radiative measures																
			T3.3	Programme experiments																
			D3.1	**First research flights completed**									X							
			D3.2	**All targets successfully sampled**															X	
WP4	WP4 Regulation and	Professor Richards		Work Package Tasks and Deliverables																
	Readiness planning, monitoring deployment strategies and targets of opportunity.		T4.1	Regulation Planning																
			T4.2	Rapid response development																
			T4.3	Safety case																
			D4.1	**Safety case first draft**							X									
			D4.2	**Safety case complete**													X			
WP5	Project Management	Project manager		Work Package Tasks and Deliverables																
	Project Management, Impact & Outreach		T5.1	Regular online project meetings																
			T5.2	In person quarterly review meetings																
			T5.3	Outreach material and publications																
			T5.4	Project review reporting and deliverable monitoring																
			D5.1	**Project reporting / stagegate**				X				X				X				X
			D5.2	**Outreach video**				X				X				X			X	

Figure 3. MACE Gantt Chart with Work Packages (WP), Tasks (Tx.x), Deliverables (Dx.x) and denoted by X on the timeline, shown over the four years of the project.

1.6 Justification for physical experimentation, regulatory, legal ethical risks and their mitigation.

Volcanoes, as sources of both CCN and aerosol precursors allow us to investigate natural analogues to SRM to investigate the efficacy of both MCB and SAI. Experimentation using natural analogues present less risk and less opposition than outdoor experiments, particularly those that are perturbative. Because we are explicitly not releasing material, nor are we developing the capability to do so, our experiments should be considered as passive monitoring of processes that SRM would seek to enhance and, if required, supporting small scale outdoor experiments within this programme. We do not propose to work on geopolitical risk directly, but note that constraining epistemic uncertainty will reduce broader risk by better quantifying physical processes that will control outcomes of any potential deployment. This project's primary regulatory and legal risks are around airspace management. We are measuring natural systems using established measurement technologies, a new airframe and a new autonomous control system that will facilitate quantification of aerosols and cloud physical and radiative properties. Whilst the team (see below) has extensive experience of high-altitude plume sampling, regulatory challenges around safe operations increase in complexity as airline cruise altitude is approached. Our mitigation strategy is to use our experience as an opportunity to develop protocols for a safety case to operate at, and beyond, cruise altitudes.

Section 2: The Team

[redacted]

[redacted]

[redacted]

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The Bristol Flight Laboratory (BFL) designs, builds, and tests a variety of flying vehicles. The lab is fully equipped for UAS development and assembly, including propulsion, systems and structures development and integration. The University of Bristol owns and operates Fenswood Farm, a 62-hectare research facility which has a large airspace for field-testing UAS. The University of Bristol is also part of the **Bristol Robotics Laboratory** (BRL) partnership which houses one of the largest indoor flight arenas in the UK to support the development and flight testing of aerial robots, including agile vehicles and precision aerial manipulation. **Bristol Volcanology** is a leading research group which uses a combination of field studies, petrology, geophysics, remote sensing, analogue experiments and numerical models to understand the physical processes that control volcanic eruptions and their impacts, and to develop methods of hazard and risk assessment. The group has access to a suite of world-class instruments for quantifying and analysing volcanic aerosols. Together with the BFL, the group has studied volcanic emissions around the world and has obtained permissions to fly BVLOS in many countries across several continents through a reputation built upon safe flight operations and professionalism.

This effort is built on a decade of focused collaboration across the University of Bristol and is self-contained. We work closely with many other groups, and are keen to provide significant additional value to the broader ARIA programme by offering monitoring capability to those groups undertaking outdoor experiments. The senior team have worked together for over a decade and currently co-supervise several PhD students. We are collectively motivated by ambitious and difficult challenges, working in extreme environments and, most importantly, by delivering societal benefits. Investigating potential solutions to climate change is the challenge of our age and could have profound implications at a planetary scale. We feel it is critical to work in these spaces transparently and openly and we aspire to put all our designs into the public domain for others to emulate if helpful. The team are keen to publish any and all relevant data and the project will have a public-facing element, coordinated by the research manager with support from [redacted] Both have significant media experience and will also utilise the University of Bristol's press office as appropriate.

Each of the three senior academics will take responsibility for the line management of one of the post-doctoral researchers, noting that we have deliberately designed the programme so that all PDRAs can contribute to all of the four work packages. There is funding for a 20% FTE research/project manager who will be responsible for interface with the funder (along with the PI), management of deliverables and coordination of regular (at least bi-monthly) project-wide meetings. These will be augmented by both smaller group meeting and by integration into Bristol Flight Lab and Volcanology Group meetings and discussions. The three PDRAs and senior technical specialist will work at 100% FTE for four years, the PI at 25% FTE and the co-PI's at 15% FTE. We have front-loaded the equipment and consumables budget to years 1 (prototype test) and particularly year 2 (with a stage-gate to enter year 2), where the majority of the funding will be used to build three complete UAS. We estimate the cost of the prototype to be ~£100K and each system to be ~£200K (including £100K of instrument package) but will present detailed cost estimates for the three mission-ready UAS at the first stage-gate based upon down-section in WP1. A second stage-gate exists in year 2, where the UAS will need to demonstrate the required flight and measurement capabilities. We imagine a final lighter touch review and will be required to demonstrate progress in addressing the science questions in year 3.

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Evidence-based Assessments to Guide Perceptions, Governance, and Ethical Frameworks for South Asia: Comparing Marine Cloud Brightening Deployment Strategies vis-à-vis Carbon Dioxide Removal and Mitigation Efforts

Section 1: Project & Technical Information

Introduction

Highly populated and climate-vulnerable South Asia is home to nearly a quarter of the world's population (Yeung et al., 2018; Majaw, 2020). Geographically diverse—spanning vast coastlines, fertile plains, and mountainous terrains—South Asia faces climate risk exposure includes extreme weather events, rising sea level, glacial melt, and prolonged heatwaves, significantly threatening regional ecosystems, socio-economic/resource security, and geopolitics. Coastal countries such as India, Pakistan, and Bangladesh increasingly face threats from sea level rise and cyclonic storms, while non-coastal nations like Nepal and Bhutan are grappling with glacial melt, water scarcity, and rising temperatures. Addressing these challenges requires innovative and region-specific solutions. One potential approach is Marine Cloud Brightening (MCB), a 'regional' Solar Radiation Modification (SRM) technique that aims to cool atmospheric temperatures and mitigating some climate change impacts. MCB increases cloud albedo, reflecting more sunlight back into space. Its cooling effect has the potential to offset some of the severe consequences of climate change. For instance, Wan et al. (2024) concluded that regional MCB interventions in the North Pacific could significantly reduce heat exposure in the Western United States under present-day conditions, although their efficacy diminishes or even exacerbates heat stress under mid-century warming. This finding highlights the governance challenges and risks of assuming consistent outcomes from MCB as climate systems evolve. Similarly, Haywood et al. (2023) introduced a novel MCB experiment (G6MCB) using the UKESM1 Earth-system model, targeting areas of the eastern Pacific. The experiment compared G6MCB results with the G6sulfur Stratospheric Aerosol Injection scenario, revealing significant cooling, but also side effects like altered monsoon precipitation and La Niña-like responses.

Considerations for assessing potential deployment of MCB in South Asia require a holistic, tailored approach that address the region's specific socio-economic, political, environmental, and ethical complexities. The climate of South Asia is dominantly monsoon dependent (Athar et al., 2021). To demonstrate a strong scientific basis for perceptions, governance and framings activities of this proposal, climate models-based projections of MCB (GeoMIP), CDR (CDRMIP), mitigation and business-as-usual (CMIP) scenarios will be assessed (see Figure 1 for prototype output), and relevant information will be gleaned for key project outcomes: stakeholder engagement, policy analysis, and development of actionable and ethical recommendations.

CDR faces technology development limitations – high expenses, almost untested, and unclear pathways to scalability at present. Traditional mitigation efforts, such as renewable energy transitions and energy efficiency improvements, while essential, may not prevent climate tipping points in the near term (Nordahl et al., 2024). Researching SRM, and MCB, in this context of the need for time and cost-effective solutions is explored as a complementary strategy to CDR and mitigation, while acknowledging that SRM and MCB are not substitutes for mitigation, and CDR (Long and Shepherd, 2014). This is important, as developing simultaneous/side-by-side understanding of the differences in the projected climate of South Asia under MCB, CDR, and mitigation will aid in decision making about the research and potential use or non-use of MCB. This approach will help convey data driven information developed through this project by basic and social scientists to other key stakeholders.

While some research has been conducted in the Global North on MCB and its potential impacts (e.g.: Haywood et al., 2023; Wan et al., 2024), no such study has been conducted for South Asia. While these studies have primarily focused on technical outcomes, extensive stakeholder engagement has been largely missing. This study aims to fill these gaps by integrating both technical evaluations and broad stakeholder participation. By integrating climate assessments of various technologies, perceptions of MCB will be elucidated, vis-à-vis CDR and mitigation, among local communities, policymakers, academics, civil society, and the media; an assessment of governance and ethical frameworks relevant for South Asia, will also be accomplished, and provide pathways for integrating the lessons derived. This research will ensure that socio-economic, political, and ethical factors are considered alongside scientific innovation, highly relevant for such controversial technologies.

In this context, Carlson et al. (2022) noted that SRM could alter disease (malaria) transmission patterns, benefiting some regions while worsening conditions in others, particularly in the Global South, thus raising significant concerns about their implications for public health and anticipatory governance deliberative democracy (Kessler, 2019). Rahman et al. (2018) argue that developing countries that are the most vulnerable

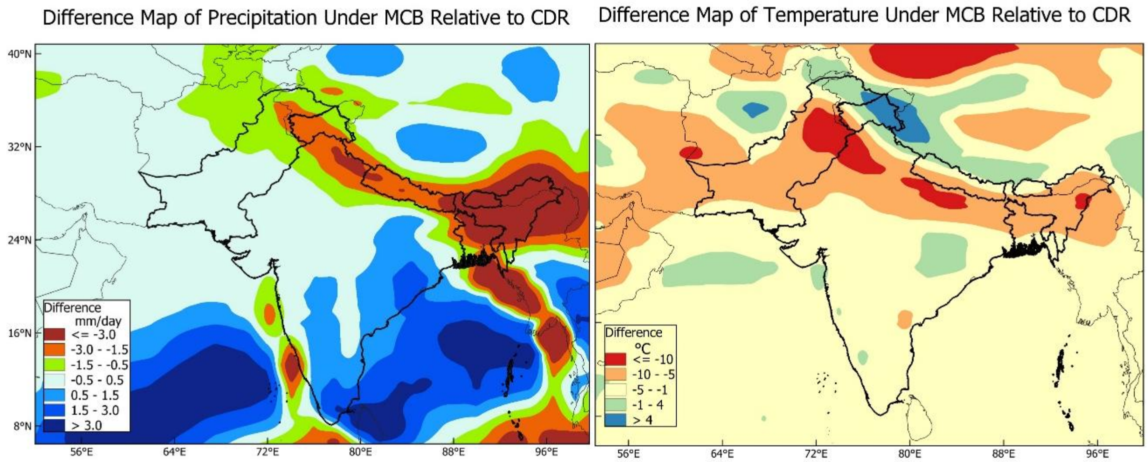

Figure 1: Mean difference of precipitation (left) and temperature (right) of MCB, relative to CDR, over South Asia (2021-2090)

countries to climate change impact must drive discussions of modelling, ethics and governance. Similarly, Sugiyama et al. (2020) critique the narrow focus of SRM research on public perceptions in the Global North, overlooking the Global South where the impacts of such technologies may be more profound. Addressing this imbalance is essential for ensuring equitable governance and avoiding a top-down imposition of SRM.

This project aims to address this disparity by centering South Asian perspectives, offering a framework for more inclusive and ethically grounded MCB research that holds global relevance. This proposal aims to explore the feasibility and implications of MCB deployment in South Asia through a comprehensive assessment of public perceptions, governance structures, and ethical frameworks. The study will compare the across selected coastal countries (India, Pakistan, Bangladesh) and non-coastal nations (Nepal and Bhutan), focusing on the socio-economic, political, and environmental dimensions critical to decision-making around its potential use/non-use. The research will integrate stakeholder perspectives—including policymakers, academics, civil society, and the media—alongside ethical considerations and policy frameworks, to develop inclusive and equitable SRM strategies tailored to the region. By bridging the gap between scientific innovation and socio-economic and political realities, this research seeks to contribute to a deeper understanding of how SRM strategies, particularly MCB, can be responsibly and effectively implemented in South Asia, if and when needed.

Proposed Idea / Solution and Alignment with Programme Objectives

This proposal focuses on the implications of potentially deploying MCB in South Asia, a region critically vulnerable to climate change.

Scientific Rationale and Justification**:** By increasing cloud reflectivity, MCB directly alters the Earth's energy balance. This approach aligns with the programme's goal of exploring interventions that can alter planetary albedo in measurable and statistically significant ways, offering a potential short-term, stopgap solution to mitigate immediate climate risks while longer-term strategies, such as CDR and mitigation**,** ramp up. Unlike energy-intensive and costly CDR techniques, i.e., direct air capture (DAC)**,** MCB could provide a scalable and cost-effective option, particularly suitable for resource-constrained regions like South Asia.

How MCB Works: By reflecting more sunlight, MCB reduces heat absorption and delivers localized cooling, which is especially beneficial for South Asia's coastal regions facing sea level rise, cyclonic storms, droughts and heatwaves. Climate models-based risk maps will visually demonstrate MCB cooling potential and impact on phenomena such as monsoons, coastal precipitation, and temperatures.

How the Solution Supports the Objectives of the Programme**:** This project addresses urgent climate vulnerabilities in South Asia by exploring MCB's potential to mitigate near-term risks, particularly in coastal and low-lying areas, and comparing them against inland areas of South Asia. It advances SRM knowledge by evaluating the feasibility, effectiveness, and side effects of MCB, contributing to global understanding of this SRM technique. A key focus is fostering public/stakeholder engagement in key South Asian countries, exploring whether MCB deployment is ethically sound, socio-economically and environmentally appropriate, and politically feasible. The study will also develop an ethical framework addressing fairness, equity, and environmental justice, guiding future MCB research and deployment in South Asia and beyond. By integrating stakeholder engagement, and ethical considerations, this proposal not only meets the programme's objectives but also strengthens the foundation for scalable, ethical climate interventions globally.

Research Objectives

- **Comparative Analysis of MCB (GeoMIP) CDR (CDRMIP), mitigation (CMIP) Projections**:
  - Compare the efficacy of MCB and ocean alkalinization (CDR) in addressing climate vulnerabilities.
  - Assess socio-political dimensions of MCB deployment strategies in coastal (India, Pakistan, Bangladesh) vs. non-coastal (Nepal, Bhutan) countries, focusing on public perceptions, technical feasibility, governance, and ethical challenges.
- **Perceptions and Stakeholder Engagement**:
  - Investigate public perceptions of MCB and CDR across coastal and non-coastal countries.
  - Examine socio-economic factors influencing acceptance of MCB and assess stakeholder engagement, including governments, civil society, and local communities.
- **Policy Analysis**:
  - Analyze national and regional policies to identify gaps and opportunities for integrating MCB into climate strategies.
- **Ethical Frameworks and Socio-Economic Dimensions**:
  - Review existing SRM ethical frameworks and develop guidelines for South Asia's geopolitical context.

Methodology: A **mixed-methods approach** will be employed, integrating qualitative and quantitative tools to achieve a comprehensive analysis.

Literature Review: Conduct an in-depth review of MCB-related studies South Asia, focusing on ethical, socio-economic, political, and climatologic/projection aspects. **(a) Surveys and Focus Groups:** Develop questionnaire-based surveys targeting diverse stakeholders in the region, including policymakers and intergovernmental/international organizations, academics, civil society members/organizations, and journalists, regarding the feasibility and implications of MCB deployment. In this context we will collect 500 feedback forms from each country, for a total of 2,500. **(b) Key informant interviews** will be held with key experts/stakeholders, alongside focus group discussions/roundtables with diverse stakeholders across three categories (academia, civil society, and policy makers), to gather qualitative insights (See details in Table 1). **(c) Advanced Decision-Making Tools:** Use Fuzzy Multi-Criteria Decision-Making (Fuzzy AHP and Fuzzy TOPSIS), Fuzzy Cognitive Maps, and Fuzzy Clustering to analyze complex data and prioritize ethical and policy considerations. Employ **multi-objective optimization** to assess trade-offs between competing environmental, socio-economic, and geopolitical goals. **(d) Climate and Policy Analysis:** Conduct sectoral policy analyses of South Asian countries, identifying gaps and opportunities for integrating MCB into national and regional climate strategies.

Table-1 The breakdown of surveys and focus group activities by country.

Country	Key Informant Interviews	Focus Group Discussions
India	12	3
Pakistan	12	3
Bangladesh	10	3
Nepal	8	3
Bhutan	8	3

Expected Outcomes: (a) **Climate Projection Comparisons:** In-depth analysis of the project climate impacts of MCB, CDR, and mitigation, on South Asia's diverse regions, focusing on regional weather patterns and the potential effects on coastal and non-coastal areas.(b) **Policy Analysis:** Comprehensive analysis of existing policies related to SRM in South Asia, focusing on how MCB could be integrated into these frameworks. (c) **Perception Analysis:** Insights into public and stakeholder perceptions of MCB and CDR technologies across South Asia's diverse geographies and societies. (d) **Ethical Framework:** Development of a detailed ethical framework for MCB deployment, addressing equity, inclusivity, and transparency, and informed by South Asia's socio-economic and geopolitical contexts. (e) **Policy Recommendations:** Propose practical guidelines for integrating MCB into South Asia's climate policies, including stakeholder engagement strategies and governance structures.

Technical and Non-Technical Risks - Mitigation Strategies: This proposal identifies and addresses both technical and non-technical risks associated with deploying MCB in South Asia, ensuring a comprehensive approach to achieving the project's objectives. Technically, uncertainties about MCB's impact on critical regional climate phenomena, such as monsoons and precipitation patterns, are underexplored. These risks will be mitigated through advanced climate modelling, localized simulations, and on the non-technical front. Also, public and stakeholder skepticism about MCB's ethical implications and socio-economic and political barriers/reservations could hinder progress. This will be mitigated by robust implementation of stakeholder engagement through surveys, focus groups, and transparent consultations across South Asia, to elucidate drivers for building understanding and trust. Governance and regulatory challenges, particularly in resource-constrained and geopolitically sensitive regions, will be tackled by analyzing existing policy gaps and developing region-specific governance frameworks that align with international ethical standards. Addressing equity and inclusiveness in decision-making, the project will create a tailored ethical framework that ensures community involvement and fair distribution of benefits and risks. Geopolitical tensions arising from transboundary impacts of MCB can be mitigated by emphasizing collaborative governance mechanisms, enabling equitable regional participation. By proactively identifying these risks and presenting clear, actionable mitigation strategies, this proposal demonstrates its feasibility, readiness, and alignment with the goals of funding agencies. Through a rigorous, multi-dimensional approach, the project aims to deliver comprehensive, scientifically robust, ethically sound, and socio-economic and politically inclusive risk assessments and outcomes, thereby contributing to equitable and effective climate interventions in South Asia. This underscores the project's capacity to responsibly advance MCB research and aligns with the funding program's emphasis on innovation, governance, and societal impact.

Differentiation from Commercial and Emerging Technologies: The proposed approach to MCB is distinctly differentiated from commercial or emerging technologies currently being funded or developed elsewhere, primarily in its focus, scale, and integration of socio-economic, political, and ethical dimensions, specific to South Asia. While many MCB initiatives and SRM technologies focus on technical efficacy in isolation, this proposal emphasizes a comprehensive framework that incorporates public perceptions, governance structures, and ethical considerations tailored to the unique socio-economic, political, and environmental context of the region based on strong scientific rationale. This integrated approach addresses the critical gap between technical innovation and societal acceptance or rejection, which is often overlooked in commercially driven projects. Additionally, the project explicitly compares MCB with CDR strategies, such as ocean alkalinization, and mitigation efforts, as SRM strategies can only be decided upon as part of an overarching climate response portfolio (Long and Shepherd, 2014). Unlike CDR, which is constrained by high costs, energy demands, and scalability challenges, especially in resource-limited regions like South Asia, this project aims to evaluate MCB as a potentially cost-effective and localized solution for addressing immediate climate vulnerabilities. By focusing on region-specific deployment strategies, the approach is better suited to address the acute climate challenges of South Asia, such as monsoon variability and coastal impacts, which are not adequately addressed by broader, globally oriented SRM studies. The project's use of advanced decision-making tools, such as Fuzzy Multi-Criteria Decision-Making (Fuzzy AHP and Fuzzy TOPSIS), for analyzing complex data and prioritizing policy considerations further sets it apart by integrating quantitative rigor with ethical and governance frameworks. By adopting a multidisciplinary, stakeholder-inclusive approach, this proposal ensures its alignment with public values, governance requirements, and ethical principles.

Proposed Activity of Work, Key Metrics, Milestones, and Assumptions. This project focuses on assessing the implications of potentially deploying MCB in South Asia. The activities are designed to integrate technical, governance, and ethical dimensions, ensuring a responsible and region-specific approach. The work will be conducted through five interrelated research components. **(a) MCB Climate Projection and Impact Modelling**: Advanced simulations and climate modelling will predict the impact of MCB on regional phenomena like monsoons and coastal weather patterns, with a focus on localized cooling and precipitation variability. **(b) Comparative Analysis with CDR and Mitigation Strategies**: The project will evaluate the efficacy, cost, and scalability of MCB relative to CDR techniques, and traditional mitigation strategies. **(c) Stakeholder Engagement and Perception Analysis**: Surveys, focus groups, and consultations will assess public and stakeholder perceptions of MCB and CDR in both coastal and non-coastal countries, identifying socio-cultural and economic barriers to acceptance. **(d) Policy and Ethical Framework Development**: Policy analyses will identify gaps in integrating MCB into national and regional climate strategies, while ethical frameworks will address equity, inclusivity, and governance concerns specific to South Asia. **Key Metrics. (a) Climate Impact Metrics**: Assessment of regional temperature reduction in targeted areas, effects on precipitation patterns, particularly monsoons. **(b) Public Perception Metrics**: Stakeholder survey completion rate (2,500 responses across five countries). Levels of public and stakeholder acceptance of MCB as measured by qualitative and quantitative analyses. **(c) Governance and Policy Metrics**: Policy gaps identified and addressed in proposed frameworks. Drafting of region-specific governance and ethical guidelines for MCB.

Milestones. Phase 1 (Months 1-6): Literature review and climate model assessment. Development of stakeholder surveys and focus group frameworks. Initial consultation with policymakers and civil society. **Phase 2 (Months 7-12)**: Completion of climate modelling and simulation studies. Data collection from surveys and stakeholder engagement activities. Policy and ethical framework draft development. **Phase 3 (Months 13-18)**: Execution of surveys in five different countries of South Asia, and their analysis. Preliminary analysis of survey and engagement results to refine governance frameworks. **Phase 4 (Months 19-24)**: Completion of survey analysis and virtual/physical meetings with stakeholders, and key experts for feedback. Finalization of governance and ethical guidelines. **Phase 5 (Months 25-36)**: Synthesis of findings and preparation of final recommendations. Dissemination of results through publications, workshops, and policy briefs.

Dependencies and Assumptions. (a) Data and Technology Availability: The project assumes access to advanced climate models, satellite data. **(b) Stakeholder Participation**: The project assumes robust participation from policymakers, civil society, and the public for surveys and consultations. **(c) Funding and Collaboration**: The activities are contingent on adequate funding and partnerships with regional and international experts.

Developing Principles for Outdoor Experiments: This study critically examines the societal, environmental, and governance dimensions of potential MCB deployment, focusing exclusively on exploring public perceptions and stakeholder attitudes and their relations to outdoor experiments. Such an approach allows for an in-depth assessment of the challenges and opportunities posed by future experiments, laying the groundwork for informed and ethically robust decision-making. Below is a critical evaluation of how the study aligns with the principles for outdoor experiments outlined in the programme thesis while emphasizing gaps and limitations that must be addressed before real-world implementation: (a) **Minimizing Risk by Design**: While hypothetical outdoor experiments are discussed conceptually, the study refrains from direct implementation to avoid unnecessary environmental or social risks. It interrogates the feasibility of designing experiments at minimal scales to ensure reversibility and control. Stakeholder feedback will critically inform the trade-offs between scientific data quality and the potential for unintended consequences. The study challenges assumptions about "natural and benign" perturbations, emphasizing the need for a robust scientific and ethical justification for any future deployment (b) **Transparency and Public Participation**: Transparency is foundational, yet this study critiques the limited extent to which public participation has been integrated into prior SRM research. By directly engaging communities, policymakers, and other stakeholders, the study highlights gaps in trust and knowledge about MCB technology. Public consultations aim to elicit critical concerns about governance, inclusivity, and accountability, ensuring that future experiments are not only scientifically rigorous but also socially acceptable. (c) **Risk Assessment and Impact Monitoring**: The study underscores significant uncertainties and potential blind spots in assessing the risks of MCB experiments. It critically examines how risks—technological, environmental, and socio-economic—are perceived by various stakeholders and identifies the challenges of designing monitoring systems that can adequately address these concerns. This exploration aims to highlight the disparity between scientific risk modeling and public perception, advocating for more integrative and precautionary approaches in future experiments. (d) **Reversibility and Containment**: Public skepticism about reversibility and containment is a major focus of this study. By exploring stakeholder concerns, the research highlights the ethical challenges of ensuring that unintended consequences can be mitigated in real-time. The study critiques over-reliance on technological solutions for containment, instead advocating for a precautionary approach that prioritizes minimizing risks before deployment. This critical lens aims to ensure that future experiments do not proceed without a proven ability to halt or reverse potential harms. (e) **Governance and Legal Compliance**: Governance remains a contentious and underdeveloped area for SRM in South Asia. This study critiques existing legal and regulatory frameworks for their inability to adequately address the complexities of MCB experiments. By engaging stakeholders, the research identifies gaps in domestic and international laws, emphasizing the need for robust, inclusive, and enforceable governance mechanisms that prioritize ethical and environmental integrity. The findings aim to challenge the status quo of fragmented and reactive regulatory approaches. (f) **Independent Review and Oversight**: Independent oversight is not merely a procedural formality but a critical safeguard against conflicts of interest and ethical lapses. This study questions the adequacy of current oversight mechanisms and highlights the need for transparency, diversity, and impartiality in future review processes. Stakeholder input will help define the criteria for truly independent and representative oversight committees, ensuring that public trust is not compromised by opaque or biased decision-making processes. This critical evaluation exposes the complexities and challenges inherent in planning outdoor MCB experiments. By centering public perceptions and stakeholder concerns, the study aims to bridge the gap between technical feasibility and societal acceptance, underscoring that robust governance, transparency, and precautionary measures are prerequisites—not afterthoughts—for future experimentation.

Areas Requiring Support. (a) Regulatory Navigation: Assistance may be required to navigate the regulatory frameworks of South Asian countries, particularly for ensuring alignment with national and international SRM governance standards, if any. **(b) Community Engagement**: Additional support in organizing large-scale public consultations and managing cross-border stakeholder collaboration will help address regional sensitivities. **(c) Access to Technical Expertise**: Guidance in refining dispersal technologies and monitoring systems to meet high precision and safety standards. **Estimated Timelines and Project Plan**: The following project plan outlines the estimated timelines and key deliverables across the lifecycle of the proposed MCB scientific-socio research project. The project will span approximately 36 months, with clear milestones for each phase. Below is a breakdown of activities and expected outcomes by period:

Timeline Overview

Phase	Months	Key Milestones
Phase 1: Project Initiation	1-6	Literature review completion, climate modelling, finalizing survey and focus group frameworks.
Phase 2: Data Collection	7-13	Survey data collection, initial policy framework, first round of focus groups.
Phase 3: Experiment Design	14-19	Final design and completion of ethical framework.
Phase 4: Stakeholder Engagement and Ethical Frameworks	20-27	Stakeholder engagement, public consultations, data collection on public perception, mid-phase analysis of findings, refinement of ethical frameworks.
Phase 5: Analysis and Reporting	28-36	Data analysis, report preparation, dissemination of findings through reports, workshops, and publications.

Regulatory, Legal, and Ethical Risks and Mitigation Plans.

Regulatory Risks: The deployment of MCB in South Asia may face significant regulatory challenges, particularly related to environmental regulations, SRM protocols, and international laws governing climate interventions. These challenges could impede the approval and execution of hypothetical future outdoor experiments and potentially hinder the broader adoption of MCB in the region. **(a) Approval for Future Outdoor Experiments:** Obtaining the necessary regulatory approvals for potential future outdoor experiments in South Asia, particularly in countries like India, Pakistan, and Bangladesh, may face delays or resistance due to stringent environmental and safety regulations. **(b) Cross-border Regulatory Concerns:** MCB interventions may have transboundary effects, especially on neighboring countries with shared resources (e.g., monsoons, river systems). This could trigger geopolitical concerns and require international cooperation and regulation. **(c) Alignment with International Agreements:** South Asian countries may be hesitant to engage in SRM strategies like MCB due to concerns about compliance with international climate agreements, such as the Paris Agreement or the Convention on Biological Diversity (CBD).

Mitigation Plans (a) **Engage with Regulatory Authorities:** Early and continuous dialogue with national and local regulatory bodies in the project's target countries will be essential to align with existing environmental regulations. This will ensure that the project complies with local environmental laws and international obligations.(b) **International Collaboration:** To address cross-border regulatory challenges, the project will seek cooperation and consultation with neighboring countries and international bodies, including UNFCCC, to ensure that MCB deployment is aligned with broader climate policy frameworks. (c) **Detailed Impact Assessments:** Comprehensive environmental impact assessments and strategic environmental assessments will be conducted to evaluate the potential risks of MCB. These assessments will provide the necessary documentation for any future regulatory approvals. Independent third-party reviews will ensure transparency and credibility in the process.

Legal Risks: Legal risks associated with MCB deployment primarily concern the potential liability for unintended environmental harm, property damage, or adverse health impacts resulting from SRM interventions. Additionally, there may be issues related to intellectual property (IP) and the management of patents for technologies developed as part of the research. **Key Legal Risks:** (a) **Liability for Environmental Harm:** If MCB causes unintended environmental consequences (e.g., alterations in rainfall patterns, disruption of marine ecosystems), it may lead to lawsuits or legal challenges from affected communities or environmental groups. (b) **Cross-border Legal Implications:** Since the effects of MCB may cross borders, there could be conflicts with neighboring countries regarding the legality of deploying such technologies within shared environmental spaces (e.g., rivers, oceans).(c) **Intellectual Property (IP) Issues:** New technologies developed for MCB may encounter challenges related to IP rights, especially if commercial interests become involved in scaling the technology **Mitigation Plans:**(a) **Risk Mitigation and Liability Insurance:** The project will ensure proper legal protection by obtaining appropriate liability insurance to cover potential environmental damage or unforeseen impacts from any future interventions. Legal counsel will be consulted regularly to ensure the project complies with national and international laws governing environmental and SRM risks.(b) **Cross-border Agreements:** To address legal concerns over cross-border impacts, the project will advocate for agreements with neighboring countries outlining the terms of potential future MCB deployment. These agreements will emphasize shared responsibility and mutual consent under international law.

Ethical Risks: The ethical risks of MCB are substantial, given that SRM interventions directly modify natural systems with the potential for unforeseen and unequal consequences. These concerns include equity issues, environmental justice, and the involvement of affected communities in decision-making processes. **Key Ethical Risks:**(a) **Equity and Inclusivity:** future MCB deployment may disproportionately affect marginalized or vulnerable communities, particularly those in coastal areas or regions directly impacted by changes in weather patterns. (b) **Public Consent and Transparency:** Ethical concerns could arise around the lack of public consent, especially if MCB is discussed or implemented without sufficient consultation or public engagement, leading to distrust in the project. (c) **Environmental Justice:** If the risks and benefits of MCB are not distributed equitably, it may exacerbate existing environmental and social injustices. For example, cooling effects might disproportionately benefit wealthy regions while poorer communities bear the costs of unforeseen side effects.

Mitigation Plans:(a) **Community Engagement and Consent:** The project will prioritize an inclusive approach to stakeholder engagement, ensuring that all affected communities can participate meaningfully in decision-making. Surveys, focus groups, and public consultations will be conducted regularly to assess public perceptions and concerns. A consent-based decision-making process will be employed, ensuring that local communities are well-informed and empowered to influence key project decisions.(b) **Ethical Framework Development:** A comprehensive ethical framework will be developed in consultation with local communities, policymakers, and ethical experts. This framework will address issues of equity, inclusion, transparency, and environmental justice, ensuring that the potential risks and benefits of MCB are fairly distributed.(c) **Independent Ethical Review:** An independent ethical review committee will be established to monitor the project's implementation. This committee will ensure compliance with ethical guidelines and monitor the impact of the project on vulnerable populations and the environment. Recommendations for mitigation and corrective actions will be made as necessary to address any negative outcomes or ethical concerns that arise during the research process.

Section 2: The Team

Research Team: Relevant Experience, Expertise, Skills, and Capabilities: Our CUI research team specializes in several aspects of SRM research. [redacted]

Additional Expertise: As the project progresses, we anticipate the need for additional expertise in legal frameworks related to environmental interventions and socio-economic impact assessments. The strategy for integrating this expertise will be developed in consultation with the team members, based on project timelines and specific resource needs. The PI understands the value of engaging with various entities already working in the SRM space, such as The Degrees Initiative and the Resources for the Future, particulary with respect to the scientific, governance and stakeholder engagemnt aspects. The PI has strong linkages to these organizations and is currently (or was previously) working with these entities on SRM projects and seeks to expand engagement with other organizations in and looking to enter this space. Furthermore, we have a potential collaborator, [redacted], who will serve as a technical expert for the project. [redacted] with a focus on making policies, plans, programs, and project developments which are environmentally sustainable and climate resilient. [redacted] guidance will be instrumental in shaping the project's guidelines and ethical framework, ensuring they are grounded in practical, evidence-based approaches that promote balanced, sustainable, and climate-adaptive decision-making processes. Expertise of other team members comes from a mix from basic sciences [redacted]), social sciences ([redacted]), governance ([redacted]), with support for data development ([redacted]).

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Defining the minimum scale of an SAI test:
A fundamental first step towards an outdoor large scale experiment

Introduction and Program alignment: Stratospheric aerosol injection (SAI) could be used to reflect a small amount of sunlight back to space, cooling the planet. We know with certainty that this would cool, and if it were started at high latitudes where the tropopause is lower, it could potentially be conducted using existing (but modified) aircraft, making this the most near-term option for radically reducing the risks of climate change. Nonetheless, there are still critical uncertainties that would need to be narrowed before informed decisions about a deployment could be considered robust.

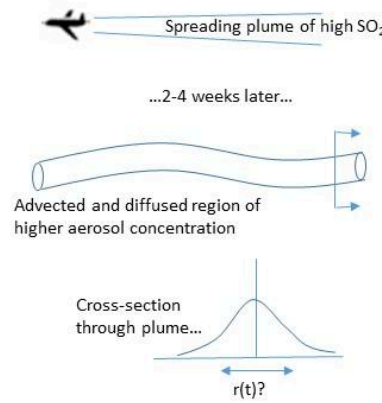
We start from the assumption that the nearest-term deployment of SAI is highly likely to be with sulfate aerosols, with gaseous dispersal of a precursor (SO_2 being the obvious candidate), and released from aircraft. The expectation that sulfate is the nearest-term option is due to the close similarity with natural analogues, and due to our knowledge of the environmental impacts of sulfate compared to novel materials; releasing as a gaseous precursor is expected to be more straightforward, and is again consistent with natural analogues. (And analyses consistently show that aircraft are likely the cheapest means of lofting material, e.g., Smith and Wagner, 2018). This makes reducing the remaining uncertainties associated with SO_2 release a high priority for near-term research.

With SO_2, the biggest source of testable uncertainty that could be reduced at a scale relevant for an outdoor experiment is associated with aerosol microphysics, leading to uncertainty in the aerosol size distribution, and hence both lifetime and radiative efficacy; this ultimately affects the overall amount one needs to inject to achieve a given amount of cooling. This uncertainty comes from the potential competition between nucleation (new particle formation) and condensation/coagulation (particle growth) of H_2SO_4 vapors and already nucleated sulfate aerosols, which in turn is strongly dependent on spatial inhomogeneity, as well as on initial conditions (such as ion-induced nucleation within the plume of an aircraft). In a climate model, these small-scale processes are represented by simplified parametrizations, based on a small amount of existing observations after volcanic eruptions, pyrocumulus etc. However, these representations have already been demonstrated to be highly model dependent (roughly a factor of two range across models), including even dependent on the physical timescale of the calculations (Vattioni et al., 2023), due to competition between different simultaneous processes (nucleation versus coagulation) that need to be resolved at a high temporal scale. Even more critically, the existing observations that lead to current parameterizations are from analogues that are not fully representative of the conditions that would happen during SAI, and there is little basis to guess how large an effect this might have on predictions without direct experimentation.

An outdoor experiment could be designed specifically aimed at reducing this uncertainty, but it is unclear what scale this experiment would need to be. This is the primary question we address here - not the detailed experiment design, but rather a robust scientific definition of the scale that such an experiment would need to be conducted at in order for it to meaningfully constrain some of the key microphysical uncertainties. This would not just be a critical first step in the design of the experiment, but would provide critical information for supporting evidence-based conversations on research governance.

There are two key observations that guide our thinking in the potential design of such an experiment:

1. It would be essential to conduct the experiment in as close a way as possible to the way SO_2 would be released in an actual deployment, in order to ensure that the conclusions are applicable to a realistic deployment. This requires release from an aircraft, and at release rates (kg/s or kg/km of travel) similar to rates expected in an actual deployment. This ensures both that the initial plume concentrations are relevant, and also that the test does not over- or under-represent effects from exhaust ions or aircraft wake turbulence for example.
2. It would be essential to be able to track the resulting plume until oxidation and aerosol formation are mostly complete, so 2-4 weeks. This requires a sufficiently large initial injection of material to ensure that after several weeks of mixing, the aerosol concentrations remain locally high enough that the plume can be found.



The initial plume of SO_2 from the aircraft would gradually spread, advecting with the local winds, and diffusing (see sketch at right), but even after a few weeks would lead to a broad plume or tube of higher aerosol concentrations that is not at all close to uniformly mixed throughout the scale of a climate model grid cell (Newman et al., 2001).

The first of the observations above sets both a lower and upper bound on the possible scale. E.g., the payload of a business jet capable of reaching 15km (adequate for high-latitude dispersal) is of order 10 tons; this is similar to the high-altitude bespoke design of Bingaman et al. (2020). If all of the mass is released over no more than 5 minutes, to avoid excessive loiter requirements (which would drive cost both through fuel and number of aircraft needed), this would produce an initial "tube" with higher concentrations of SO_2 that is of order 100 km long, probably longer than is necessary for an experiment. A reasonable expectation is thus that an experiment that captures relevant conditions will be at least a few thousand kilograms, but not likely to be more than 10 tons. Larger experiments are plausible but only with larger aircraft, as any deployment involving multiple aircraft would result in multiple plumes, and thus the single-aircraft payload sets the upper bound on the size of any plume one might track: furthermore, one would be expected to only move to larger scales once smaller scales have been explored. More critically, the second requirement above sets a lower bound on the size of the experiment, but one that requires quantification - what is the minimum size experiment that could still be tracked for a month? Note that over this period, the plume would have circled around the world; continuous tracking over this time is not likely plausible.

Designing an experiment would thus ultimately involve three components: (i) how to loft and release material, (ii) how to track that material for the next month, and (iii) how to sample and observe the resulting plume. If one knows exactly where the resulting plume is, it is straightforward to use existing observational assets (see Fiske and Siggurdson, 1979; Hòrvat et al., 2022; Li et al., 2023 for various airborne and satellite-derived data from at least two small-sized eruptions from the Soufriere Volcano; for background conditions see also Froyd et al., 2019, Schneider et al., 2021 and NOAA's SABRE mission[1]) to fly into the plume and sample the aerosols to determine size distribution. Designing modifications to existing aircraft to store and release SO_2 is in part dependent on the second task, because the second task determines the scale that the experiment would need to be conducted at.

As pointed out above, similar observational systems exist already, both for monitoring after volcanic eruptions and for monitoring background stratospheric conditions. Therefore, the main constraint is not as much observational (balloon-borne or aircraft measurements of particle number, size and chemical composition, tracking from satellites, etc.) but experimental: a controlled release will always be different from a volcanic eruption, due to its lower concentrations over time (as an example, the last Soufriere eruption released 0.3-0.4 Tg of sulfate in 6 hours, so 5-6 orders of magnitude larger than what we're thinking about) and the lack of co-injection of other materials (such as volcanic ash, or water vapor), and therefore exploring the lower bounds of such an experiment is crucial to inform its potential future development. However, there is also the potential to leverage existing observations of smaller volcanic eruptions as a means to bound our results in terms of limits of detectability of current and future satellites observations (Gorkavyi et al., 2021).

The most critical aspects to designing such an experiment thus address how one would find the plume, which depends not just on observational capability but on how rapidly the plume spreads, and how well one could predict its location with forecast modeling. Once that aspect is well understood, then of course a more complete experimental design would involve designing both how the material would be released, and the details of the in-situ sampling observations that would be conducted assuming that the location of the plume is already found. Our proposal therefore focuses on this first step - the modeling that is required to answer the question of the minimum size for such an experiment.

Our goal is to determine the minimum size of an experiment that would allow for a substantial reduction in this uncertainty. This is critical information both for defining future research needs, and for informing the governance of research. Therefore, it is highly aligned with the program scope of "developing a strong predict → test → monitor → validate loop" for SAI. We are not planning on performing the experiment, nor even thoroughly designing it, but rather that, before somebody does, there are crucial steps that need to be taken to be ready to fully take advantage of one.

Description of research and methodology:
The ability to track the plume depends not only on initial concentrations, but on (i) the ability to forecast the plume location given current location (to reduce the search space), (ii) how rapidly the plume diffuses, which affects the concentrations, and (iii) observational capabilities. These

[1] SABRE: https://csl.noaa.gov/projects/sabre/

will be addressed in the first 3 tasks below. In addition, the scale of this class of experiment, while negligible compared with current anthropogenic emissions, would involve significantly larger material released than the previously proposed SCoPEx experiment[2] or the somewhat arbitrarily-proposed 1000 kg limit suggested in the 2021 US National Academies report[3]. Just as it is important to be able to track the plume in order to sample it, it is essential to be able to provide information to policy and the public about the detectability and transboundary implications of a test, and the dependency of these impacts on the size and location of the test, as this will also influence experimental design. Task 4 addresses this.

1. The first task is to assess the ability to forecast the future location of the center of the plume if the current location is known. The Whole Atmosphere Community Climate Model (WACCM) can be used in forecast mode[4], where it is initialized with stratospheric winds (based on re-analysis). By comparing short-term WACCM forecasts of volcanic aerosols against observations, initialized at different times in the evolution of the volcanic plume, this tool will allow us to quantify the likely predictive accuracy with lead time, better constraining the search region that would need to be explored to find the aerosol plume (assuming that it is not always continuously tracked).

2. The second task is to quantify the range of plausible rates of plume diffusion over the first month. To answer this, we will use satellite observations from TROPOMI[5] after volcanic eruptions, which have been demonstrated to be capable of tracking plumes of SO_2 at a scale relevant to a large-scale SAI experiment (Theys et al., 2022). While this can only be used to determine spreading rates for spatial scales larger than the spatial resolution of TROPOMI (about 25 km horizontally), that can be extrapolated to bound spreading rates at smaller spatial scales as well. Analysis after different volcanic eruptions will provide information about how variable these rates might be under different stratospheric conditions. This will therefore allow us to determine, as a function of the initial SO_2 mass release rate, estimates for how broad the resulting plume is as a function of time and the estimated peak aerosol concentration within the plume; this will feed into the next task associated with the detectability threshold.

3. The third task is to clarify the potential sensitivity of observational capability for remotely detecting SO_2 and detecting sulfate aerosols. The aerosols can be detected through upwards-facing LIDAR on aircraft; these instruments are already in use (on the NOAA SABRE missions, for example[6]), but we will engage in conversations about the potential for modifications or redesign for this particular mission.

4. Task 4 aims to provide statistical information about the movement of air plumes at different geographical locations and altitudes based on reanalyses and trajectory models

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[2] https://www.keutschgroup.com/scopex
[3] https://nap.nationalacademies.org/catalog/25762/reflecting-sunlight-recommendations-for-solar-geoengineering-research-and-research-governance
[4] https://www.acom.ucar.edu/waccm/forecast/
[5] https://www.tropomi.eu/
[6] https://ntrs.nasa.gov/citations/20230008368

(e.g. Sun et al., 2024, Peace et al., 2024) in order to inform future discussions around potential transboundary issues with outdoor SAI experiments. This will allow us to clarify under which conditions and injection amounts there might be foreseeable chances of some of the plume material falling into the troposphere within a country's airspace and hence the potential for deposition. This will provide information for the modality of "safe" outdoor experiments that do not significantly infringe on other countries' airspaces. This will allow us to address the potential relevance of the experiment in light of current, established protocols around environmental pollutants, such as the Convention on Long-Range Transboundary Air Pollution, by communicating at which scales, and from which locations, detectable transboundary effects could be relevant. This task can also inform the first task, as it can clarify whether there are altitudes or locations that an experiment could be conducted at that would lead to more or less predictability.

Collectively, these tasks will be integrated to determine what spatial scale of experiment would be needed to allow reliably finding the plume if it is not continuously observed. Once the plume location is known, existing observational assets could be used for in-situ sampling to determine aerosol concentrations, size distribution, etc. Knowing the required mass release is an essential precursor to designing details of aircraft release system as well. **Thus the work proposed herein is the first step towards designing a plausible test of SAI with SO_2.** Furthermore, the process one would use to follow and subsequently sample the plume in the first aircraft-scale test of SAI, considered herein, is essentially the same process that would be needed on the first days, weeks, or months of a deployment, to validate that the observed behaviour is sufficiently consistent with predictions; this effort is therefore also useful in defining observational needs more generally, and thus is complementary to the research proposed by [redacted] and colleagues.

There are of course other uncertainties associated with SAI. However, uncertainties in the climate response at scale (how would surface climate respond to a certain aerosol layer in the stratosphere) cannot be addressed through experiments, while many of the other uncertainties in stratospheric processes would primarily affect the response to SAI at high cooling and would not substantively affect results if SAI is used to cool by, for example, 0.5°C. Given that that level of cooling would not be reached for *at least* a decade after the start of deployment, some of these stratospheric uncertainties will not meaningfully affect a decision on whether or not to start a deployment, and thus are not as high a priority today. For SAI using SO_2 injections, the potential experiment described here would thus be both the most scientifically relevant perturbative experiment to pursue in terms of reducing policy-relevant uncertainty, and also the smallest perturbative experiment that is relevant; as a result it is likely the first such experiment that would be conducted for SO_2-based SAI. Yet despite more than a decade of discussions around research governance of SAI, there has not yet been an effort to quantify the size or the transboundary impacts of such experiments. We thus believe that our research could significantly improve debates around SAI experiments, highlighting detection and design needs, as well as strengthening discussions around future governance by providing a robust, science based foundation of topics such as detectability and long-term fate of the plume.

In parallel with the proposed work it would be valuable to conduct more detailed small-scale modeling that captures fluid turbulence and aerosol microphysics; as this can be decoupled from the work above we do not include it herein, but are discussing with other funders.

Metrics, Milestones and Timeline: The work described above will be completed over two years. The bulk of the effort is in the modeling and analysis in tasks 1, 2, and 4. As this will largely be conducted by one postdoc and one graduate student (see below), tasks 2 and 4 will be largely sequential, and conducted in parallel with task 1. Key milestones include (1a) identifying key volcanic eruptions and downloading reanalysis data (Q2, yr1), (1b) testing WACCM in forecast mode (Q3, yr1), and (1c) generating a data-base of forecast errors as a function of lead-time and location (Q2, yr2); (2a) identifying relevant volcanic eruptions and downloading TROPOMI data (Q2, yr1), (2b) analysis of TROPOMI spreading rates (Q4, yr1); (4a) testing of Langragian transport models (Q1, yr2), (4b) simulating transport for a range of stratospheric conditions and experimental locations/seasons (Q3, yr2), (4c) summarizing transboundary implications from that (Q4, yr2). All results will be documented in archival journal articles throughout (with expected publications corresponding to tasks 1, 2, and 4).

Section 2: Project team:

[redacted]

[redacted]

Working closely together, our group at Cornell University has over the years been at the forefront of SAI research. Our combined expertises would allow us to push forward this yet underexplored venue, which requires a tight coupling between the atmospheric sciences and engineering disciplines. We thus believe that we are ideally situated to address these questions.

The research above will be conducted by a postdoctoral associate and a graduate research assistant, under the guidance of the project PIs. [redacted]

[redacted]

In addition there are potential collaborations that we will explore to strengthen the effort if funded, including [redacted]

Motivation

Early research on SRM was highly idealized, often simply "turning down the sun" in coarse resolution climate models or specifying aerosol distributions. Over the last decade there has been extensive research conducted with injecting SO_2 into the stratosphere in higher resolution climate models that capture stratospheric aerosol processes; this research includes exploring the dependence of the response on the latitude of injection, considering different strategies, applying feedback to manage temperature targets despite uncertainty, as well as an increasing body of research looking at the effects on a wide variety of impacts throughout the world based on this climate modeling. All of this research to date points to the potential for a limited deployment of SAI to reduce many climate impacts, provided that it is a supplement to mitigation and not a substitute. In order to provide better support for future decision makers, it is time to take another fundamental step towards realism in our assessments. That must include a willingness to consider perturbative outdoor experiments provided that there is a clear scientific justification, and no other pathway available to reduce the uncertainty. Thinking clearly about experiments is important first because such experiments will improve model predictions and hence improve the information available to support decisions, it is also important for improved clarity on thinking about what the first steps would look like outside of model-land; thinking about the evolution of a single plume is not only the first experiment, but what one would see in the first days or months of early deployment. And finally, it is also essential to ground discussion of research governance in actual rather than hypothetical experiments, and their actual impacts. For all of these reasons we could not be more excited to take this next step in SAI research!

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PULSE Project: Public Understanding, Leadership, and Social Ethics in the Governance of Earth Cooling Technologies in Communities Impacted by Volcanic Activity in the Philippine Context.

Section 1: Technical Aspect

Project Research Summary

As climate change intensifies alarmingly, the global community is urgently exploring geoengineering solutions like Solar Radiation Management (SRM) to reduce global temperatures by reflecting solar radiation back into space (Harding & Moreno-Cruz, 2019). In addition, SRM, particularly stratospheric aerosol injection (SAI), could offer climate benefits but raise significant ethical, social, and governance concerns. These considerations and uncertainties in the risks and effectiveness underline the immediate need for vigorous research on climate science and social responses in anticipation of large-scale deployment.

The PULSE Project (Public Understanding, Leadership, and Social Ethics) addresses several critical gaps in understanding and governance of SRM technologies. This two-year project examines public perceptions in volcanic regions, ethical considerations, and governance and leadership frameworks concerning the deployment of SRM in the future.

The Philippines, located on the Pacific Ring of Fire, is highly vulnerable to climate change impacts, natural disasters, and the activity of many active volcanoes. These intersecting challenges give the country a unique perspective that could be valuable in informing SRM. The volcanic eruptions, such as Mount Pinatubo in 1991, serve as natural analogs for SRM technologies like stratospheric aerosol injection, providing critical lessons on the likely environmental, social, and governance implications of geoengineering as a climate intervention strategy. According to a 1997 USGS publication, the 1991 eruption of Mount Pinatubo in the Philippines released approximately 17 million tons of sulfur dioxide into the stratosphere, forming sulfate aerosols that reduced global temperatures by about 0.5°C (0.9°F) over the following two years.

By adopting a multidisciplinary team, the project will contribute to inclusive, transparent, and ethical decision-making processes regarding climate interventions that must respect community needs and future generations. The proposed research project addresses how to respond to these challenges by studying public understanding of SRM, especially in communities near active volcanoes in the Philippines. The project will investigate how past experiences of those communities with volcanic eruptions influence their perception of SRM technologies, focusing on Luzon Island (Mt. Mayon in Albay province, Mt. Pinatubo in Zambales, Mt. Taal in Batangas), Visayas Island (Mt. Kanlaon in Negros Oriental) and Mindanao (Mt. Hibok-Hibok in Camiguin). Surveys, focus group discussions, workshops, and key informant interviews will be conducted to gauge local awareness of issues and ethical considerations regarding the possible deployment of SRM in such vulnerable regions.

This project aims to comprehensively examine the community's views about SRM, explore ethical issues, analyze the present governance frameworks, and design policy recommendations that provide ample opportunities for inclusive decision-making. This mixed-method research approach will involve surveys, interviews, and expert workshops to facilitate open ethical leadership within climate governance. Expected outputs from this research include capacity-building workshops, academic presentations, policy briefs, and peer-reviewed journal articles toward responsible and equitable approaches to technologies for cooling the Earth that set up a robust foundation to underpin informed climate governance.

Research Plan

Problem Statement

Solar Radiation Management (SRM) is a promising yet quite controversial technology. It is a geoengineering method that involves influencing climate by reflecting sunlight from the Earth's atmosphere. However, SRM is extremely controversial due to its likely environmental impacts, ethical implications, and governance challenges, though it has some potential applications in mitigating global warming (Union of Concerned Scientists, n.d.).

SRM may provide a potentially transformative pathway to countries like the Philippines, which are highly susceptible to climate change and natural disasters. However, introducing SRM technologies in such regions may raise ethical, social, and governance challenges, especially within communities that have already been disturbed by volcanic activities and other environmental disasters.

Understanding the social and ethical implications before widespread implementation is more pressing than ever. SRM would provide solutions to the problem of climate change, but it will also give rise to new risks and uncertainties (McLaren & Corry, 2021). Many uncertainties persist about SRM; therefore, further research must be conducted in climate science and the social sciences before policymakers seriously consider developing capabilities for deploying SRM. Secondly, SRM presents significant governance and accountability challenges that must be addressed through an ethical framework to protect future generations and vulnerable populations.

The proposed PULSE Project will seek to meet the challenges outlined above by exploring the perception, ethical, and governance/leadership concerns about using SRM technologies in the context of the volcanic community of the Philippines. This is historically and culturally attached to their environmental setting; the relationship and experience of this community with natural disasters would strongly shape views about new technological interventions such as SRM. The PULSE Project, therefore, plays a crucial role in investigating how these communities perceive SRM, particularly SAI, their awareness of it, and their concerns concerning the potential risks and benefits. Through this research, regional governance structures and leadership can be informed and guided to ensure that any SRM technologies deployed in the future are used transparently, ethically, and in a manner that is respectful to local needs and intergenerational justice.

There is a critical research gap concerning localized, context-specific ethical and governance issues of SRM deployment in the volcanic region of the Philippines. Without framing for public comprehension and accountability in SRM governance, ethically sound decision-making concerning its development and deployment becomes undermined. The lack of clarity creates uncertainties that may alienate vulnerable communities and potential risks, increasing social divides and undermining trust in climate interventions. The PULSE Project will fill this gap in knowledge by investigating the social, ethical, and governance challenges that SRM technologies pose for these communities to foster inclusive and responsible decision-making processes.

The project will yield necessary insights through comprehensive surveys in communities situated around areas where volcanic eruptions have occurred in the Philippines, with an emphasis on Mt. Mayon (Albay), Mt. Kanlaon (Negros Island), Mt. Pinatubo (Pampanga, Tarlac, and Zambales), Taal Volcano (Batangas), and Mt. Hibok-Hibok (Camiguin). The historical volcanic activities of the sites selected will be assessed, along with the likelihood of similar issues concerning SAI, a proposed SRM technique. The survey aims to determine the communities' stand on SAI, their awareness, knowledge, and concerns, and how this relates to their past experiences concerning volcano eruptions, changing climate, and aspects of their environment. Focus group discussions and workshops will also be conducted to complement policy recommendations and governance frameworks and ensure that SRM technologies characterized by transparency and accountability concerning the welfare of vulnerable populations may be deployed. The project aims to "gauge society's pulse" and ensure future climate interventions are grounded in ethical leadership, inclusive governance, and public accountability.

Study Objectives

The main focuses of the PULSE projects are

Study 1: Investigate the awareness, understanding, and perceptions of communities in the volcanic regions concerning Earth cooling technologies and the associated impacts and risks,

Study 2: Examine ethical issues and intergenerational perspectives of SRM, including equity, justice, and protection in communities prone to volcanic eruptions;

Study 3: Analyze leadership roles and governance frameworks for assuring transparency, accountability, and inclusivity in decision-making for cooling of the earth technologies and

Study 4: Recommend the structures of governance and policy recommendations for making decision-making inclusive and ethical.

Significance and Justification

The PULSE Project identifies and addresses ethical, social, and governance challenges surrounding Solar Radiation Management in communities affected by volcanic activity in the Philippines. The study will ensure that SRM interventions are ethically founded, socially responsible, and inclusive by assessing local perceptions, awareness, and concerns. Therefore, the project shall explore governance frameworks and propose policy recommendations to fill the critical research gaps responsible for climate decision-making in the most vulnerable volcanic regions, particularly in the Philippines as a developing country.

Area of Studies

The Philippines is in a tectonic setting, ideal for volcanic and earthquake activity (Philippine Institute of Volcanology and Seismology, nd.). In addition, there are 24 active volcanoes in the country, which means these volcanoes have erupted within the last 10,000 years. However, volcanologists have no consensus agreement on how to define active volcanoes. According to

Klemetti (2015), volcanoes that are unrest or showing signs such as earthquakes, inflation, and abundant release of carbon dioxide and sulfur dioxide are also considered active.

This proposed research project will conduct a case study in communities near active volcanoes in the Philippines, such as those around Mt. Mayon, Mt. Kanlaon, Mt. Pinatubo, Taal Volcano, and Mt. Hibok-Hibok. These volcanoes pose significant threats to surrounding communities, as their eruptions lead to environmental destruction, displacement, economic loss, and psychological impacts. These communities near active volcanoes experienced extreme impacts of volcanic eruption that can also be impacted by the subsequent effect of geoengineering on the environment.

Research Methodology

The PULSE project will apply a mixed-method approach by combining qualitative and quantitative research in a single study of SRM's public understanding and trust, social acceptability, and governance challenges.

- Comprehensive surveys will be conducted across communities surrounding active Philippine volcanoes, such as Mt. Mayon, Mt. Kanlaon, Mt. Pinatubo, Taal Volcano, and Mt. Hibok-Hibok. The comprehensive survey measurements of public awareness, trust in the scientific institution, and support for SRM will be anchored on knowledge of SRM, safety concerns, and confidence in governance frameworks.
- FGDs will be carried out in volcanic regions among diverse participants, such as local community members, government officials, scientists, and civil society representatives. The FGDs shall examine public attitudes, knowledge gaps, and factors influencing SRM acceptability, including transparency, trust, and risk perception.
- In-depth interviews with policymakers, scientists, environmental activists, and industry leaders will capture perceptions of SRM's feasibility, safety, and potential role in global climate strategies.
- Workshops and expert panels on ethical frameworks, focusing on intergenerational justice and the fair distribution of risks and benefits, would ensure that SRM does not cause disproportionate harm to vulnerable populations.

Method of Data Analysis

Data analysis in the PULSE Project will use qualitative and quantitative methods to address the different research objectives. Quantitative analysis will be done through statistical techniques to analyze the results of the surveys regarding awareness and understanding of SRM technologies in the target communities. Qualitative analysis will include thematic and content analysis of the ethical concerns, governance issues, and local perceptions gathered through interviews, focus groups, and expert workshops. Comparative analysis will also explore differences in attitudes and concerns from communities affected by volcanic activities. A meta-synthesis approach will also integrate findings across data types, giving a comprehensive view of the social and ethical implications of deploying SRM in such regions.

Expected Outcomes

1. Capacity Building. Training workshops will help stakeholders better understand SRM technologies and governance challenges and instill ethical leadership in climate governance.

2. Paper Presentations and Conferences. Present research findings at relevant academic and policy conferences to engage a broad audience and stakeholders.

3. Policy Briefs. Produce policy briefs that summarize key findings and recommendations for policymakers to use in the decision-making on SRM governance.

4. Publishable Journal Articles. Produce peer-reviewed journal articles to enrich the academic discourse on SRM, ethics, and governance.

Research Activities

Year 1:

1. Project Kick-Off. Team meetings and project planning, completion of research ethics review, and site visits to target communities Mt. Mayon, Mt. Kanlaon, Mt. Pinatubo, Taal Volcano, and Mt. Hibok-Hibok.
2. Literature Review. Conduct a comprehensive review of existing studies on public perceptions, ethical concerns, and governance frameworks regarding SRM technologies.
3. Questionnaire Design and Administration. Design and administer questionnaires to gauge community awareness, knowledge, and attitudes regarding SRM, emphasizing the local perception of risks and benefits.
4. Community Engagement. Use focus groups and interviews among community members and local leaders to explore ethical concerns and governance priorities related to SRM.
5. Data Analysis. Analyze survey data and qualitative responses from focus groups and interviews to identify trends and patterns in public perceptions, ethical concerns, and governance issues.

Year 2:

1. Governance and Ethical Frameworks. Review the governance frameworks and ethical considerations of SRM in vulnerable communities. Based on data from Year 1, identify gaps and issues.
2. Stakeholder Workshops. Hold workshops with local leaders, policymakers, scientists, and NGOs to discuss and refine governance frameworks and the ethical implications of deploying SRM in volcanic regions.
3. Policy Development. Synthesize the data analysis and the stakeholder workshops into policy recommendations that ensure inclusive and ethical decision-making on SRM technologies.
4. Final Report and Dissemination. Prepare and present the final research report, including academic papers, policy briefs, and governance recommendations. Disseminate findings through conferences, workshops, and publication in peer-reviewed journals.

Section 2: The Team

Individual	Role / Expertise	FTE	Total time on project (months, rounded)
[redacted]	[redacted]	50%	12
[redacted]	[redacted]	50%	12
[redacted]	[redacted]e	50%	12
Hiring of Full-time Research Assistant		100%	24
[redacted]	[redacted]	10%	2.4
[redacted]	[redacted]	20% (Policy workshop/dialogue and give critics on the research protocols)	4.8
[redacted]	[redacted]	20% (Policy workshop/dialogue and give critics on the research protocols)	4.8
[redacted]	[redacted]	20% (Policy workshop/dialogue and give critics on the research protocols)	4.8
[redacted]	[redacted]	20% (Policy workshop/dialogue and give critics on the research protocols)	4.8
[redacted]	[redacted]	20% (Policy workshop/dialogue and give critics on the research protocols)	4.8
[redacted]	[redacted]	20% (Policy workshop/dialogue and give critics on the research protocols)	4.8

Project Budget

EXCHANGE RATE OF GBP TO PESO: Php73.98 (DEC. 04, 2024)					
GBP CONVERSION	73.98				
Particular	Quantity	Amount		Total	
		GBP	PHP	GBP	PHP
1. Personnel					
Research Assistant	1 x 24 months (2025 - 2027)	543.00	40,171.14	13,032.00	964,107.36
Research Assistant	1 x 12 months (2026 - 2027)	543.00	40,171.14	6,516.00	482,053.68
Subtotal		1,086.00	80,342.28	19,548.00	1,446,161.04
2. Materials and equipment					
Laptop	1 unit	800.00	59,184.00	800.00	59,184.00
Supplies		1,300.00	96,174.00	1,300.00	96,174.00
Subtotal		2,100.00	155,358.00	2,100.00	128,100.00
3. Project Team Meetings / Updating (food / snacks)	11 pax	150.00	11,097.00	1,650.00	122,067.00
Subtotal		150.00	11,097.00	1,650.00	122,067.00
4. Travel and Accommodation during data gathering					
4.1 Community-level Data Gathering					
Transportation cost: Van rental + driver going to communities to conduct surveys, FGDs, and dialogues	3 visits x 5 sites x 4 days	300.00	22,194.00	18,000.00	1,331,640.00
Air Fare: Plane ticket going to Camiguin (Mt.	Camiguin / CDO: Max. 5 pax per travel x 3 times	250.00	18,495.00	3,750.00	277,425.00

Hibok-hibok), and Negros (Mt. Kanlaon)	Bacolod: Max. 5 pax per travel x 3 times	230.00	17,015.40	3,450.00	255,231.00
Accommodation	3 visits x 5 sites x 4 days x 11 pax	40.00	2,959.20	26,400.00	1,953,072.00
Per diem	3 visits x 5 sites x 4 days x 11 pax	21.00	1,553.58	13,860.00	1,025,362.80
Subtotal		841.00	62,217.18	65,460.00	4,842,730.80
Food during workshops / FGD and policy dialogues	35 pax x 5 sites x 2 events	25.00	1,849.50	8,750.00	136,826.01
Community Survey Cost	35 pax x 5 sites	30.00	2,219.40	5,250.00	164,191.21
Subtotal		55.00	4,068.90	14,000.00	301,017.22
4.2 Policy forum and workshop					
Van Rental to conduct policy forum/workshops	5 sites	300.00	22,194.00	1,500.00	110,970.00
Food during workshops / FGD and policy dialogues	30 pax	28.00	2,071.44	4,200.00	310,716.00
Policy presentations and validation	35 pax x 5 sites	25.00	1,849.50	4,375.00	323,662.50
Per diem	5 sites x 11 pax	21.00	1,553.58	1,155.00	85,446.90
Invite resource persons to discuss SRM technologies	2 persons at 2000 per hour for 5 hours	28.00	2,071.44	280.00	20,714.40
Subtotal		402.00	29,739.96	11,510.00	851,509.80
5. Project write shop/workshops among the project members of policy paper, report writing and publication	Per diem: 11pax x 3 times or days x GBP 21 Transportation: GBP 2000 (3 times or days, 10 pax)	2,693.00	199,228.14	2,693.00	199,228.14
Total		3,991.00	295,254.18	93,663.00	6,194,485.96
6. Travel Insurance		21.00	1,553.58	231.00	17,089.38

Overall Total		**7,348.00**	**543,605.04**	**117,192.00**	**7,907,903.38**
7. Institutional fee for the UPLB Foundation Incorporated	**15%**			**17,578.80**	**1,300,479.62**
Grand Total		**7,348.00**	**543,605.04**	**134,770.80**	**9,208,383.01**

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SAFEGEOGOV – Strategic Foresight on Climate and Geopolitics:
Toward Governance of Solar Radiation Modification

1. SAFEGEOGOV's Programme Contribution & Technical Description

❓ The ARIA funding program asks whether one or more climate cooling methods may one day be used to effectively, responsibly, and ethically prevent or counter severe climate outcomes, including from tipping points. This question needs two types of answers: one on the technical capabilities and another on decision-makers' ability to make wise decisions. On the latter, the feasibility of responsible climate cooling is powerfully shaped by geopolitical dynamics. Examining political scenarios may allow the identification of a range of non-ideal deployments that can inform the technical research on the physical consequences of deployment under various conditions, including cases of imperfectly rational decision-making.

The proposed project examines plausible futures of solar radiation modification (SRM) deployment by 2035. A baseline and four geopolitical SRM scenarios will be developed in partnership with the OECD – a major, highly credible, multilateral organisation with direct, high-level Ministerial access across its 38 member states and a positive impact far beyond those.[1] The project contributes to the social science research on the geopolitics and anticipatory governance options for SRM, and it may inform the scientific research on SRM impacts in case of non-optimal deployment conditions. The project develops four strategic foresight scenarios with input from a broad range of scientific and policy experts and practitioners. This work would help bridge the science-diplomacy chasm, which – alongside the lack of technical research – poses a severe obstacle to informed decision-making.

A slowdown in climate policy and broader political developments, as well as the crossing into increasingly dangerous climate territories above 1.5°C raise the spectre of a sudden rise in interest in SRM use at a time when the scientific knowledge is not sufficient and international governance of SRM is inadequate – as is decision-makers' awareness of the stakes. Knowledge levels about the coming climate impacts as well as about the science and potential politics of SRM, remain very low amongst key officials, including in developed countries.

The project bridges the chasm between science and policy by serving both communities: the tangible future scenarios make the – otherwise abstract – climate intervention techniques "more real" and help policymakers understand the potential risks, benefits and uncertainties – and why they should care. It also helps researchers better understand the kind of questions policymakers - and the public they serve - want answered. It allows for the identification of non-ideal scenarios in which SRM testing or use may happen. Researchers and decision-makers will learn from each other's realities, empowering more judicious and informed decision-making. Advancing a nuanced and humble understanding that SRM is not 'just' a science issue but an 'everything' issue is crucial and most governance literature outlines extremes – either a top-down ban (however enforced) or unilateral deployment followed by conflict. Geopolitical analyses may show both unlikely. More nuanced scenarios may examine how threats from climate change and interests associated with SRM might intersect with geopolitics, security, migration, human rights and other social objectives. The development of the scenarios starts with baseline political realities of the next ten years in which it grounds testing and deployment scenarios.

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[1] The OECD's senior leadership is intent on collaborating and willing to confirm this publicly once CFG can assure the funding and a formal cooperation agreement can be signed on such basis.

The project's insights could help devise solutions to reduce the chances of dangerously uninformed decisions and uncertainties on multiple levels. They would also help identify and advance no-regret, near-term governance solutions, which would be desirable regardless of one's views on a future with or without SRM. Such measures may include strengthening the transparency of research and monitoring of testing/deployment, clear criteria for large-scale outdoor testing, actionable opportunities for significant public engagement along the way, and exploration of possible governance bodies. The project would also unearth additional questions requiring further technical and scientific research.

The four scenarios will be developed through a rigorous process involving a wide range of expert and practitioner perspectives; our interlocuters have already raised some ideas – and the literature also provides suggestions – toward SRM testing and deployment scenarios, including under non-ideal conditions: SRM deployment by one or more major economies to slow or avert a global climate tipping point related to the Arctic; a unilateral and unannounced large-scale test of SRM; unilateral global deployment by a major power reducing temperatures excessively); geopolitical tensions from a proposed global-scale deployment by several permanent members of the UN Security Council – opposed by another (considering each has veto power); a multilateral deployment in the Amazon or the Sahel by climate-vulnerable countries jointly with Northern European Nations; intentional mis- and disinformation and their implications for political debate and decision-making will also be examined and woven into one or more of these scenarios. We intend to strike a careful balance to ensure that the scenarios do justice to the range of possibilities – including the significant benefits of successful SRM protection from climate harm.

SAFEGEOGOV empowers policymakers and researchers with a shared understanding of the stakes involved with climate change and SRM. It

1. contributes to ethical, governance, law, security and geopolitical research,
2. highlight implications of using - or not using - SRM and the consequences for the SDGs,
3. identifies factors of (non-)feasibility (social, political, scientific, and engineering),
4. identify cross-cutting questions,
5. and co-creates evidence for informed and effective decision-making.

The participatory development of scenarios, briefings, and subsequent policy engagements places the SRM governance issue squarely on the diplomatic agenda of the OECD and its members' Ministries of Foreign Affairs, Finance, Energy and Economy, including those tasked with the clean energy transition.

State of SRM governance

Governance research remains highly theoretical and inadequately grounded in political realities. Decisionmakers have told us they need concrete governance proposals and have explicitly asked us to develop them. Existing literature highlights ethical, environmental, and technical issues of SRM governance, but often without delving into options that could help address them. When options are given, such as for a sweeping non-use agreement or calls for broad deliberation, they have not been backed by analyses of the political interests and institutional structures that would largely determine their feasibility. Few studies delve deeply into the practical geopolitical dynamics or strategic decision-making scenarios surrounding individual countries' potential decisions for strategies of testing, deployment or deterrence of SRM.

A key gap in the field is the lack of forward-looking exploration grounded in realpolitik: With limited use of geopolitical and game-theoretical analyses examining strategic testing, deployment or non-deployment decisions, most governance research relies on stylized, extreme cases, such as direct great power conflicts weaponizing SRM on the one hand or idealized fully cooperative rational actors under UN decision-making on the other. These approaches fail to capture the complex, iterative, and often fragmented nature of the geopolitical undercurrents that would likely shape SRM governance. We are aware of a separate proposal for expert-involved work on analyses of non-ideal deployments forward by [redacted] and are highly supportive of such endeavors. We plan to draw on early insights from [redacted] 3-year project in SAFEGEOGOV and vice-versa, offer insights from our work to [redacted] team (see below).

Most discussions on potential governance frameworks have emphasized a predetermined outcome (use or non-use of SRM) – mirroring the presumed preferences of authors. The weakness of a sweeping "non-use agreement", for example, becomes evident based on three observations: 1. An international norm seeking to prevent the use of SRM is only as strong as its capability to deter the government(s) most keen on using SRM; 2. Growing climate impacts and tipping point threats will increase the perceived attractiveness of SRM in a world of 2-3°C of warming; 3. Countries proved reluctant even on an international assessment of SRM - for fear of prematurely locking in a particular international process or negotiation venue.[2]

The SRM governance literature is heavy on arguments and light on rigorous analysis. This creates a false impression of certainty and coherence. More exploratory analysis of governance proposals' feasibility, enforceability, and/or long-term implications - including in the context of overall global climate policy, growing public mistrust of both science and the state, and social media echo chambers - is critically needed. The current state of governance studies also emphasizes extremes and lacks a range of intermediate governance contexts and models. This is required to balance diverse stakeholders' interests while addressing risks and opportunities associated with SRM. This underdeveloped state of SRM governance research underscores the urgent need for studies integrating political realities, exploring a wider range of geopolitical scenarios, and incorporating robust strategic modelling for effective and equitable governance.

State of governance activities

Several actors have sought to empower international decision-makers and UN fora to strengthen governance mainly by raising awareness and fostering dialogue among policymakers (C2G) and civil society (Alliance for Just Deliberations on Solar Geoengineering - DSG, Heinrich Böll Foundation). Some have focussed on individual national governments (e.g. Silver Linings in the US). The issues are increasingly discussed in English-speaking media and among some UN entities (UNEP, UNCBD, UNESCO, WMO). However, these discussions remain abstract and lack a real-world understanding of crisis decision-making and the political

[2] We believe that agreement for greater cooperation and informationa sharing under the UN (incl. UNEA and IPCC) was stifled to date by a lack of a shared understanding of what may be at stake and an inadequate vision of what is to gain by cooperating. Our scenarios should help with both.

factors that heavily influence policymaking at the highest levels. There is no public, transparent registry of SRM research and who funds it, nor is there any agreement on what constitutes SRM research and how it could be monitored across borders. No major government has yet pronounced its position on questions of future use of SRM. Even the question of selecting an agency to conduct an international assessment of the scientific evidence of SRM and its governance challenges remains contested.

Approach and timeline

In contrast to many existing governance studies, we favour a more outcome-agnostic approach, prioritizing the exploration of multiple potential futures using strategic foresight that is grounded in the input of a wide range of perspectives: we will involve relevant practitioners and experts from a range of fields (including game theory, international relations, behavioural economics and/or risk communications) as input and helpful complements to strategic foresight. Such involvement through interviews or workshop participation can strengthen our analytical base (reference scenarios) and vice-versa, stimulating reflection on a broader range of possible geopolitical dynamics. Consequently, policymakers should see themselves or their peers in these scenarios and take much more seriously the awesome responsibilities they will soon face as the climate crisis worsens and decisions on SRM are thrust to the top of the global agenda.

The strategic foresight process for scenario development is at the project's core – accompanied by extensive communication and engagement activities. Strategic foresight is a structured way to think about the future through the eyes of multiple stakeholders, each of whom can bring distinct insights to broaden or deepen the range of considerations. Its purpose is to equip governments, societies, and researchers with the capacity to explore and prepare for multiple plausible futures, risks, opportunities and challenges to guide decision-making today.

The strategic foresight methodology used in this project is a comprehensive deductive approach that allows for generating evidence-based, defensible and robust SRM future scenarios. It mirrors processes employed by other International Organisations, including the UNIDIR, and is widely considered one of the most rigorous strategic foresight processes. ScMI software will be used for structured data analysis that supports the scenarios. The scenario development includes the following five steps:

1. Conducting Delphi interviews with SRM, technology, climate policy, geopolitical, governance, and foresight experts to map the analytical background and create a long list of factors that are defining aspects of SRM presently and in the future;
2. Prioritizing a shortlist of the most impactful factors and assessing possible future projections for each;
3. Assessing the consistency between projections to elucidate groups of factors that are logically most likely to co-occur;
4. Developing four reference scenarios about the future of SRM to explore tensions, trade-offs and potentially fitting (global) governance arrangements;
5. Modelling of the broad geopolitical and socio-economic-environmental implications of SRM future scenarios with an international set of thematic and policy experts.

The synthesis report will show and explain the four 2035 SRM scenarios in a clear and concise format. For each scenario, the opportunities and challenges that might have to be anticipated and managed by policymakers will be clearly articulated. The report will be complemented with one or more research articles and at least 5 customised briefings (meetings or phone calls) for specific actors (policymakers, NGOs, the media). Additionally, 2-3 written policy briefs may introduce specific governance opportunities, including potential multilateral and international measures for anticipating and minimising risks and research funding design options for responsible and transparent SRM research, testing, and monitoring.

Target audiences: The synthesis report and its key findings will be presented in research and policy contexts and multiple tailored briefings to senior policymakers and their advisors in the EU and other major economies, as well as with climate-vulnerable countries and civil society networks. Relevant policy fora may include the Climate Vulnerable Forum, G7, G20 and World Bank annual preparatory meetings, Arctic Council's Arctic Monitoring and Assessment Programme (AMAP) working group meetings, and more. Relevant international research conferences may include AGU, DEGREES' Global Forum, and Gordon Research Conferences. Relevant science-policy contexts may include WCRP, IPCC, and IPBES meetings or those by the Ozone Secretariat's science panels. Relevant multilateral contexts include UN venues such as UNEP, WMO, UNFCCC, UNCBD, or Montreal Protocol.

Targeted media outreach will also help create an impact by informing NGO and public discussions. The aim is to stimulate and broaden balanced (risk-risk) reflections on the future contexts in which SRM might be tested or deployed and the consequences - socio-economic, environmental, geopolitical and social (in)stability of each. This will include the range of climate change-related impacts and the associated governance needs, as well as potential SRM field tests or deployments and the potential geopolitical, socio-economic and environmental consequences thereof.

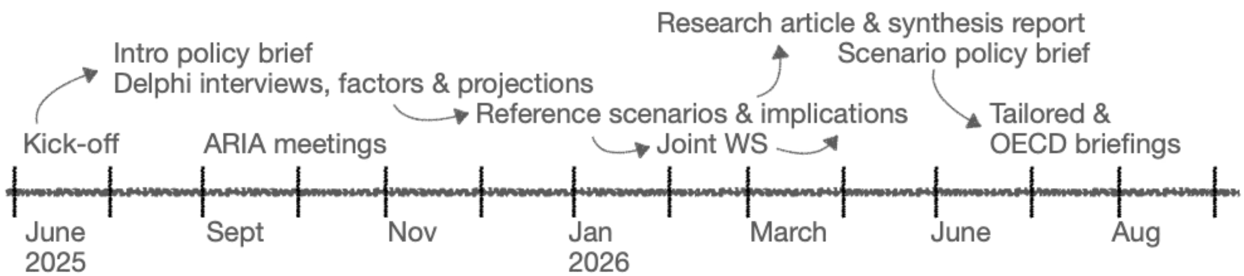
The OECD's involvement and the presentation of the scenarios to senior officials immediately raise awareness of the challenges of SRM governance to new heights.

Work Arrangement and Timeline

The work would be conducted from Brussels, New York, Australia, and Paris, with regular meetings held at CFG's headquarters in Brussels and the OECD's office in Paris. Additional regular meetings can be arranged with ARIA, ARIA-funded researchers, and other UK-based stakeholders to inform this project and, vice versa, convey insights to other projects.

This substantive work is done in a staggered sequence, whereby the five scenario-development steps (Delphi interviews, impact factors short- and longlist, projections, reference scenarios, and implications analysis) are undertaken sequentially and in consultation with thematic experts and policymakers from the OECD Environment and OECD Science, Technology and Innovation Directorates. From the beginning, the project scope and objectives will be communicated to policymakers, including a first policy brief seeking to ensure interest and buy-in. Engagements with other ARIA-funded groups and broader scientific communities are also planned in parallel. We primarily seek to mobilize experts' feedback on key scientific, technical, geopolitical and governance aspects of the scenarios, including the pace and scale of potential deployment, hardware development bottlenecks and the plausible pace of development under varying assumptions, as well as the pace and scale of earth system responses, including in cases of tipping points.

One specific cooperation we can already foresee is a joint workshop with the project proposed by [redacted] in which we would seek to cross-pollinate the respective works, including by participating – where appropriate – in [redacted] (online) symposia, two in-person meetings between project teams, and an in-person joint workshop – tentatively scheduled for January or February 2026. The latter will allow us to overlay and compare our draft scenarios with the simulation space framework of [redacted] project to identify similarities and differences in assumptions and policy/technology implications. Additionally, we foresee two coordination meetings between the two teams – one in London or Leeds and another in Brussels for which we include travel costs for at least one mutual visit of each team.



Seven months into the project (December 2025) could constitute a milestone to assess progress, adjust the work plan, and start 2026 with fresh momentum and guidance from ARIA—in addition to brief quarterly meetings (if desired).

Opportunities to expand the scope: Beyond testing and deployment scenarios, synthesis reports, policy briefs, and outreach activities, CFG may pursue additional complementary work (funding permitting): deeper dives into specific scenarios of interest, informed by deliberations and analyses. This could involve follow-up workshops with SRM researchers and policymakers and targeted dissemination activities focusing on areas like the Arctic, tipping point emergencies, or unilateral large-scale testing or deployment. It may also include the potentially more positive possibilities of relatively coordinated testing or deployment. Further analytical and policy engagement efforts – involving workshop engagements with academic and policy communities – might explore issues such as deliberate climate policy sequencing that ensures robust application of all relevant climate action strategies, including scale-up of CO2-removal, robust SRM assessment and communication, as well as deeper analysis of geopolitical or domestic policy factors shaping future SRM decisions. These activities could extend beyond SAFEGEOGOV's scope, requiring further fundraising if such gaps persist.

Project risks and mitigation measures

The project does not include any physical experiments. Yet it includes potential political risks and, therefore, will also consider whether or how the principles for outdoor experiments outlined in the programme thesis might apply. Political risks include the project's own contribution to the growing salience of SRM testing or deployment – that some governments might eventually consider or threaten in the future. It may be important to anticipate regular interaction with ARIA staff to monitor such risks and to identify options for additional (communication or engagement) measures. The table shows risks, issues at stake and our plan to manage them.

Project risk	Key issue at stake	Risk mitigation measure
Criticism from anti-SRM NGOs for unduly normalizing or legitimizing the issue.	The project's legitimacy and the assertion of moral hazard levelled against it.	Proactive, honest communication: Whether one abhors or supports the possibility of SRM used, it needs governance; for this, policymakers need to grasp what's at stake – tangible scenarios convey that despite short attention spans.
Lack of interest among policy communities – SRM is too "out there" as an issue.	Diversity of policymakers' viewpoints in the analysis & awareness-raising impact.	The team leverages its unparalleled global network to mobilize further voices to underscore the urgency of foresight and SRM governance: SRM researchers and experts in governance, climate policy, and climate science, as well as policy advisors and decision-makers in national and regional governments, the UN system, climate (e.g. climate envoys), security, economic, and foreign affairs.

2. SAFEGEOGOV's Team, its Collaboration, and Motivation

The Brussels-based Center for Future Generations (CFG) provides key EU officials with governance options, timely research and international contacts to help inform decision-making. As the only organization in the Union's de facto Capital with a team dedicated to SRM governance, it supports European leadership in stepping up (as the US steps away from international efforts). With excellent relations in global research communities, key UN system actors, NGOs, and media, we ensure strategically relevant findings – are communicated to key decision-makers informing governance of SRM in Europe, various UN fora, among the G20 and wherever else opportunities to safeguard the interests of present and future generations arise.

The project's PI is [redacted]

[redacted]

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[redacted]

Additional supporting research and corresponding staff input will be commissioned from relevant OECD Directorates (Environment and Science, Technology and Innovation) to ensure methodological rigour and the full briefing of all 38 OECD countries of the resulting report and policy briefs. The OECD prides itself on delivering analyses on emerging issues to its members – ahead of the curve and with excellent quality – this project promises to do just that.

Novel Materials for Stratospheric Aerosol Injection

Section 1: Programme & Technical

1.1 Background and Programme Alignment

This document outlines a proposal for a 3-year study of Stratospheric Aerosol Injection (SAI) as a potential intervention to mitigate the effects of global warming.

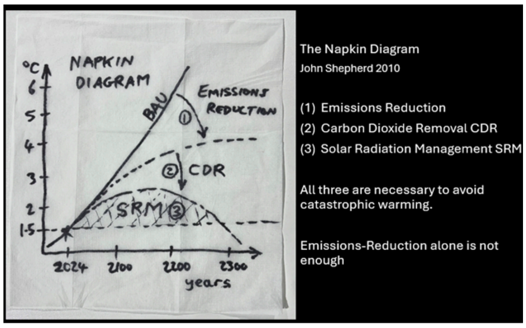

Figure 1. Napkin Diagram

The importance of SAI was made plain by a graphic from John Shepherd in 2010 which soon became known as "The Napkin Diagram", shown here. Emissions reduction alone is insufficient and must be supplemented by Carbon Dioxide Removal (CDR) and Solar Radiation Management (SRM). SAI is one of the most-studied forms of climate engineering, but research has virtually exclusively been limited to numerical simulations. Most of the studies investigating different strategies look at the effects of introducing sulphur dioxide (SO_2) into the stratosphere, which reacts to become sulphuric acid aerosol (H_2SO_4) [1-6] and which reflects some of the radiation from the sun back into space increasing the planetary albedo (**α** in equation for T_{surf} in Programme Thesis). This has in part been inspired by observations from volcanic eruptions, especially 1991 Mount Pinatubo which lofted ~20 million tonnes of SO_2 into the stratosphere resulting in global cooling by approximately 0.5°C for around a year.[7-9] Injection of aerosols into the stratosphere rather than the troposphere reduces the required mass injection rate in part due to longer residence times. Depending on the latitude of injection, the aerosol cloud will be dispersed across the globe within a period of weeks. SAI is considered by a number of scientists as a potential way of actively cooling the earth.[10-11]

1.2 Research Methodology

For stratospheric SO_2 injections[1-6], the resulting sulphuric acid aerosol has the potential for undesirable side effects, such as stratospheric warming and ozone loss, which changes atmospheric circulation, precipitation patterns and ultraviolet radiation.[12-24] The composition and size of volcanic sulphuric acid particles are not optimal for scattering solar radiation[25] and other materials could reduce the injection mass per unit of radiative forcing (cooling).[19,26,33] This is because the refractive index of manufactured aerosols is much larger than that of sulphuric acid. Alternative SAI materials (ASAIMs) are solid/crystalline in nature, e.g., alumina, calcite, silicon dioxide, diamond and other materials. These have the potential to reduce risk to the chemical balance and the dynamics of the stratosphere.[21] Particles engineered to a specific size range can optimise their scattering efficiency and their stratospheric lifetime. ASAIMs have been studied using models investigating global and regional effects[6,19-21,28-35] and laboratory-based experimental studies[36-43]. To understand the efficacy, deliverability and risks of ASAIMs validated models are required. ASAIMs are instantaneously effective whereas SO_2 develops optical effectiveness over a period of weeks thus small-scale indoor experiments are relatively easy with ASAIMs.

Central issues are the (i) scattering efficiency per injection mass, (ii) amount of radiation absorbed, primarily in the long-wave atmospheric window, and (iii) chemical impact on stratospheric composition. First-order questions are what is the ideal ASAIM with respect to radiative and chemical impacts and can these materials be delivered and dispersed effectively? Radiative impacts depend on bulk composition while the chemical ones depend on the particle surface layer. A key feature of this proposal is a unique approach to investigating these aspects of real stratospheric surfaces, in contrast to previous laboratory studies that have largely studied fresh aerosol surfaces or those aged under idealized conditions.

Particles will be investigated in terms of i) practical aspects of system engineering including the near-point source dispersal of material (because agglomeration of materials in a container or the coagulation of particles after their release could seriously impede the overall viability), ii) the medium-scale mixing of material in the stratosphere (because the current spatial resolution of modelling used to assess a global cooling effect is too coarse to examine the behaviour of plumes), iii) the options for delivery of candidate aerosols to the stratosphere, and iv) the lifetime of the aerosols/particles in the stratosphere, their effects on stratospheric circulation and ozone, and regional deposition rates tied to potential biosphere impacts. Other questions, such as impact on cloud formation[42] and surface particulate matter exposure[44] are beyond the scope of this proposal.

1.3 Project Overview: Three Parallel Work Packages

The research will involve three integrated work packages configured to identify which novel ASAIMs are most effective at light scattering relative to potential risks and deliverability.

<u>1.3.1 Work Package 1 (WP1): Stratospheric evolution of chemical and physical properties of ASAIMs</u>

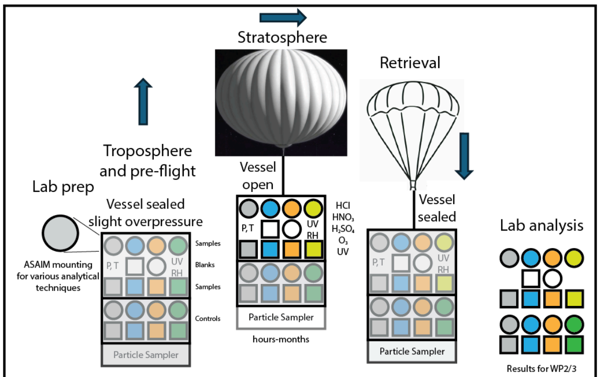

Figure 2: WP1 No Release Experiments

WP1 addresses the evolution of chemical and optical properties of ASAIMs, which control efficacy and risks. A non-release ASAIM field experiment (Fig 2) will solve two fundamental shortcomings of laboratory experiments: laboratory experiments struggle to reproduce (i) the complexity of the real stratospheric system adequately (realism), and (ii) the evolution of ASAIMs over weeks to months. Achieving the realism and timescale requires innovative hardware that combines (i) a novel method of ageing particles in the real stratosphere without any particle release with (ii) offline aerosol analysis techniques regularly used in the [redacted]. The solution, not available with any other approach, is a series of stratospheric balloon flights of increasing duration from hours to months with candidate ASAIMs permanently adhered to grids for offline analysis in a low-weight, sealable vessel equipped with temperature, humidity, pressure and UV radiation sensors, as well as communications. Once in the stratosphere this vessel exposes particles to the full stratospheric environment (UV, temperature, pressure, and chemistry) before sealed descent (preventing tropospheric contamination) and recovery. Substrates coated with particles and no exposure and blanks will provide insights into particle ageing. We will also collect and characterise background aerosols, ensuring accurate representation of the nascent stratospheric environment. Offline nanochemical/imaging analysis techniques, which we regularly apply to background stratospheric aerosol *collected* on electron microscopy and other grids, will measure the evolution of the chemical, physical and radiative properties of ASAIMs as a function of exposure time. These data are needed in **WP3** for accurate numerical modelling to quantify the risks of ASAIMs to stratospheric composition, circulation, and human health.

WP1A Preparation for stratospheric balloon flights: characterise unaged materials not included in our existing laboratory grant (Simons); completion of design, fabrication of existing prototype vessel; selecting and adhering ASAIMs on grids; thermal vacuum tests of complete system analogous to tests of existing stratospheric instrumentation; conduct short duration balloon engineering test flight building on system developed by Sandia National Labs (shared with us); complete ARIA governance framework compliance (*<u>product is material mounting and vessel functional and for stratospheric conditions</u>*).

WP1B Initial short duration science flights: 2 short (~4 hr) duration science flights; 2nd flight only if iteration needed; *<u>deliverable is 3 science ready systems and publication of technical approach.</u>*

WP1C Series of short duration balloon flights to 10 hours; offline characterization of all materials; *<u>deliverable is scientific publication and readiness for WP1D</u>*.

WP1D Preparing and conducting 3-week stratospheric balloon flight: integration with Aerostar's Thunderhead leverages experience in integration complex payloads into stratospheric balloon and aircraft platforms; 3 vessels with ASAIMs and controls exposed 4 d, 10 d, 3 week; characterization of retrieved aerosols; *<u>deliverable is publication of first scientific results on realistic ageing of ASAIMs providing input for WP1E, WP2 and WP3</u>*.

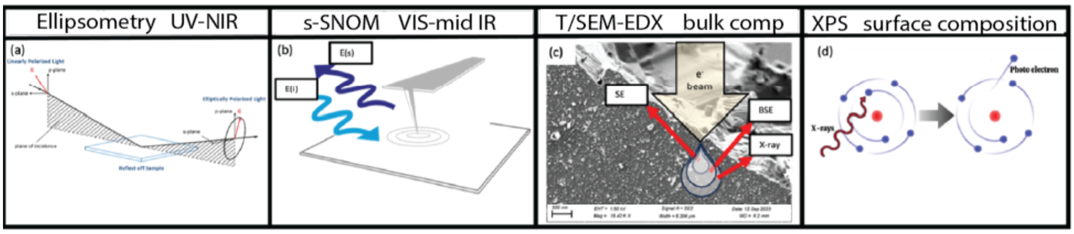

Figure 3. Some employed spectroscopic and imaging techniques. (a) Ellipsometry: UV-NIR refractive index (b) s-SNOM: nanoscale spatially resolved VIS-mid IR absorption and reflectivity; shape, size, morphology and surface roughness (c) T/SEM-EDS: high resolution imaging of topography/morphology and bulk elemental composition, morphology (d) XPS: surface elemental composition/chemical bonding.

WP1E 5-Week stratospheric balloon flight; material choice guided by WP1D; offline characterization of all materials; _deliverable is additional scientific publication on 5-week exposure of ASAIMs to stratospheric conditions._

Characterization of fresh and exposed ASAIMs WP1A-E: Changes of ASAIM morphology, bulk and surface composition, and optical properties over stratospherically relevant lifetimes will be determined via established nanoanalysis techniques. SEM/AFM will determine morphology/size. Optical properties of individual particles will be quantified in Mid-IR to VIS via scattering-scanning near field optical microscopy (s-SNOM) as well as electron energy loss spectroscopy (EELS) at Harvard. Optical properties will also be determined for differently mounted samples via ellipsometry and FTIR-ATR at Harvard. Chemical bulk composition will be determined via SEM/TEM-EDS, STXM (including NEXAFS) and XPS for surface composition. We have been partnering extensively with PNNL-EMSL, e.g., on the STXM-NEXAFS cc-SEM-EDS and others. These methods have been applied by the [redacted] for stratospheric background aerosol collected with an impactor as well as some unaged commercial ASAIMs. Unreactive ASAIMs, such as alumina, are expected to have little bulk chemical change but the UV environment could result in optical changes as can coatings of sulphuric acid or surface roughness changes. Reactive ASAIMs, such as calcite, magnesite, dolomite and others are expected to have extensive surface and even bulk chemical changes from reaction with sulphuric acid, HCl, HF and HNO_3, also affecting optical properties. In addition, changes in surface roughness / topography are important to explore as it affects light scattering directionality and efficiency, ice and mixed phase cloud formation and agglomeration/coagulation. We will also extend previous laboratory contact angle measurements for sulphuric acid and bulk ASAIMs to see if sulphuric acid forms lenses or envelops ASAIMs. The complex refractive index and surface chemical analyses provide important input for WP3 and the global SOCOL-AER v4 model in our group that will be used for improved prediction of impacts of different ASAIMs, e.g., stratospheric ozone and dynamics as well as radiative forcing.

Milestones
M1: Publication of all technical developments including custom vessel design
M2: Determination of contact angle measurements for sulfuric acid for fresh and lab-aged surfaces
M3: First detailed characterization of evolution of ASAIMs in real environment (morphology, bulk/surface composition, complex refractive index UV to mid-IR) representing key parameters for radiative and chemical impacts of ASAIMs
M4a,b: Input for WP2 from two long duration balloon flights (in terms of identifying target ASAIMs for assessment of deliverability), WP3 (modelling), as well as global climate models currently used for SAI modelling which will reduce uncertainties in impacts of ASAIMs

1.3.2 Work Package 2 (WP2): Dispersal and deliverability of aerosols.
WP2 addresses the dispersal and deliverability of alternative aerosols. Solid particles tend to agglomerate due to surface effects, such as van der Waals forces and electric charges,[45-46] making their separation from the bulk state into a desired Particle Size Distribution (PSD) a considerable challenge on a stratospheric platform. Coagulation of particles is undesirable because gravitational sedimentation decreases particle lifetime and may reduce the optical scattering efficiency per unit mass. An efficient dispersal system is needed to release particles at controlled sizes and rates to ensure a consistent and controlled global distribution both at the point of release and beyond. Cambridge University will modify their “spray tunnel” laboratory facility to test potential dispersal systems, measuring particle size distribution using methods including optical and scanning mobility particle sizers. This work will determine options for stratospheric dispersal and provide insights into optimal dispersion of ASAIMs.

WP2A will determine a range of potential candidate particles to assess, taking input from WP1. It is envisaged that an initial set of candidate particles may be some of those previously identified in the SPICE project[57]. Important properties are size, shape, surface properties, chemical composition and refractive index as well as lifetime of the particle in the stratosphere, effects on human health and supply/manufacture/handling issues.
WP2B will explore the surface properties of the various particles and review the specific needs for dispersion and anti-clogging agents for different materials. The surface chemistry and structure of small

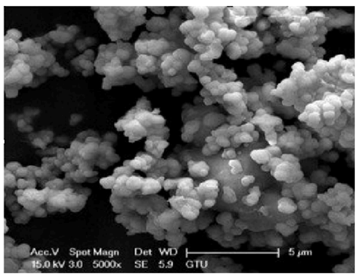

Figure 4. electron microscope image of a TiO2 nanoparticle

particles is complicated as in Fig 4, which shows that tiny particles agglomerate to form bigger clusters; the properties of a cluster differ from those of individual particles.
WP2C will use laboratory experiments to investigate how the agglomeration properties of particles are affected by being immersed in a fluid in the form of a slurry. We will seek to determine whether a scheme can be devised which creates a homogeneous stream of particles from the nozzle. One of the potential devices we will investigate is a micronizer, which is a jet mill that uses a fluid stream to grind clusters of particles to a sub-micron size. It is used in the paint industry to create accurately-tinted pigments. We will also investigate different potential nozzle designs. Once we have a slurry which carries a well-defined set of particles it will be necessary to expel the flow into the atmosphere. It is likely that a choked-flow device will be required, typically comprising a "converging-diverging nozzle". Such devices are commonplace but for abrasive flows it will be necessary to minimise the boundary layer content of particles in order to to avoid excessive abrasive wear. We will design such a nozzle.
WP2D will investigate the electrostatics of the plume, gravitational sedimentation, thermal effects and other mechanisms that might cause the plume to disperse unevenly and perhaps to subsequently coagulate. There may be circumstances when the plume ends up being denser than the surrounding air and if it falls to earth then the benefit of high-altitude injection of the plume will have been lost. It is noted that the timescale for assessment of the plume in the laboratory is limited by the length of the wind tunnel facility, but facilities are being investigated to extend the current ~6m tunnel to up to ~30m.
WP2E involves measurement of the particle size distribution. It is impossible to photograph these sub-micron particles and in the stratosphere it may also be extremely challenging to sample the particles as they exit the nozzle. We will examine closely the size distribution of particles in the plume in the laboratory using a number of particle measurement systems such as an SMPS and DMS500.

The rest of WP2 will investigate different potential delivery methods of manufactured aerosols into the stratosphere. A useful feature of novel materials is that a variety of delivery methods can be explored. The most researched method of delivery is via aircraft[58] but other delivery options may be rendered viable with ASAIMs, such as tethered balloons, and these have the potential to reduce the costs associated with SAI.[47] SO_2 cannot be easily delivered by tethered balloons as the gas becomes a solid at the pressures which would need to be used. However, solid particles can be transported as a mixed phase slurry, for example using nitrogen gas as the transport medium. **WP2F-WP2I** will focus on engineering aspects of various delivery methods.
WP2F will evaluate the supercritical properties of the transport media (particles and fluid as a slurry). Nitrogen and Argon are abundant in the atmosphere and they may be well suited for slurry transport, and at high pressures and low temperatures neither become solid. However, their properties may be "supercritical" at pressure of ~2000 bar (see Figure 5) and the transport characteristics of supercritical fluids can be unusual. We will seek to identify the potential fluid carriers which could be used for non-aircraft delivery schemes.

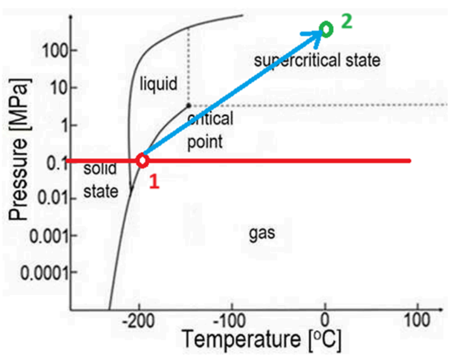

Figure 5. Phase diagram for nitrogen

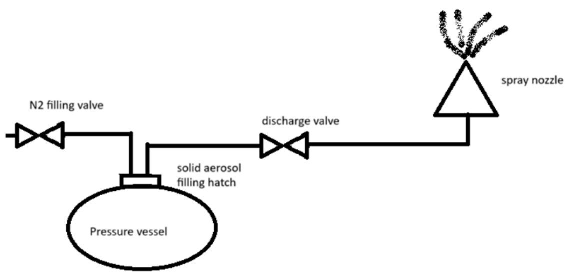

Figure 6. Example pressure vessel

WP2G will involve the construction of a pressure vessel for cold-room-temperature pressurisation (e.g. Figure 6). The testing proposed will be in a laboratory with a vessel of capacity less than one litre, linked via a set of control valves to a delivery system over a length of pipe of ~25mm diameter and 10 metres long. The design and fabrication of the system will be undertaken by the University of Cambridge design engineers and fabrication technicians.

WP2H will experiment with delivery of a powder as a slurry using the vessel developed in WP2G. The target slurr(ies) will be those identified in WP2C-WP2E. The investigation will focus on examination of particle segregation, bridging, slugging, pipe flow and other issues common in mixed-phase flow. The Department of Chemical Engineering in Cambridge University has historical expertise in dealing with fluidized beds, and [redacted] will provide guidance on this aspect of the work. In this work package we will investigate pumping both horizontally and at inclined angles as these will have different segregation characteristics.

WP2I will investigate phasing of multiple vessels to give continuous flow. With a single pressure vessel it will be necessary to stop the flow while the vessel is refilled with liquid nitrogen (or other carrier fluid) and hence if multiple vessels are used then filling of the vessels can be phased and interleaved. The energy involved in the charging of the pressure vessels will be calculated with modelling and compared with electrical usage in the experiments as part of the assessment of the overall potential energy savings which a non-aircraft delivery scheme may provide.

Milestones

M5a: design of a dispersal system to deliver particles with narrow size distribution and without clumping

M5b: Manufacture and testing of the dispersal system.

M6a: Design of a multi-phase (slurry) high-pressure pumping system.

M6b: Manufacture and testing of the pumping system.

<u>1.3.3 Work Package 3 (WP3): Climate impact of non-sulphate aerosols</u>

WP3 is targeted at investigating the climate impacts of ASAIMs: *what is the impact of using ASAIMs on the climate, and how do they differ from use of sulphur dioxide as a precursor?*

WP3 provides the necessary context for WP1 and WP2 by evaluating how their findings change the overall efficacy of SAI using ASAIMs. Through regular assessments, it also provides feedback to the other WPs, indicating which ASAIMs have the greatest promise in producing a global negative radiative forcing (i.e. a climate cooling effect). The work is split into four subpackages: WP3A (plume dynamics), WP3B (efficient plume representation), WP3C (ambient condition estimation), and WP3D (simulating plume effects at global scale). Connections between subpackages and to external information or other WPs are shown in Figure 7.

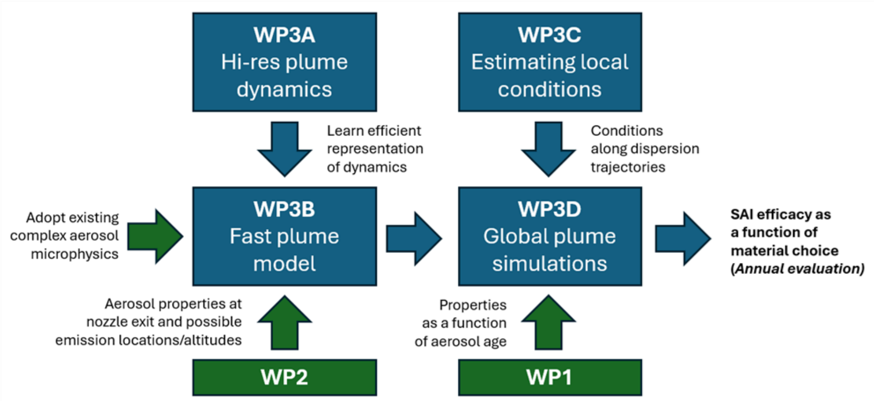

Figure 7. Schematic of the internal relationship between WP3 subpackages and external connections to other work packages.

WP3A will focus on the early stages of evolution from the delivery scale (metres) to the tens of km scale represented in WP3B. The turbulent flow encountered immediately after delivery will produce a relatively well-mixed but highly localised plume in which aerosol concentrations are relatively large. This plume will then be mixed into the stratospheric environment by the ambient flow. This flow is a complex combination of large-scale wind fields associated with stratospheric 'weather systems', smaller scale wave motions, and intermittent turbulence (clear air turbulence). The key information required to predict aerosol evolution and radiative effects are the rate at which the envelope of the plume grows and the rate at which internal heterogeneity within the plume, controlling maximum concentrations (and therefore aerosol coagulation rates), is systematically reduced. The approach taken will be detailed numerical simulations of a family of flows which contain these ingredients, designed to cover a useful range of characteristics of the ambient flow, capturing, for example, effects of geographical and seasonal variation, informed by early results from WP3C. This approach will build on expertise gained in recent studies.[48-49] Initial simulations will represent the aerosol as an inert tracer. Diagnostics of the spatial structure of the evolving tracer field will be used to assess the implication for aerosol evolution. Later simulations, which will be designed and prioritised according to the results obtained, will include more complex tracers that capture effects such as sedimentation, size evolution and aggregation. The results of the detailed numerical simulations will be combined with statistical models of tracer structure in stratospheric flows[50] to provide a probabilistic representation of the aerosol structure that can be evolved further in time using the methodology of WP3B.

This work will be initiated immediately and conducted over months 1-30. This will inform WP1 by providing information on the requirements for the injection material, and inform WP2 by providing information on which materials should be the focus of feasibility investigation. In both cases progress on other work packages isn't dependent on this activity, but will be enhanced by it.

In **WP3B**, we will develop a flexible, low-cost model of plume evolution designed to simulate many (>100,000) evolving Lagrangian air masses travelling through an atmosphere with prescribed reacting chemicals and wind fields. Each individual air mass will represent a discrete quantity of SAI material, emitted either from an aircraft or from a stratospheric balloon and subsequently carried by stratospheric air currents as it disperses. This new model of plume evolution will be designed to evaluate how quickly aerosols coagulate in the plumes, given the evolution of the properties of the trial materials over time and (from WP3A) the degree of spreading and internal inhomogeneity of the early plume.

This model will use two phases. The early plume will be simulated using a simplified representation of internal mixing based on the results from WP3A, but will embed a detailed representation of solid and liquid aerosol microphysics.[e.g.,20] The structure used to represent the plume itself will be statistical, representing the probability distribution of different aerosol mass densities across the plume cross section (in kg per m^3 of air) as a function of time from the results of WP3A. This is expected to yield a much more efficient simulation than an explicit cross-section resolving model as was previously used for the early plume.[51] Once the plume reaches scales of tens of kilometres and is no longer represented by the work from WP3A, a simplified plume representation would be used to support simultaneous simulation of a large number of plumes.[51-52] **This work will be initiated immediately and will be conducted over months 1-30**.

In **WP3C**, the necessary dynamical and chemical fields will be determined to provide boundary conditions to the plume model. Background chemical and wind shear fields will be calculated using global simulations with the UKCA model,[53] and the NAME Lagrangian Particle Dispersion model[54] will be applied to determine the trajectories that injected plumes will take through said field. This way we will be able to provide full chemistry-environment data to the newly developed plume model in **WP3A**, including the levels of background aerosols. UKCA is the chemistry and aerosols component of the UK Earth System Model, a leading model in the field of stratospheric geoengineering research.[e.g.,55] The atmospheric chemistry performance of UKCA was reviewed, and improved performance found when run using atmospheric nudging to meteorological reanalysis data.[53] We will follow this approach in the work here, nudging the model to the latest meteorological reanalysis available through ECMWFs ERA5 product. NAME can be run on the native output data of UKCA and we will use NAME to calculate back trajectories from the base of the tropopause to 25 km (mid stratosphere) going backwards 10 days in time. We will calculate these back trajectories under conditions of weakly disturbed polar vortex, strongly disturbed polar vortex, different QBO phases and different seasons. The nudged simulations will focus on the recent period (late 20th Century) but we also plan to re-run the 2050s and 2100s (decadal averages) for three SSP-RCP scenarios from the IPCC database (SSP1-2.6, SSP2-4.5 and SSP3-7.0) so that we can also run the plume model under a range of future climate change scenarios. In total we anticipate calculating on the order of 1 million trajectories, using code to cluster these based on the history of meteorological conditions and chemistry along the trajectory path.[56] This will allow WP3A simulations to determine the rate at which aerosols become dispersed in the atmosphere, and subsequently inform WP3D to quantify the significance of observed changes in aerosol microphysics. **This work will be initiated immediately and will be conducted over months 1-12.** This would provide WP1 with additional information on which key sensitivities and uncertainties in modelling most need to be addressed through experimentation. WP1 is not dependent on this work but will benefit from it.

Finally, in **WP3D** we will incorporate calculation of aerosol optical properties into the plume model from WP3B which will then be used with the trajectory data from WP3C, enabling an estimate of how SAI efficacy varies between candidate materials and the potential for local heating as well as impacts on chemical compositions, in particular ozone. WP3D synthesises results from across the project but also can be used to provide feedback to the other WPs; as such, we also plan to perform preliminary evaluations during months 12 (integrating chemical information along trajectories from WP3C) and 24 (using the prototype WP3B model) which can help inform the prioritisation of materials for WP1 and WP2. **The bulk of this work would be conducted over months 25-36, with preliminary evaluations performed in months 12 and 24.** The final year work depends fundamentally on aerosol data; both optical properties and in particular chemical composition from WP1, and dispersion data from WP2. This stage is complex as the ageing of particle properties from WP1 will have to be included, which is critical for evaluating both the efficacy and unintended impacts on the stratosphere.

Milestones
M7a: Characterization of plume-scale mixing for stratospheric plumes
M7b: Finalized plume-scale mixing model
M8a: Global Lagrangian model of air mass transport
M8b: Incorporation of plume model
M9: Quantification of chemical conditions along trajectories
M10a/b/c: Annual simulations of ASAIM efficacy

1.4 Work Plan

		Project Year & Quarter											
WP	**Stage**	**Y1Q1**	**Y1Q2**	**Y1Q3**	**Y1Q4**	**Y2Q1**	**Y2Q2**	**Y2Q3**	**Y2Q4**	**Y3Q1**	**Y3Q2**	**Y3Q3**	**Y3Q4**
1	A												
	B				M1,2								
	C								M3				
	D												
	E								M4a				M4b
2	A												
	B						M5a						
	C												
	D												
	E												M5b
	F												
	G											M6a	
	H												
	I												M6b
3	A						M7a		M7b				
	B						M8a				M8b		
	C				M9								
	D				M10a				M10b				M10c

The three WPs come together as a single cohesive project by virtue of covering the breadth of issues relevant to ASAIMs. Chemical and radiative impacts modeled in WP3 depend on input of the evolution of ASAIMs from WP1 and also the dispersion characteristics in WP2. Also the three Work Packages collectively evaluate various attributes of aerosols and if the three WPs deliver GREEN LIGHTS for a particular aerosol then a non-sulphate SAI methodology has been arrived at. If any one of the WPs comes up with a RED LIGHT then that particular aerosol must be ruled out.
We plan four project-wide meetings: the first an inception meeting (online hence no costs currently included) followed by three in-person meetings in the UK – Review Meeting 1 in project Y2Q1 (£7500 + inflation costed), Review Meeting 2 in project Y3Q1 (£7500 + inflation costed) and a Final Meeting in project Y3Q4 (£15000 + inflation costed). Greater cost for the Final Meeting is included to either: widen scope, e.g., inviting relevant stakeholders as a route to impact; or repurpose cost of this meeting as a contribution to a Final Conference, co-organised with the other projects funded through this call.

1.5 Identification and Mitigation of Risks

1. Foreign material introduced to the stratosphere.
WP1 uses very small amounts of natural materials and contains very low environmental risk based on existing protocol and there is no release of material. There is no technical risk as methods are all well established in the [redacted]. Functionality (technical risk) of the vessel under stratospheric conditions is very low risk based on prototype design and thermal vacuum testing. Our communication system allows evaluation of system performance in flight enabling adjustments.

2. Failure of balloon. Even though the risks are very low, we will review each balloon flight and cancel subsequent ones if sufficient data is already collected, thereby reducing the overall risk. We will also follow standard procedures for balloon launches which are established to minimise risk.
3. Unable to secure formal permits or negative publicity prevents outdoor experiments. Non-release experiments will make the application of necessary formal permits easier. We will engage extremely closely with the ARIA ethics and governance team for support on engagement with necessary stakeholders, since this work will need to be viewed in the context of the overall ARIA programme and cannot be considered in isolation. We will align our project with ARIA's governance framework for full transparency, compliance, and oversight. By month 6 we will have completed ARIA governance framework compliance and finalise experimental protocols.
4. Accidents in WP2 laboratory experiments. Only materials which are considered non-hazardous will be investigated. Risk assessments and guidance provided by the University of Cambridge Department of Engineering will be followed.

1.6 Conclusion
SAI represents one of the most significant opportunities for affecting the climate in the near term. This project will advance the field considerably by expanding our knowledge of different candidate particles, and the combination of outdoor experiments, laboratory work, and modelling represents a unique strategy for determining which materials will be effective at radiative forcing while reducing risks to stratospheric composition and dynamics compared to SO_2.

Section 2: The Team

[redacted]

[redacted]

[redacted]

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BRIGHTSPARK: CLOUD BRIGHTENING WITH ELECTRIC CHARGE

SECTION 1 - PROGRAMME AND TECHNICAL

Introduction

Changing the planetary albedo via the reflectivity of marine layer clouds is well-established as a geoengineering suggestion, but practical methods for achieving it remain in their infancy. We propose a new approach, inspired by conversations with the originator of cloud brightening, John Latham[1], by release of electric charge into marine stratus. Establishing the method's effectiveness and practicality offers a possible new route to achieving planetary cooling, without the use of environmentally unfriendly materials.

Background

Electric charge is present on most atmospheric particles and droplets. It is enhanced in some natural circumstances (e.g. at layer cloud edges, in dust clouds or by release of radioactivity) and can be directly artificially augmented using charge emitters. We have shown that charge influences droplet behaviour[2], including lengthening small droplet lifetimes by reducing their evaporation rate[3], and through the disintegration of strongly charged drops into smaller droplets by the Rayleigh instability[4]. By injecting charge, a cloud's reflectivity can be increased by shifting the drop size distribution to more numerous smaller droplets, through a combination of evaporation reduction and/or Rayleigh mechanisms.

We have demonstrated the effectiveness of this approach in real world experiments, which showed an increase in fog reflectivity following charge release from an overflying aircraft[5]. (Fig 1a shows our aircraft pre-flight, and fig 1b the same aircraft programmed to fly over an instrumented mast.) These proof-of-concept experiments showed changes in fog properties occurred with either positive or negative charge emission, but not with both polarities emitted simultaneously, indicating that the effects were associated with unipolar charging. We have also proven several methods for the release of atmospheric charge through ion emission, including using uncrewed[6] and crewed aircraft[7],[8].

Proposal concept

In this proposal, we aim to fully evaluate this method for modifying a natural droplet system, as an essential step in preparing the technology for scaled-up deployment in marine clouds. An important aspect of the electrical approach to cloud brightening is that only lightweight payloads are required for the charge releasing platforms employed, allowing a swarm of small airborne vehicles to be used, and without generating environmentally harmful residues. This brings an additional and environmentally friendly route to achieving the climate cooling sought by the programme.

Figure 1. (a) Catapult-launched Skywalker X8, modified for charge release and droplet monitoring in a valley fog. (b) Skywalker X8 viewed in flight from above, over a measurement site. (c) "Shooting star" display event using a swarm of 330g microdrones.

Through this project we propose to scale up the technology developed for fog reflectivity enhancement to make it suitable for the marine cloud brightening application, by using a swarm of microdrones, similar to those typically used for visual display purposes (fig 1c). This would raise the technology readiness level (TRL) of our methodology from TRL5 (reduced scale verification) to TRL6/7 (full scale/operational). The microdrone as a carrier technology is highly suited to this, as the charge emitters can be made lightweight, and they consume negligible power compared with that already available for propulsion. In addition, the relatively low cloud base height of marine stratus is readily accessible to modest sizes of microdrone. Methods for controlling microdrone swarms continue to evolve – hundreds operating simultaneously in flight have already been demonstrated[1]. Ultimately, we envisage a system of myriad microdrones all equipped with charge emission technology, flying and recharging from marine platforms 24/7 to provide targeted release of charge into the stratiform cloud above.

Methodology

The work in this proposal provides a critical first step in developing a deployable technology and is intended to establish the practicality and scalability required for the final marine stratus application. Because the basic charge release methodology has already been demonstrated in the real world, proof-of-concept laboratory experiments are not needed. In any case, experiments in laboratory chambers are poorly suited to this science area, as their representativeness is significantly limited by electrostatically enhanced wall deposition. Extensive real-world experiments in natural fogs are therefore proposed, building on our existing track record with such experiments, and to overcome the problem of representativity. Fogs are useful for this as they provide an accessible alternative to stratiform clouds, and, although different droplet processes are active due to the droplet size distribution tending to smaller sizes, the electrically induced change in behaviour of the smallest droplets is comparable with that expected in marine stratocumulus clouds which are important for the short-wave reflectivity properties.

A range of sites will be assessed for suitability, but operating in shallow fog, for example at the valley scale, is envisaged, ideally at a remote site to minimise inconvenience and simplify permissions. We expect to operate field experiments across two winters of a three-year project, responding to suitable weather conditions likely to provide a persistent period of fog. Experience indicates that maintaining multiple experimental opportunities are necessary to mitigate the variability associated with fog, and the associated anticyclones generating persistent foggy conditions.

Our field experiments (fig 2) will employ instrumented microdrones to provide multiple point charge emission, to test and understand their use in swarms for influencing more extensive regions of natural fog than our initial single point emission previous experiments.

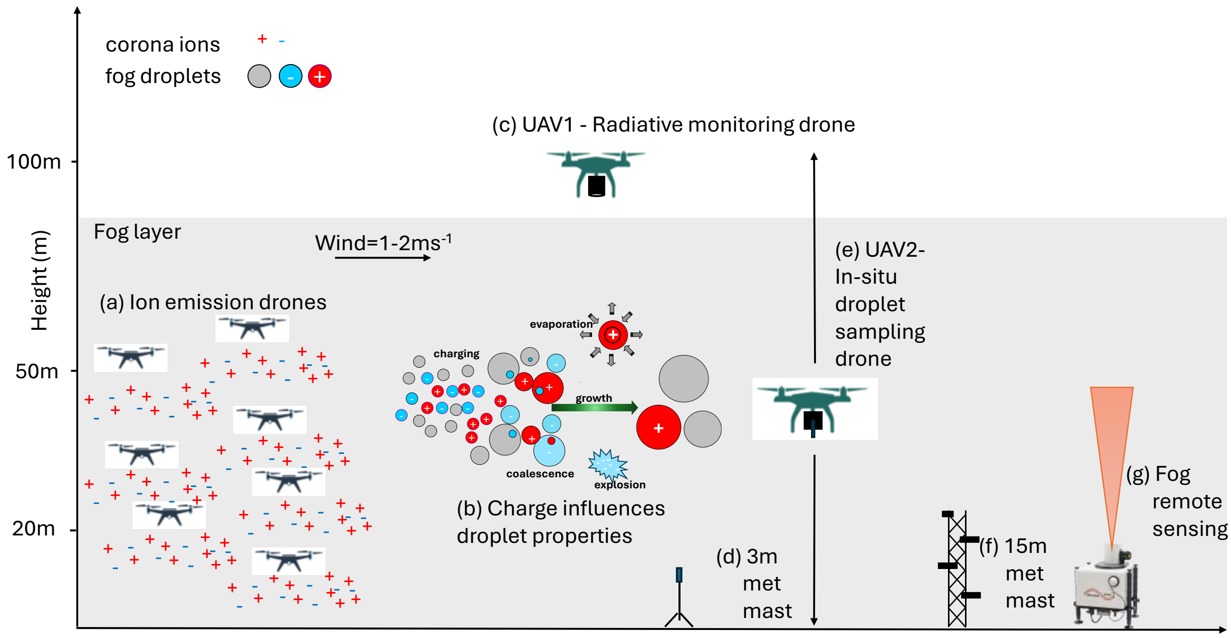


Figure 2. Schematic diagram of experimental campaign setup. (a) Up to 20 ion emission drones (Celestial) will emit bipolar ions into a fog layer, whose droplet properties are expected to change according to processes shown by (b). Changes in fog properties will be monitored by (c) an instrumented drone UAV1 (Menapia) carrying a radiometer and hovering above the fog layer, (d) a vertical profiling drone UAV2 carrying a cloud droplet sensor, and temperature and humidity sensors (Menapia), (e) (f) surface meteorological masts at 3 and 15m respectively, (instrumented with temperature, humidity, visibility, turbulence, cloud droplet sensors, and an electric field sensor) and (g) fog remote sensing instruments such as a doppler lidar and microwave radiometer.

[1] https://www.forbes.com/sites/grrlscientist/2020/06/30/drone-light-shows-way-cooler-than-fireworks/

We will progress this in collaboration with a commercial UK partner (Celestial) who are world-leading in drone display work, in designing and operating a dense array of controllable charge emitting microdrones. The physical responses in the droplets following charge release will be monitored using instrumented mast systems able to monitor the electrical environment and droplet properties, and by using an instrumented aircraft flying above the microdrones – fig 1b was obtained in this manner. A further instrumented aircraft will be deployed to sample vertical profiles of droplet properties within the fog, including electrostatic sensors used previously in studying the electrical properties of stratus clouds[9] . Both these monitoring systems will be developed in collaboration with a second commercial UK partner, Menapia, a specialist Uncrewed Aerial Vehicle (UAV) measurements company.

As the ionisation released is dissipated naturally within minutes, there are no ongoing consequences after each experiment. Acoustic nuisance would be equally brief. Nevertheless, from experience of international media interest – and associated poor or fabricated reporting - we will collaborate on communication and providing context with a science philosophy/ethics academic, experienced in the specific questions of meteorology. However, whilst effective communication with the broader community is clearly necessary it is likely not to be sufficient in convincing people of the value and need of the work. Consequently, we will work with the [redacted] consultancy on establishing best practice for undertaking novel experimental field work in the environment, with the intention of contributing to developing the necessary decision-making tools and ethical standards ultimately needed for international marine stratus modification.

As well as the direct in situ monitoring, the effectiveness of the charge release will be evaluated by comparison with the natural variability expected, as quantified by high resolution atmospheric modelling of fogs and clouds with the additional charge-induced changes represented.

Description of work proposed
This three-year project consists of multiple workstreams addressing theoretical and experimental aspects, summarised in the Table below. The project will principally employ two PDRAs to carry out the experimental (PDRA1) and modelling (PDRA2) science aspects, and a senior PGRA support scientist to coordinate the fieldwork and instrumentation development. A further part-time PDRA (PDRA3) will work with external consultants on engagement activities, explaining and communicating the work.

Workstream	Scope	Purpose
WS1	Charge delivery systems	Optimising size and efficiency of ion emitters for microdrones
WS2	UAV instrumentation integration	Integration and testing of cloud and reflectivity sensors with monitoring drones
WS3	Site identification and engagement	Assessment and prioritising of experimental sites, and engagement with stakeholders
WS4	Swarm technology	Develop control and deployment systems for the microdrones. Legislative submissions for field experiment and other permissions
WS5	Charge microphysics modelling	Representing charge microphysics in high resolution models and Met Office NERC Cloud Model to derive albedo. Model runs with “extreme effect” scenarios on albedo: derive optimal intervention strategies and bounding adverse effects
WS6	Site instrumentation	Constructing surface measurement and monitoring systems
WS7	Field experiments	Range of experiments to test the microdrone swarm in clear and foggy air
WS8	Field experiment modelling	Ensembles of high-resolution model runs to assess natural variability in reflectivity. Evaluate if interventions lie outside the control ensemble
WS9	Marine stratus scoping	Evaluating marine platforms for a microdrone system, considering naval deployment options
WS10	Reporting and data archiving	Ongoing throughout project through international conferences and peer-reviewed publications. Data archiving activities also.

Detailed workstream (WS) descriptions:

WS1 Charge delivery systems (PDRA1, PGRA)
Charge emission using corona discharge requires an emitter operated at a high voltage, (~3 kV). Only a small (μA) emission current is required, hence the electronic system can be compact. For our experimental fieldwork, optimisation of the ion emission efficiency is sought, together with quantifying the emission current. In this WP, our novel system for isolated current measurement[10] would be combined with a high voltage source, to provide a lightweight and compact device. The electrode design would also be optimised for maximum charge delivery into the surrounding air, and ideally durability against micro-corrosion which can reduce the efficiency. WS1 is a precursor to the fieldwork (WS7); the charge delivery systems would be designed to work with the carrier microdrone to provide active control and monitoring of the actual charge release.

WS2 UAV instrumentation (PDRA1, Menapia)
Monitoring the region of charge release is essential to evaluating and quantifying the effectiveness of the technique. For this, two multirotor UAV aircraft will be instrumented in collaboration with engineers working at Menapia, to carry sensors providing droplet size information in one case, and short-wave reflectivity in the other. One aircraft (UAV1) will fly above the fog test region (performing both hovers and overpasses), carrying solar and terrestrial radiation sensors (Apogee SN-500) to evaluate the change in radiation. The other (UAV2) will be used to vertically sample the droplet properties within the fog, downwind of the charge emission drones, and perform vertical profiles from near the surface to the clear air above. Establishing this capability is necessary prior to the fieldwork (WS7). This aircraft will also be instrumented with the standard suite of meteorological sensors (including temperature and relative humidity) routinely flown by Menapia. The droplet sensor used is anticipated to be the LOAC sensor from Meteomodem (which has previously been deployed on drones by[11] and [12]), but this is an emerging area and Menapia is currently evaluating other available small aerosol/cloud droplet sensors for use on UAVs such as the Alphasense N3 OPC and the UCASS[13] The UCASS itself is planned to be further developed by another ARIA proposal SUA-MCB, who we intend to work with if both proposals are funded: these may be used instead if their scientific capabilities are found better than the LOAC.

WS3 Site identification and engagement (PDRA2, PDRA3, [redacted])
Evaluation of possible sites for the experiments in WS7 will be based on fog statistics, accessibility to the site for the different parties involved, and the acquisition of flight permissions and safety cases. If possible, this will be carried out in collaboration with [redacted] potentially also engaging with relevant local stakeholders as necessary. It will form the basis for engagement activities. A combination of two or more sites which typically experience very different weather conditions will also be considered, to mitigate the negative effects of persistent unsatisfactory conditions at a single site. This workstream will also engage with the University of Reading press office, who have experience, not least through our previous work, in handling sensitive media topics.

WS4 Swarm technology (PDRA1, PGRA, Celestial)
This workstream is to test and implement the deployment of multiple microdrone devices. The standard microdrones used by Celestial in their displays can operate as close as 1m to each other. For our experiments, a charge emission equipment package will be added to their standard microdrone, to be controlled remotely. This is an important aspect, as switching of the emitters in a defined sequence is a method we have found very effectively previously, as it provides a defined signal to be sought in the fog data as a reliable indication of cause and effect. We would also establish that the emitter payload did not influence the flight performance, and design experimental protocols compatible with the microdrones' flight endurance. The effectiveness of the charge release would be tested from individual microdrones in a controlled environment, flying above an electric field sensor (mounted on a 3m mast) corroborated with satellite location data (GNSS) which each microdrone routinely provides.

WS5 Charge microphysics modelling (PDRA2)
Existing fog and cloud models do not include charged microphysics, and the droplet interactions are assumed to be solely thermodynamic and ballistic. This WS will develop charge microphysics parameterisations to investigate the electrical modification of droplet properties to be evaluated. It will allow evaluation of cloud and fog evolution with and without charge. The parameterisations will be designed to be included in existing community weather forecasting models after selection for suitability, such as WRF

and the MetOffice-NERC cloud model. Representation of the droplet physics for this modelling work will consider evaporation, growth by condensation, coalescence efficiency and Rayleigh disruption, for droplets charged to a prescribed extent.

WS6 Site instrumentation (PDRA1, PGRA, Menapia)
The surface instrumentation to be deployed will be procured and assembled in this WS, to provide two monitoring masts for use in WS7. A combination of sonic anemometer, electric fieldmill, visibility sensor and Light Optical Aerosol Counter (LOAC) to determine the droplet size distribution near the surface (using 3 m masts and a vehicle-borne 15 m tilt-over mast) will be constructed, with dataloggers based on RPi and Arduino single-board computers as used previously. The field mill is a critical piece of equipment as it responds directly to the charge emitted, for verifying that the release systems are operating. We will also apply to deploy the NCAS Doppler lidar and HATPRO microwave radiometer from their Atmospheric Measurement Facility (AMF), to provide detailed high temporal and spatial information on the fog droplets present.

WS7 Field experiments (PDRA1, PDRA2, Menapia, Celestial)
Deployment of the equipment for the fieldwork is envisaged to be of a week's duration, approximately twice per winter in the second and third years of the project. The fieldwork will be conducted in shallow fogs, into which the controlled swarm of the charge-emitting microdrones will be flown at heights of tens of metres, using a prescribed pattern of charge release. An overview of the arrangements for the field experiments is shown in fig 2. The microdrone separation will be varied to evaluate the relative effects of direct turbulent disturbance of the fog and effects from charge release. Individual microdrone position information will be captured together with the charge emission performance. During the microdrone swarm activation, a UAV1 overpass will be arranged to measure the reflectivity from above, integrating across charge release area. Further, UAV2 will obtain vertical profiles of the droplet properties and meteorological parameters (temperature and relative humidity). Although horizontal wind speeds in fog are typically very small (1 to 2 ms^{-1}), to mitigate unwanted effects from this, the microdrone swarm will be situated upwind of the vertical profiling UAV (UAV2), measurement masts and doppler lidar, to maximise detection of fog droplet changes.

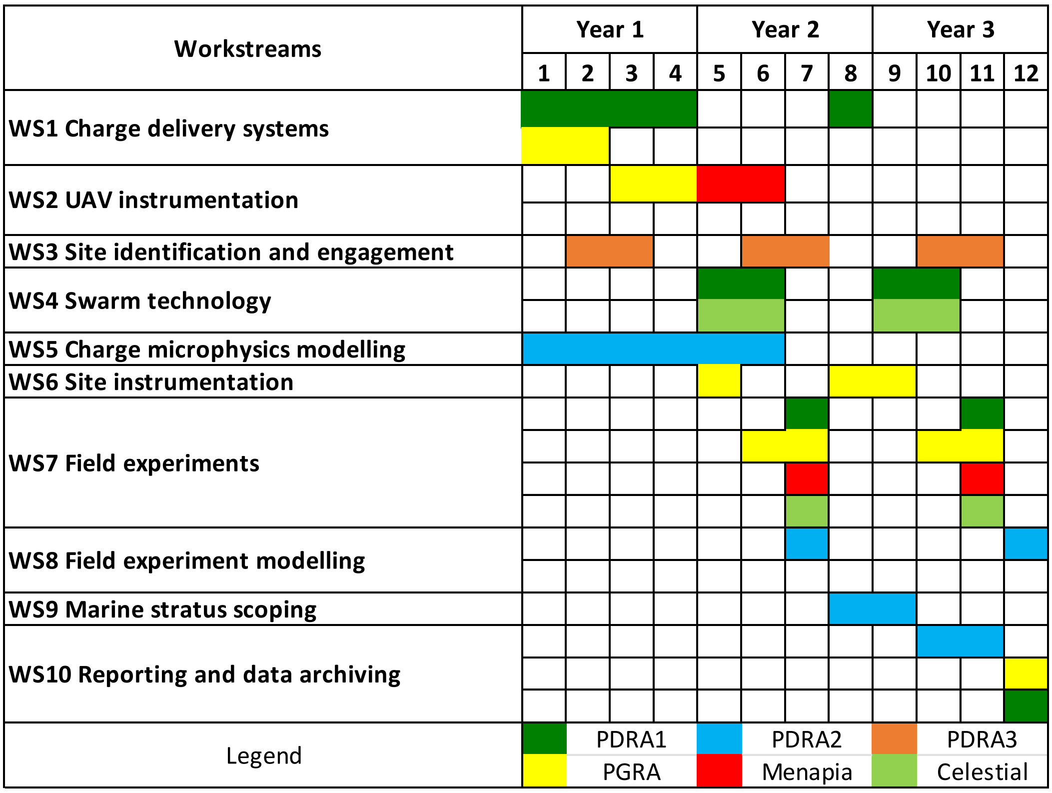
WS8 Field experiment modelling (PDRA2)
The circumstances of the field experiments carried out will be simulated, and the sensitivity to the charge released obtained using the representation of droplet behaviour obtained in WS5. This will also allow the expected charge effects to be constrained against natural variability, using an ensemble of runs. Testing for the apparent effects observed against the variability generated in this way offers a more promising methodology than simply comparing predictions with observations, as is sometimes previously used, e.g.in evaluating cloud seeding These simulations would be undertaken at high spatial resolution to allow the local reflectivity effects to be evaluated by averaging over the domain in the same way as the measurements of UAV1.

WS9 Marine stratus scoping (PDRA2)
The ultimate application of this project work is to the marine stratus brightening problem, which brings additional scaling and deployment issues well beyond those of the evaluation experiments. The modelling capabilities developed and validated throughout this project will be applied to this problem and the reflectivity changes estimated for a feasible microdrone fleet. Knowledge of the microdrone separation appropriate for the charge emission possible will be new and essential information with which a marine deployment can be planned, and the effectiveness of the charge emission approach evaluated. Sustaining airborne microdrones of specified endurance will allow the effective area able to be influenced to be estimated and the necessary resources required to be calculated. With this information, ship-based deployment of this system at practical scales will be evaluated.

WS10 Reporting and data archiving (PDRA2, PDRA1, PGRA)
Throughout the project one national and one international conference annually will be sought to report the progress of the different aspects of the work. Our previous experience of related work is that many publications in peer reviewed journals are extremely likely to be produced. High quality international journals will be sought, as previously, for example *Geophys Res Lett*, *J. Atmos&OceanTech*, and *AIP Advances*. Encouraging a journal special issue (or issues) for related work through other ARIA-supported projects may provide an additional route to proceed, through our presence on different journal editorial boards. Data management and archiving will also be achieved through this workstream.

Project plan

Across the three years of the project, the expected phasing of the workstream activities is given in the Gantt chart below, with the field experiments scheduled for the winters of project years 2 and 3, assuming a project start in April 2025.



The key milestones in the technical progress project will be:

Milestone	Objective	Audit point (quarter years)
1	Identify scientifically suitable field experiment sites	End of Q2
2	Demonstrate charge delivery systems for microdrones	End of Q4
3	Establish UAV1 and UAV2 monitoring capability	End of Q6
4	Demonstrate charge microphysics modelling capability for layer cloud properties	End of Q7
5	Provide marine stratus scaling plan	End of Q9
6	Complete a successful field experiment	End of Q11
7	Complete data archiving	End of Q11
8	Simulate scientific results from field experiments	End of Q12

Unknowns and risk mitigation

Our previous fieldwork experience will be brought to this project, including approaches for successful outcomes whilst adapting and responding to weather conditions and strategies for safely mobilising and rapidly deploying a science team at a site in poor weather. We are familiar with the extensive safety cases needed to the CAA, but this is unlikely to be needed for fog experiments. The charge emitters are an established technology, which, due to electronic component supply shortages arising from the pandemic, have previously been specifically designed to be robust to fluctuations in electronic component availability. However, small commercial USB negative ionisers are widely available which would provide an alternative to developing new emitter designs, but with reduced efficiency and no ionisation output monitoring: we have assessed and deployed these previously, and established how they can be modified to meet our science requirements. Working with two expert subcontractors in related areas of drone deployment will also bring some redundancy in obtaining permissions and offer routes to mitigating hardware problems. It has already been demonstrated that a simple photodiode[14] can provide reflectivity information, for which there are other platforms available (e.g. our existing Skywalker X8 of fig 1a), should the improved quantification expected from more extensive radiative sensors prove unreliable, and other pilots are available from within the Department of Meteorology at Reading. An existing Windsonde balloon system could be deployed for thermodynamic profiles should UAV2 be inadequate.

Staffing and resources justification

The estimated cost for this project is £1.9M, arising from staffing and equipment. Resources are sought to employ two post-doctoral scientists – one for the experimental aspects (PDRA1) and the other (PDRA2) for the theoretical aspects, able to work independently. An experienced PGRA is also requested, to operate as a support scientist and coordinator [redacted]. Further admin support is also requested [redacted], from existing staff. Support for a science engagement PDRA is requested [redacted] who will design an engagement programme, and collaborate with the [redacted] consultancy too [redacted], or, if the [redacted] proposal is not funded, progress the development of our own decision-making tools as an in-house project. [redacted] will provide the microdrone display system and deploy it for the science experiments [redacted]. [redacted]) will jointly develop instrumented drones for operating charge emitters in fog, [redacted]. Funding is also requested for international conferences ([redacted] and fieldwork travel [redacted] [redacted] in total. Supercomputer, facilities and equipment time support, and each of the staff members recruited will require standard desktop PC and network access is sought ([redacted]), and the equipment items required are summarised below. External financial auditing costs are also sought ([redacted]. Publication costs for dissemination of the work are requested too (4 papers x [redacted]).

For workstreams requiring specific items of equipment and instrumentation, the costs are identified below:

Workstream	Scope	Equipment	Total
WS1	Charge delivery systems	Electronic consumables for multiple charge emitters (50 x £500)	£25k
WS2	UAV instrumentation development	Radiometer (Apogee SN-500) (£3.5k x 2) LOAC droplet counter (£5k)	£12k
WS6	Site instrumentation	Biral SWS-050 visibility sensor (2 x £3.6k, total £7.2k inc VAT) Electric field mill, Vaisala (2 x £17k inc VAT), £34k total Windmaster sonic anemometer (2x £3.6k) £7.2k total inc VAT LOAC droplet counter (2x £5k), £10k total RPi and Arduino computers (10 x £50) £500 total inc VAT Mast hardware (2 x £1.2l), £2.4k total inc VAT Electronic consumables and weather-proof enclosures, £2k Campbell CCFC field camera (£1k)	£61.3k
WS7	Field experiments	AMF Doppler Lidar and HATPRO Radiometer (£41K for 3 month deployment)	£41k

SECTION 2 - THE TEAM

[redacted].

[redacted]

[redacted]

[redacted]

Menapia (https://www.menapia.tech/) provide scientific services with UAVs, such as atmospheric profiling, which is part of this proposal. They are a technology driven company developing new measurement techniques for specific applications. [redacted]

Celestial (https://celestial.show/our-story/) are an international drone display company, with offices in the south-west of the UK. They are specifically interested in bringing their existing technology and expertise to the new application we have proposed. The experience of atmospheric measurements using drones we bring to this potential partnership, forged through experiments conducted in the south-west, offers highly promising synergies.

[redacted]

Management plan
As explained in the technical work programme, the project consists of a series of workstreams. The project will be led by [redacted] (WS3, and overall), [redacted] (WS1,2,4,6,7), and [redacted] (WS5,8,9), through weekly meetings with the staff employed and by maintaining active contact with the external companies providing support activities. This will be through site and company visits, and online meetings. The PGRA support scientist will lead in the scientific and logistical coordination and apparatus provision, with some additional involvement in the scientific aspects for staff development. Associated admin support will be provided to help this.

The research staff employed on this project will be allowed autonomy in how their work is organised, within the project requirements. All the project staff will collaborate on disseminating the results through papers and conference presentations, throughout the three-year life of the project. The PDRAs will have full access to courses run by the University of Reading's Centre for Staff Training and Development, with career development encouraged. Significant support is available to PDRAs through the local implementation of the Concordat, which is a national agreement between funders and employers of researchers: it articulates key principles for the support and management of research careers.

Research staff at Reading have annual development reviews to reflect on their work progression and future career plans; in such reviews, the reviewer is deliberately not the PI, to ensure a broader view of staff development is achieved. Staff are encouraged to attend presentations made during the term-time Departmental seminar programmes (two each week: one for internal and one for external speakers), to enhance awareness of wider issues in atmospheric science and its related disciplines. The PDRAs will attend national and international meetings to ensure the project's visibility and will be encouraged to engage in other activities of the science community such as paper and proposal reviewing and contributions, as well as to the regular meetings of the Space and Atmospheric Electricity (SPATE) group at Reading and Royal Meteorological Society's Special Interest Group in Atmospheric Electricity.

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Full Proposal: Ethics and governance of solar geoengineering research: from concepts to implementation

Section 1: Program and Technical

1. **Programme alignment.**
The ARIA 2024 Call on climate cooling seeks to fund projects exploring "ethical, governance, law, and geopolitical dimensions" of climate interventions (ARIA, 2024a). Our team has previous experience working on the ethics and governance of solar geoengineering (SG)[1].
We apply a "Fundamental Questions" methodology (Box 2) to allow for a seamless transition from "conceptual engineering" (Chalmers 2020) to the implementation of responsible participatory governance (Reynolds 2019), making our project intentionally incorporable with other ARIA proposals. We focus our approach on small outdoor SG research and small non-validated deployment instances (e.g. Make Sunsets), the intended scale of the call (p. 3 ARIA, 2024a). We will build a research team across Latin America and the Caribbean (LAC) and the UK to address the ethics and governance of this international, disruptive technology.

2. Description of research and methodology.
2.1 General aims. The project has two interrelated general aims: (i) contribute to ARIA's mission of enhancing responsible governance of R&D and eventual deployment of SG for the common good (Rayner et al 2013, ARIA 2024b); (ii) build a research team across Argentina and further afield in Latin America and the Caribbean (LAC), alongside collaborators in the UK; (iii) protect global society from destabilisation and negative social tipping points associated with irresponsible use of SG (Spaiser et al 2024). Here, we understand responsibility from a common good, interspecies, and intergenerational justice perspective (London 2022, COMEST 2023).
2.2 Specific objectives. There are three specific objectives: (i) provide an enhanced theoretical framework for proper governance of SG research that serves UK ARIA projects, (ii) build global south research capacity around SG by hiring new researchers, research assistants (PhD and/or postdoc), and advisors tailored to the novel work packages (WP) & research questions, (iii) build inclusive, participatory governance for LAC that emphasises centralised public engagement.

2.3 Methodological approach
The overall approach of our project is to provide a conceptual foundation (via "conceptual engineering") leading seamlessly to a governance framework. Importantly, our approach is agnostic to—and can be therefore be applied broadly to—different climate cooling strategies, including but not limited to stratospheric aerosol injection (SAI), marine cloud brightening (MCB), and contrail management, or hybrid interventions. Box 1 focuses on the applicability of our reasoning to marine cloud brightening. The idea of the movement from concepts to implementation is that the conceptual categories offered are not just normative (to distinguish right from wrong action), but also analytical (if certain actions are (not) undertaken, then certain consequences may be more likely to occur), exemplified in Box 1.

Box 1. Climate experiments require public participation: the case of marine cloud brightening

The University of Washington's Marine Cloud Brightening (MCB) experiment may be free of legal flaws, negative environmental impacts and public health risks (1). However, if the climate science community does not foster public participation through sustained interaction and clear societal objectives, it is likely to create conflict (2). As seen in this and other cases (3), inappropriate public participation can lead to outdoor experiments being delayed, stopped or even banned. Moreover, a loss of public trust can affect not only individual projects, but the climate science community as a whole (4).

[1] Our application is enriched by three recent funded projects (see Box 2) on ethics & governance of SG: 1) enhancing definitions of experimentation, research, & deployment (Degrees 1: 06.24-08.26, 45K USD); 2) public engagement of SG research and experimentation in Argentina and comparative research with Brazil (Degrees 2: 10.24-12.26, 35K USD,); 3) public health & geoengineering in the Global South (WHO: 09.24-08.25 in collaboration with the Alliance for Just Deliberation on Solar Geoengineering (DSG), 50K USD).

According to the Oxford Principles for governance of solar geoengineering, public participation of affected parties is a required normative principle, but its appropriate implementation can take different forms depending on context and culture (5). For example, small-scale MCB experiments in Australia that involved community members and had clear social objective (e.g., protection of the Great Barrier Reef) did not encounter similar problems (6). More robust forms of participatory research are more costly and time-consuming than their alternatives. However, in hindsight, they may produce better outcomes for the climate science community and all those affected by the negative impacts of climate change. Different perceptions of social and scientific value of small-scale outdoor MCB experiments in Australia (linked to potential regional deployment) and the US (linked to planetary deployment) may be also at play.

References (see Box 1 references).

Conceptual engineering

Our conceptual engineering approach involves the development of precise concepts to carve out the reality of SG projects according to their aims. The goal is to enhance precision of terms and reduce confusion. This aims-based definition has the following three properties:

1) It distinguishes between SG research and deployment
2) It applies to interventions with an insufficient level of evidence for regular use
3) It is neutral to scale, mechanisms of action, outcome, and ethical status.

Responsible participatory governance

Public engagement is crucial to ensure transparency in decision making and to support democratic governance. Improving participation and engagement should be treated as a standard operating procedure for research and deployment on emergent, complex and uncertain technologies as SG (Jasanoff, 2004). Discussions concerning the risks, benefits, and governance challenges of SG are growing, and governments need to be prepared for inclusive, transparent, and participatory dialogues.

There is a growing interest in SG in the Latin American and Caribbean (LAC) region, and countries will need to build capacities to make informed decisions and foster collaboration to nurture multilateral science-policy processes. In the LAC region, SG is not yet a priority in the climate change portfolio of mitigation and adaptation strategies nor a topic in the radar of LAC governments, but in any case, as discussions are growing and unexpected events are occurring, governments will need to be part of the global conversations, establish regulatory processes and governance structures.

According to Jinnah *et al.* (2024) comprehensive research governance on SG framework should include: “several dimensions: engineering and safety, technical and scientific merit, financial conflict of interest and transparency, legal compliance, and societal engagement” among others (Jinnah, 2024: 602). High-quality engagement requires early collaboration with communities before research plans are set (Jinnah *et al.*, 2024: 603).

A responsible participatory governance for LAC should emphasise centralised public engagement and standard procedures for SG small outdoor research (Jasanoff, 2003;Jinnah et al. 2024), social equity, diversity, and political representation (Fischer, 2012) to mitigate threats of SG research governance backlash both international (Gupta et al 2024, Biermann and Gupta 2024) and local (Biermann 2023), with negative rhetoric and misinformation (Ribeiro 2024).

2.4 Primary output

[redacted] We will organise an in-person week of meetings in Buenos Aires with our UK advisors, [redacted] as well as other potential UK collaborators. The primary output of the project will be a report based on this in-person meeting that will offer the following:

1) An aims-based glossary
2) Principles of governance
3) Guidelines for policymakers

2.5 Fundamental questions methodology (Box 2). The "ethics and governance of SG" is a "multidimensional overlapping landscape" (Reynolds 2019). Our model (see Box 2) breaks down this unclear concept with a logically interrelated and practically oriented set of fundamental questions developed for biomedical innovation (Mastroleo & Holzer 2020) and applied to SG (Degrees 1 & 2, WHO).

3. Workflow overview: delivery of four Work Packages (WPs) over a 2-year period (extendable to 5)

3.1.WP1. Clarifying SG as a socio-technical intervention to reduce misunderstanding
Aim. Explain the meaning of SG as a transformable "socio-technical intervention" to understand small-scale perturbation field or outdoor trials as part of the larger research pathway of climate engineering on SG interventions (Lenferna et al 2017).
Working hypotheses.
WH1: Good technical performance is not sufficient for an intervention to provide overall benefit. SG is usefully understood as an "intervention ensemble" (Kimmelman 2012) emphasising the relationship between technical materials and the information required to use them to a given end (Kimmelman & London 2015). A socio-technical understanding of an intervention ensemble underlines the need for harmony between "people, processes, and environment" for successful implementation of interventions (McCradden et al. 2023).
WH2: Small outdoor research on SG requires increased research governance (socio-technical co-interventions, e.g. independent oversight and monitoring by a research ethics committee (REC), national system of accreditation of RECs) to function within an acceptable level of risk-benefit balance for a just global society (Jinnah et al 2024, Parson et al 2024, London 2022).

Box 2. Ethics and governance of SG research: a fundamental questions model

	Objectives	Product	Project
Part 1. Conceptual engineering	**Clarifying concepts.** What does the claim "SG is a socio-technical intervention" mean?	**WP1***	**ARIA**
	Defining activities. What is SG experimentation (research and/or deployment)?	-	Degrees 1
	Debating reasonableness. What is a reasonable disagreement on SG research?	**WP2**	**ARIA**
	Justifying ethical status. Is SG research forbidden, permissible and/or mandatory?	**WP3**	**ARIA**
Part 2. Ethics and governance of SG small outdoor research	**Reconstructing Standard operating Procedures principles of Responsible Research.** If SG research is ethically permissible or mandatory, what principles should guide responsible instances of SG research?	-	Degrees 1 & 2 (focus on public engagement principle)
	Designing institutional mechanisms. If SG research is ethically permissible or mandatory, what institutional mechanisms or regulations can help to implement responsible SG research?	-	WHO
	Implementing regional governance. What is an appropriate model of ethics and governance of SG in LAC?	**WP4**	**ARIA** (focus on Mexico). Degrees 2 (focus in Argentina and Brazil)

*WP: Work package.

WH3: Improving understanding about SG as a socio-technical intervention minimises unreasonable disagreements in SG (Clark 2023) and may protect global society from destabilisation and reaching negative social tipping points because of irresponsible SG research and deployment (Spaiser et al 2024). Formalising the concept of socio-technical interventions provides the conceptual tools to capture basic dimensions in non-formalised analysis, including types or pathway activities (e.g. exploratory vs. confirmatory research vs. deployment), the intent or main aim of an intervention, scales, evidence thresholds, etc. (Lenferna et al 2017, MacMartin et al 2019) in regimented and consistent language, fostering better understanding of socio-technical interventions in general and SG in particular. For an example of this tool see SCoPEx small scale outdoor experiment analysis in figure 1 below and its comparison with other SG interventions.

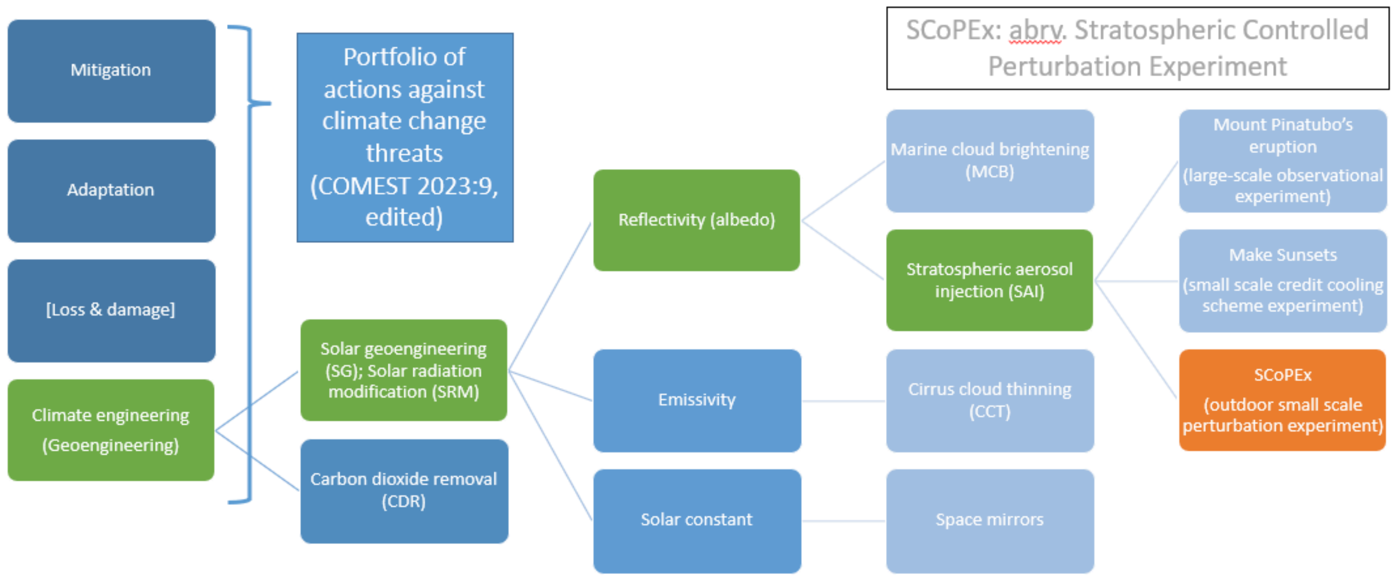


Figure 1. Analysis of SCoPEx experiment: SG SAI climate intervention of small scale outdoor research

3.2.WP2. Defining reasonable agreements in SG research using analogies

Aim. Map a multi-agent continuum of rejection-hesitancy-acceptance of SG research based on analogs from bioethic research.

Working hypothesis. WH1: This continuum works similarly to other forms of planetary technology, e.g. experimental COVID-19 vaccination research (Mastroleo 2024).

WH2: Two experts may disagree on a particular SG intervention belonging to the borderline cases of permissible SG interventions. One may example e.g., that large scale SG research may not be ethically permissible (Lenferna et al 2017)–, while the other may think it is ethically mandatory (e.g. Make Sunsets, Gelles & Bates 2024) (for the concepts of clear and borderline cases, see Fine, 1975; Williamson, 1994; Cobreros and Tranchini, 2019).

WH3: The difference in these reasonings is based on a theory about different formal and material cross-commitments involving doxastic attitudes of accepting, rejecting and suspending judgement (withholding, hesitation) about theories and claims (Sturgeon et al., 2010; Friedman, 2013). There are different forms of suspension of judgment, some grounded and other undergrounded (Ferrari and Incurvati 2021). Rational forms of disagreement involving suspension of judgment are only of the first kind. This theory, then, can be used to distinguish between reasonable and unreasonable disagreements in SG small outdoor research.

3.3.WP3. Justifying the ethical status of SG research as prohibited, permissible or mandatory

Aim. Dealing with the research question of justification of SG small outdoor research.

Working hypothesis: WH1: An analytical difference exists between the justification of SG research as an activity and the principles of responsible SG research. For instance, the first of the Oxford Principles impliesthat only SG research, development and eventual deployment of SG interventions for the common good (including SG small outdoor research) is ethically permissible(Rayner et al 2013) wich forbids other

uses such as SG for war. Moreover, others consider that SG research is not only ethically permissible but that SG research may beethically mandatory (Lawrence & Crutzen 2017).
WH2: Reasons for opposing SG research at the extremes of the rejection-hesitancy-acceptance continuum of possible SG deployment (see ARIA WP 2) are inadequate, insofar as they are based on unexamined assumptions (see as examples, “moral hazard” (Biermann et al 2022, as interpreted by Parsons et al 2024); “cooling credit schemes” as an alternative to the traditional scientific research pathway (see ARIA WP1) and there is sufficient evidence of favourable risk-benefit balance given the current level of climate change-related disasters, harms, and risks (Gelles and Bates 2024).
WH3: Mapping this basic discussion clarifies the ethics and governance of SG research and leads to further refined specific fundamental questions related to our governance model including**:** If ethically permissible, do potential host communities (e.g. LMICs) have ethical and prudential general reasons to host (e.g. cooperation) or to refuse to host (e.g. unpreparedness, exploitation) SG small outdoor research? (Camilloni 2024, personal communication).
WH4: To answer this important question foundational models of research ethics and political philosophy can be extended, e.g. London’s (2003, 2022) general interests model of the common good can be partly used to understand what a moral imperative or ethical duty to research means in the case of SG research, or using Gilabert’s (2018) model based on the concept of dignity to explain the global south rights and duties of potential host countries from the LMICs (e.g. if national authorities are planning to or forsee the potential use of SG at a national, regional or global scale they have a duty to research to protect basic interests or dignity of their citizens).

3.4. WP4. Building models for Implementing good and fair governance based on North-South Collaborations
Aim. Learn from the Mexican government's intention to ban experimentation on SG following the Make Sunsets small-scale experimental deployment and put forward a participatory governance model.
Working hypotheses. WH1. In Latin America and The Caribbean region (LAC) and elsewhere, SG is not yet a priority in the climate change portfolio of mitigation and adaptation strategies nor a topic on the radar of LAC governments.
WH2. Any appropriate, just, fair and equity global governance model must take into account significant cultural and ethnic diversity (ARIA 2024b) and build its principles in climate justice. Building good participatory governance requires mapping the sparse SG landscape in the LAC region and explore new ways of North-South early collaboration to strengthen Global South capabilities. Including boundary organisations (such as the Interamerican Institute for Global Change Research (IAI), Economic Commission for Latin America and the Caribbean (ECLAC) and regional stakeholders, policymakers, scientists, Indigenous communities, and greater civil society throughout the process of knowledge co-production will strenghten the legitimacy, relevance and saliency of research and experimentation (Jasanoff, 2004; Carabajal & Hidalgo, 2021)
WH3. The Mexican intention to ban SRM "experimentation" (following the Make Sunsets episode) may increase public resistance and discourage Global South governments, experts, and civil society from participating in international discussions and undermining responsible climate intervention research and practice (e.g., at UNEA 2025).
WH4: Increased access to science-based information for Global South countries and strengthening North-South collaborations will improve international participation, informed decision-making and build effective, fair and legitimate governance frameworks to advance research and practice or SRM.

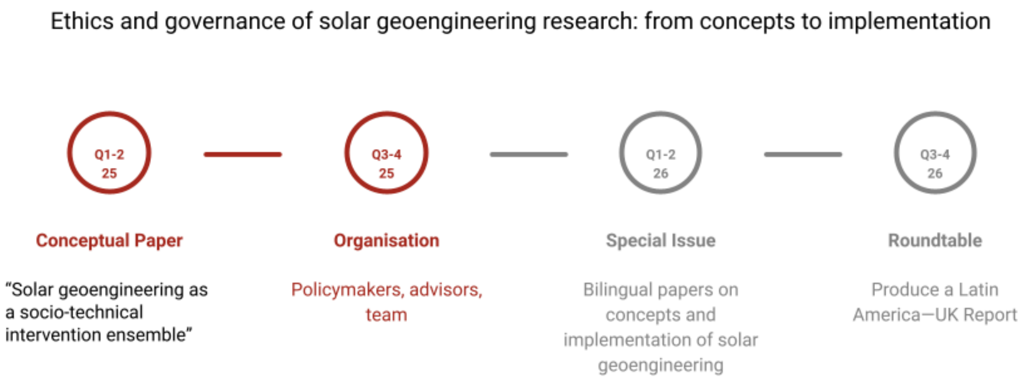
3.5. Common deliverables. All WPs are expected to produce one conceptual (WP1-3) or empirical paper (WP4) with the research assistant as first author within 24 months, and it is expected to be part of their thesis (students) or research program (post-docs).

3.6. WP Methods. WP1-3 will draw on standard conceptual research methods of philosophical analysis and conceptual engineering (Chalmers 2020) guided by scooping literature review and consultation with experts in the field. WP4 will use standard empirical research methods from anthropology and qualitative methods, including interviews, focus groups if necessary, mapping of actors and discourse and media analysis.

3.7. Timeline, activities and milestones

Period	Workflow objectives	Capacity-building objectives
Q1-Q2.25	.Establish monthly whole-project reading group with UK advisors. .Finish WP1 with a multi-authored theoretical paper (logic branch, see 4.): "Solar geoengineering as a socio-technical intervention ensemble"	. Identify research assistants (1 MA student for each WP) and enrol them in suitable institutional research projects (e.g. MA programs). . Train research assistants and researchers in conceptual analysis.
Q3-Q4.25	.WP4: Contact regional boundary organisations such as IAI, ECLAC, and other social and institutional actors for roundtable (Q4.26)	. Train research assistants and researchers in qualitative methods and dialogical skills to reach out to actors from different backgrounds: academics, politicians and international organisations members.
Q1-Q2.26	.WPs 2-3: Edit a bilingual special issue on ethics and governance of SG small outdoor research (e.g. National Autonomous University of Mexico Bioethics Journal).	. Foster ethical thinking and argumentation on the governance of small-scale SG research among researchers assistants. . Strengthen their academic writing skills.
Q3-Q4.26	. WP4: Organise a North-South workshop in Buenos Aires with UK advisors and different local, regional and international organisations (such as IAI, ECLAC) and different stakeholders - indigenous groups and civil society on SG research.	. Public-facing presentation of work . Train research assistants and researchers in the organisation of large-scale academic events involving academics, members of international organisations and civil society actors. In particular, to train them in the development of cultural competences.

Graphical representation of the two-year project.



Section 2: The Team

[redacted]

- [redacted]

- [redacted]

Advisors:

- [redacted]

Roles and Responsibilities

Principal investigators responsibilities:

- Lead the current project and collaborate with other researchers to realize the achievementment of the current application.
- Attend international conferences to promote the project.

Academic coordinators responsibilities

Academic coordinators are academic colleagues who work on the project as collaborators and have the following coordination roles:

- Contribute to publications as academics on at least one work package.
- Prepare monthly LAC-UK reading group
- Organise the in-person meeting
- Co-author publication of the LAC-UK report

Students and fellows' responsibilities:

- Collaborate with PI's and AC's in writing grants and articles based on the current project
- Collaborate with PI's and AC's in presenting partial results in academic meetings.
- Develop a dissertation (students) or similar project (postdoc fellows) within a suitable research program (e.g. PhD in Philosophy, PhD in Anthropology or Social Sciences)

Advisors responsibilities

- Follow the students' research
- Propose bibliography for the monthly journal club
- Collaborate on the LAC-UK report

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How to speak about climate cooling?: co-creating a climate engineering engagement toolkit in the Arctic and the UK (previously "Entangled Futures: Geoengineering, Youth, and Indigenous Futures in the Arctic")

Section 1: Programme & Technical Overview

1. **Background:**

Public engagement is an essential and as of yet underdeveloped part across all scales of climate engineering research.[1] On a project specific scale, the examples of the cancellations of SCoPEx[2] and the University of Washington's experiments with Marine Cloud Brightening[3] show that adequate community engagement is a prerequisite for conducting field experiments. Not only is engagement valuable for informed collective decision making, but in the absence of formal governance on climate engineering research, some authors argue that "*co-producing research could serve as a de facto form of governance*"[4]. Yet, although several research projects have made such engagement an essential part of their research design, with the recently published AGU Ethical Framework[5] setting out some general guidelines, broadly applicable studies on useful engagement strategies are lacking. On the larger national or international scales, public engagement studies have recently proliferated. These have, however, so far mainly been limited to the scoping of opinions and stances towards research or future deployment[6]. Whilst such efforts have provided valuable snapshots of public opinion and provided important insights into contextual specificity and complexity in opinions, these studies fundamentally leave two critical gaps in our understanding.

First, these studies have failed to capture the process through which participants form, refine or change their views when exposed to new information or perspectives on climate engineering. Second, many of these approaches have not focused on key climate actors – especially individuals whose concerns will be impactful for governance – environmental and social justice advocates, indigenous communities, community organisations and other engaged citizens[7].

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[1] We use climate engineering, climate cooling, and climate interventions as synonyms throughout this application to refer to large-scale interventions to artificially intervene in (parts of) the climate system in order to mitigate some of the effects of global warming.

[2] https://www.saamicouncil.net/news-archive/saami-councils-statement-to-the-harvard-decision-to-halt-the-scopex-project

[3] https://www.sfchronicle.com/climate/article/geoengineering-alameda-study-stopped-19453924.php

[4] Ilona Mettiäinen et al., "'Bog Here, Marshland There': Tensions in Co-Producing Scientific Knowledge on Solar Geoengineering in the Arctic," *Environmental Research Letters* 17, no. 4 (March 9, 2022): 045001, https://doi.org/10.1088/1748-9326/ac5715.

[5] https://www.agu.org/learn-about-agu/about-agu/ethics/ethical-framework-for-climate-intervention

[6] i.e. Brutschin, E., Baum, C.M., Fritz, L., Low, S., Sovacool, B.K. and Riahi, K., 2024. Drivers and attitudes of public support for technological solutions to climate change in 30 countries. Environmental Research Letters, 19(11), p.114098.; Contzen, N., Perlaviciute, G., Steg, L., Reckels, S.C., Alves, S., Bidwell, D., Böhm, G., Bonaiuto, M., Chou, L.F., Corral-Verdugo, V. and Dessi, F., 2024. Public opinion about solar radiation management: A cross-cultural study in 20 countries around the world. Climatic Change, 177(4), p.65.;
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[7] Sapinski, J. P., Holly Jean Buck, and Andreas Malm. 2021. *Has it come to this?: The promises and perils of geoengineering on the Brink*. New Brunswick, NJ: Rutgers University Press.

Understanding how people form, refine or change their views on climate interventions is as important as the opinion they ultimately express[8]. Focusing on this process will provide insights into the journey of engagement – the way individuals grapple with climate engineering information, confront their assumptions and adapt to new knowledge. This matters because opinions are not static[9] – they emerge from ongoing dialogue, shaped by responses of those involved. By focusing on the process of engagement, we gain both a clearer picture of public opinion and of what drives public trust or skepticism towards climate engineering research.

Our proposal seeks to address these gaps by adopting a dual-stream framework that goes beyond static opinion measurement towards the co-creation of a climate engineering engagement process. Fundamentally, we seek to explore how participants in the UK and Arctic[10] communities think conversations around climate engineering could and should take place. While our project also seeks to understand what different communities think about climate engineering, it primarily focuses on the process of engagement – its design, inclusivity and desirability for participants.

2. Programme Alignment and Project Overview

According to the funding guidelines, this project is of direct relevance regarding the "…consideration of public perception, potential legal, ethical, regulatory and governance frameworks, ethics, community engagement, and the economic impact of those approaches". Because ARIA is a cutting-edge organisation at the forefront of innovative research, it is uniquely positioned to lead in setting new standards of public engagement for emerging tech. This makes ARIA both the ideal place to create and to implement engagement frameworks to guide the responsible development of high-impact, transformative technologies.

Specifically, we propose to use this funding for two workstreams. The first work stream will focus on co-creative workshops with engaged citizens and communities in the Arctic, especially those who are often left out of other similar climate engineering engagement endeavours. The second phase will involve conducting citizen assembly engagements in the UK with members of the public across multiple locations (London, East Cambridgeshire, and Glasgow/Aberdeen).

Aspect	WP1: Arctic Communities (section 2.1)	WP2: UK citizen assemblies (section 2.2)
Focus	Inclusivity and Indigenous perspectives	Iterative learning and opinion shifts
Participants	3 assemblies of up to 25 participants	3 assemblies of up to 25 participants
Engagement format	Two-day workshops across three Arctic sites	Repeated two-days assemblies across three UK locations

[8] Dennis Chong and James N. Druckman, "Dynamic Public Opinion: Communication Effects over Time," *American Political Science Review* 104, no. 4 (November 2010): 663–80, https://doi.org/10.1017/s0003055410000493.
[9] Ibid.
[10] We use the term "Arctic" throughout this proposal, even while our field sites will likely be primarily located in the Arctic regions of the Nordic countries, but do not suggest that our toolkit will encompass or be directly relatable to the entire Arctic region. However, given the developed inter-Arctic indigenous networks, the possibility of expanding into other Northern regions, and many climate intervention proposals refer to the Arctic, we found the Arctic to be the best term.

Outputs	Academic articles, engagement toolkit.

2.1 Work package 1 - Engaging Arctic Communities

Overview:

The Arctic is often considered as a potential location for climate engineering field tests and potential future deployment. To many living in the region, especially indigenous peoples, the controversies around such experiments resonate strongly with past and ongoing colonialist projects like the construction of wind farms and hydroelectric dams, while the Arctic has also been long constructed as an empty frontier or laboratory perfect for such experimentation[11]. There are several climate engineering research projects that conduct their own outreach[12] and there is at least one general engagement project in the Arctic conducted by the Alliance for Just Deliberation on Solar Geoengineering (SDG)[13]. While very worthwhile, the research-first projects only focus on a specific technique and location, and the SDG project is limited in scope and means, not intending to be methodologically innovative or broadly generalisable.

Objectives:

1. Explore forms of learning, deliberation, and knowledge exchange that incorporate the role, value, and norms of multiple forms of learning and knowing, such as those present among Indigenous Peoples and local community organizations in the Arctic.
2. Discuss how participants perceive the inclusivity of discussions around the issues and complexities linked to climate engineering research projects, and their subsequent willingness to take part in citizen assemblies.

Methods and Rationale:

The assemblies will consist of 3 groups of around 25 participants each who will participate in co-creative discussions/assemblies around climate engineering engagement for two full days or one weekend. Methodologically, the project combines pre- and post-session Q-sort exercises, qualitative analysis of facilitated discussions, and reflective exercises to capture the co-creative and collaborative engagement of participants. Data collection includes summaries of discussions, plans produced by participants detailing their ideas for such engagement processes, Q-sort responses, and participants' reflective journals. The combination of quantitative Q-sort and qualitative methods will help us better understand our participant's collective and individual views towards climate engineering, as well as their reasons for holding these views or how they track with other opinions (participants' view towards climate change and technology more generally, for example).

Participants will not be required to have prior experience with climate engineering, and will ideally include a mix of Indigenous and non-Indigenous participants to see how to integrate Indigenous Traditional and Local Ecological Knowledge and non-Indigenous knowledge together. Recruitment will occur through our local contacts and collaborators–many of whom are either Sámi themselves or have experience working with Sámi communities (such as Operaatio

[11] Cooper, A. M. 2023. "FPIC and Geoengineering in the Future of Scandinavia". In *Arctic Justice*. Bristol, UK: Bristol University Press. Retrieved Oct 6, 2024, from https://doi.org/10.51952/9781529224832.ch010
[12] See for example the GRISCO project: https://www.arcticcentre.org/EN/grisco/background or reports by *Real Ice*: https://www.realice.eco/cambay-comm-eng-factsheet
[13] https://sgdeliberation.org/activities/youth-engagement-program/

Arktis) and/or climate engineering topics. Specifically, these sites will likely be places with dense Indigenous Populations (taking into account seasonal reindeer herding and other events), sites of past or proposed, climate engineering experiments, and other locations with engaged citizen communities that we have contacts in, such as: Reykjavik (climate engineering experiments have already been explored in Iceland under the auspices of the Bright Ice Initiative), Kiruna (the proposed site of the 2021 ScopeX tests), Inari (home to the Sámi Parliament), Rovaniemi (home to the University of Lapland, the seat of the UArctic Thematic Network on the Frozen Arctic focused on Climate Intervention), Helsinki (home to Operaatio Arktis), and Kautokeino (a center of Sámi culture in Norway), while other sites with significant Sámi populations such as Tromso, Oulu, Mannddalensjobuer, Enontekiö, Karasjok, Utsjoki, Arvidsjaur, Jokkmokk, and Gällivare are also possibilities depending on who has the interest and capacity to work with us.

Output of WP 1:

Evidence based framework for engagement on controversial technology: out of the collaborative engagement processes, we would be able to combine participants' perspectives about how discussions concerning controversial technologies can be structured, and whether participants perceive these engagements as worthwhile or meaningful. In addition to the toolkits, the outputs of WP 1 will be a series of academic articles reporting on the challenges and opportunities of co-creating engagement processes around controversial techniques like climate engineering.

2.2 Work package 2 - Co creation of a climate engineering engagement framework in the UK

Overview of research design: This work package explores how iterative exposure to SRM knowledge supports public understanding and deliberation over time.

Objectives:

1. Identify forms of learning, deliberation and knowledge exchange that best support participants in refining their views on SRM/Climate engineering over time.
2. Explore how participants' opinions about SRM/Climate engineering evolve over time and through iterative exposure to SRM knowledge

Methodology and rationale: The research questions for this work package are: *how do participants' opinions about SRM evolve over time and through iterative exposure to SRM knowledge, and what forms of learning, deliberation and knowledge exchange best support participants in refining their views on SRM over time?* The research design involves a pilot citizen assembly model where approximately 25 participants, representing a diverse cross-section of the population, convene annually over three years for two-day sessions. This frequency allows for sustained engagement, providing the time necessary for participants to process complex information, deliberate collaboratively, and refine their views over time. Other, non-SRM interventions are less likely to be directly applicable to the UK context.

Methodologically, the project combines pre- and post-session Q-sort exercises, qualitative analysis of facilitated discussions, and reflective exercises to capture the evolution of participants' knowledge and opinions. Data collection includes transcripts of discussions, Q-sort responses, and participants' reflective journals. The longitudinal structure is critical to the robustness of the methodology, as it allows for the observation of opinion shifts over an extended period rather than relying on static, one-time snapshots.

We propose selecting 25 participants, selected to reflect a representative and diverse cross-section of three locations: East Cambridgeshire, London, and Glasgow/Aberdeen. This assembly would convene for two full days or weekends each year over the course of two years, allowing for sustained engagement, iterative learning, and longitudinal data collection.

East Cambridgeshire has been selected as a site because: (1) of the region's proximity to academic and scientific hubs (including the University of Cambridge where one of the co-authors is based), which increases the likelihood of future SRM field experiments being planned or debated locally, (2) it offers a mix of rural and semi-urban settings, providing perspectives underrepresented in discussions dominated by urban populations, and (3) the region is famously low lying and would be strongly impacted by future sea level rise.

London has been selected as a site because of its relatively underprivileged and ethnically diverse population (1), it's being part of the UK's capital and major political centre (2), and for the number of universities establishing its status as a knowledge hub (outside of Oxbridge). We have not decided on the precise Borough or neighborhood yet, but neighborhoods like Brixton (which is known for its large Caribbean population) or x are very likely

For a more Northern perspective, Aberdeen is our preferred option due to its unique connection to the fossil fuel industry that might provide an interesting perspective alongside the more engaged community groups that we will be engaging. Another option would be Glasgow for a more diverse population and spread of perspectives, as well as its climate connections through the hosting of COP26, but this will depend on the place in London we decide on.

Output of WP2: Evidence based framework for engagement on controversial technology: out of the continuous engagement, we would be able to combine participants' perspectives about how engaging discussions about controversial technologies can be structured. This aims to be directly applicable to ARIA's broader mission of engaging with cutting edge research.

Output of both projects:

The combined long term engagement and Arctic focused work packages will produce unique insights with the strengths of contextual, and in-depth/long term methodologies embracing multiple forms of knowledge, compared to other climate engineering engagement studies. For example, AGU's Ethical Framework for Climate Intervention is "A code of conduct to guide the research, experimentation and deployment of climate intervention measures"[14] by consulting experts and advisors, while the EU Co-Create stakeholder forums[15] are focused on governance and decision making, not on the process of public engagement itself. Currently existing frameworks like post-normal science[16] or other citizen science frameworks are also helpful guides, but are not designed specifically with the challenges of climate engineering in mind. While most relevant to projects taking place in the UK funded by ARIA, our toolkit may be useful to add to or fuse with engagement work done by other project proposals from the CCCR, University of Manchester, and Aker Solutions[17] which are due to take place in the Arctic/Antarctic. Even though many regions could be suited for expanding the contextual focus of the toolkit, and might indeed be included in the future, the Arctic is the most accessible and

[14] https://www.agu.org/learn-about-agu/about-agu/ethics/ethical-framework-for-climate-intervention
[15] https://co-create-project.eu/
[16] Silvio O. Funtowicz and Jerome R. Ravetz, "Science for the Post-Normal Age," Futures 25, no. 7 (September 1993): 739–55, https://doi.org/10.1016/0016-3287(93)90022-l.
[17] As per Aria recommendations, we contacted these organizations who expressed interest in our project.

relevant region. Additionally, restraining the scope to the UK and the Arctic will allow us to focus on technologies relevant to these regions, thus not stretching our expertise, time, or participants' patience. The expertise and connections of Albert and Cody will help ensure that the engagements are scientifically informed and not extractive, while helpful for raising awareness around how the Arctic is being affected by climate change.

2.3 Project management

Risks and dependencies to the project

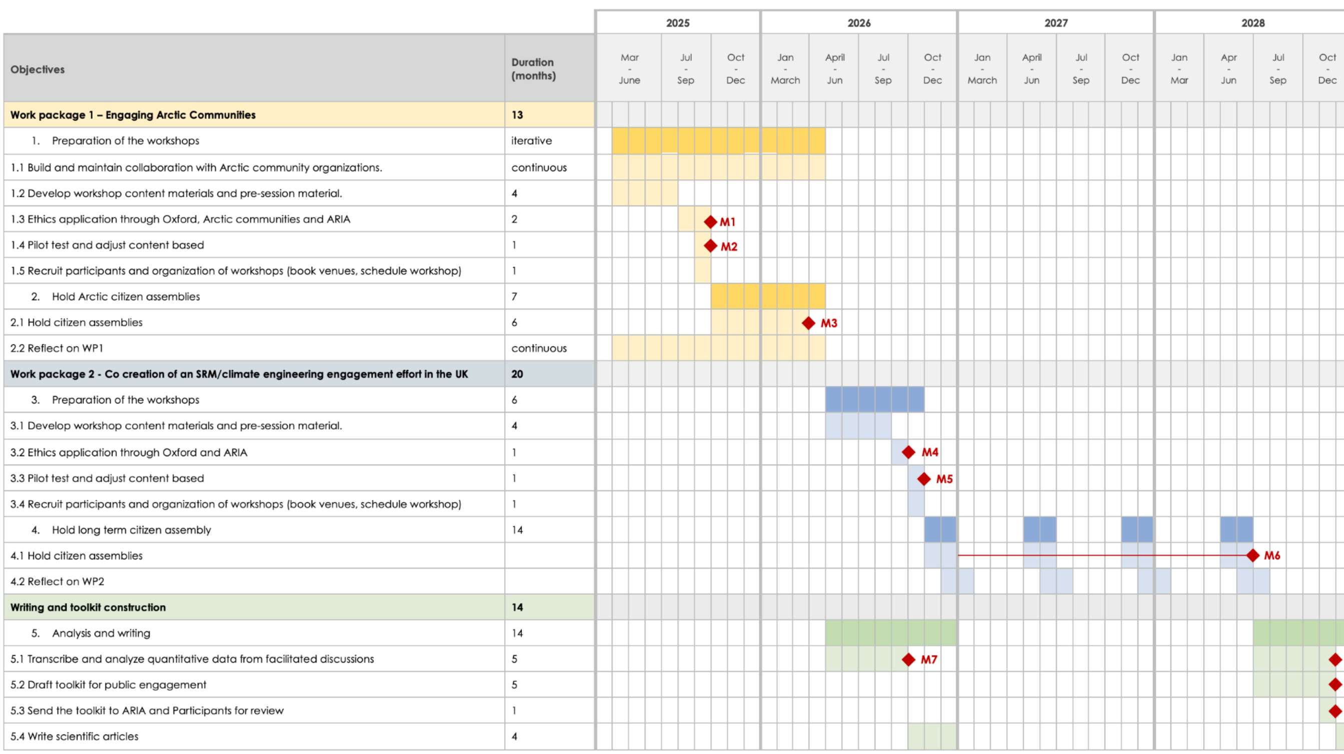
Type	Name	Description	Mitigation strategy
Risk	Recruitment challenges (WP1&2)	Difficulty recruiting diverse participants in the Arctic and UK communities.	Leverage local networks from the start, and offer flexible timelines.
Risk	Scheduling conflicts (WP1&2)	Delays due to the participants availability	The Gantt chart has been built with this in mind incorporating buffers between the different assemblies.
Risk	Cross-cultural barrier (WP1)	Miscommunication between researchers and local communities.	Co-design workshop with local partners and following guidelines for conducting research and engagement
Risk	Longitudinal drop-off (WP2)	Participants dropping out of UK assemblies over time, reducing discussion quality.	Maintain regular communication, provide participants incentives to come (minimum wage) and recognition of contribution.
Risk	Ethical concerns (WP1&2)	Criticism regarding the ethics of climate engineering discussions with marginalised groups.	Go though the internal Oxford, ARIA and Arctic organisation ethics approval processes, as well as allowing participants to go off record when desired.
Risk	Political backlash (WP1&2)	Controversy over climate engineering could affect participants or attract negative media.	From the beginning, engage the participants, transparently, on controversies.
Dependencies	Local partnership (WP1&2)	Collaboration with Arctic organisation for recruitment and workshop design.	Build early partnership with trusted organisations and co-develop engagement methods.

Timeline

We have identified 10 milestones over the course of this project lasting from March 2025 to Dec 2028. For each milestone in this project, we are committed to maintaining clear and consistent communication with stakeholders, whether it is providing updates on progress, sharing emerging insights, or gathering feedback to refine our approach. This ensures that the process remains transparent, collaborative, and responsive to the needs and expectations of those involved.

- M1 & M4: finished ethics applications we would co-create with Arctic organisations for WP1, and seek approval with the Oxford Ethic committee as well as ARIA (WP1&2).
- M2&M5L completed pilot workshops which will be held with partnered organisations to validate the methodology and the future content of the workshop (WP1&2).
- M3&M6: completed all workshops (WP1&2)
- M7&M8: completed the summary and the analysis of all material (WP1&2).
- M9: drafted the toolkit based on empirical analysis and literature review (WP1&2).
- M10: approval and integrated the feedback from participants and stakeholders within the toolkit (WP1&2).

Gantt chart showing timeline and key milestones of project (larger version available, or use zoom function to read more clearly).



[redacted]

[redacted]

[redacted]

7

[redacted]

[redacted]

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What makes us a team?

As a team, we represent a rare merging of disciplines - anthropology, engineering, humanities, environmental sciences and public policy. This diversity does not just add variety to our perspectives; it enhances our capacity to think creatively and critically. In our PhDs, interdisciplinarity has meant approaching the complexities of climate engineering engagement with depth, balance, and an openness to alternative perspectives, ensuring that every voice finds its place in the conversation. This commitment extends beyond disciplines and perspectives to the core of procedural justice: whose voices are heard, and whose are too often overlooked. This has come as a foundation of our commitment to engagement that is both inclusive and meaningful. In that sense, our commitment to public engagement has not been theoretical - it is grounded in practice. Each of us has worked directly with communities, from facilitating dialogues with Arctic Indigenous groups to collaborating with youth activists on climate interventions and bridging conversations between scientists and policymakers. These experiences have taught us how to design and guide processes that foster trust, encourage dialogue, and empower participants. We know how to engage meaningfully and create space for marginalised voices.

What brought us together on this project was a shared vision, driven not by disciplinary boundaries but by the belief that science should serve society with transparency, inclusivity, and fairness. As early-career researchers, we bring fresh perspectives. For us, this project is more than a toolkit: it is a chance to set a new precedent for how emerging technologies like geoengineering can be explored, putting people and justice at the center.

Re-thickening Arctic Sea Ice

1. Proposed Idea/Solution

The Arctic is currently warming 3-4 times faster than the global average[1]. While rapidly decarbonizing the global economy is crucial, implementing methods to specifically cool the Arctic region could significantly extend the time needed to avoid temperature-induced climate tipping points. To explore the feasibility of purposefully cooling the Arctic, we propose investigating whether sea ice re-thickening could offer a viable solution. Ice re-thickening is primarily achieved by drawing seawater onto existing sea ice to increase its thickness. By enhancing ice thickness, sea ice can endure longer during warmer seasons, thereby enhancing the reflectivity of a geographic area compared to seawater. This would reduce not only solar warming of the region but also global temperatures. Alongside direct re-thickening, we will explore how thickening key portions of sea ice can be used to help limit sea ice export out of the Arctic Ocean..

In line with ARIA's programme thesis, we propose a 3.5-year research programme to develop the essential knowledge, technology and impact assessments required for sea ice thickening to mitigate the significant loss of sea ice coverage in the Arctic Ocean[2,3].

We will integrate large-scale climate and sea ice modelling validated by field and laboratory tests to assess:

a) The large-scale *Regional Application of Arctic Ice Thickening*.
b) A targeted approach involving *Ice Arch Strengthening,* so as to limit the export of Arctic sea ice.

Alongside each of these approaches, we will also address the scalability of developed technologies.

The applications used in this project will utilise natural materials (i.e. sea water) in a reversible manner which mimics natural processes. Throughout the project, we shall assess and engage with relevant bodies to determine whether there are any adverse impacts upon local ecology, climate, and communities with whom we plan to engage and involve in local fieldwork.

This proposal brings together a motivated, diverse and expert team uniquely positioned to address the aforementioned challenges. The project is both highly ambitious and novel, with the potential for significant climatic rewards and minimal risk. The project team is exceptionally suited to deliver this goal-focused proposal, having extensive experience in implementing high risk/reward science in extreme environments[4], as well as in-depth knowledge of multi-scale modelling of sea ice rheology[5,6] and sea ice growth[7,8].

a. Regional Application of Arctic Ice Thickening

The concept of increasing sea ice thickness on a regional scale is drawn from previous work by team members, including [redacted] and [redacted] found that pumping 140 cm of seawater onto existing sea ice results in an additional 100 cm of ice thickness. Similarly, [redacted] showed that flooding a 20 cm layer of snow on top of sea ice can increase sea ice thickness by 70 cm. In this study, we seek to build upon this research by testing and validating the effectiveness of these ice thickening strategies. We also will examine the effectiveness of draining melt water pools on existing sea ice to prolong the life of the sea ice during the summer months. This will be undertaken by drilling small holes in the sea ice during the spring season.

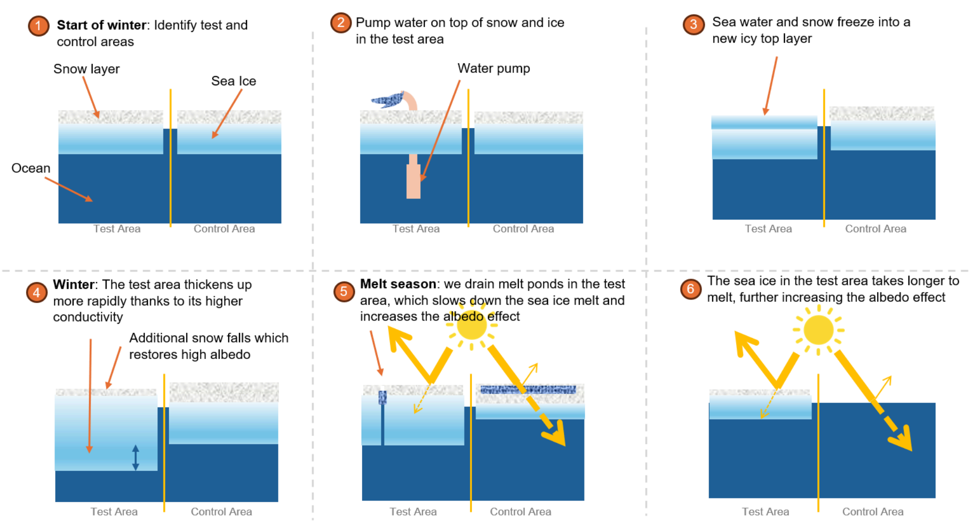

Figure 1 – A schematic diagram highlighting ice thickening field test phases, where we will compare the outcome of ice thickening with control areas.

Throughout the project, results from our field tests will continually be used to feedback and inform the modelling exercise, thereby enhancing the accuracy and certainty of parameters. Recent work by project applicants has already laid the groundwork for this research[7,8]. Over the past 2 years, project applicants have conducted field tests in Nome, Alaska (Real Ice, 2023), Cambridge Bay, Nunavut (Real Ice, University of Cambridge, Arctic Reflections, 2024) and Svalbard

[(Arctic Reflections, TU Delft and University Centre in Svalbard (UNIS), 2024)][9] with (forthcoming) publications[27].

b. Ice Arch Strengthening

In order to limit the export and subsequent loss of sea ice from the Arctic Ocean, we will explore the targeted use of ice re-thickening to strengthen certain ice arches of the Arctic region, so that they are structurally stable for additional weeks during the summer months. The end-goal of this targeted approach is the same as the regional ice thickening intervention (Arctic albedo improvement), but the key difference is that the strength of the arch post-thickening needs to withstand significant lateral forces, to inhibit the export of sea ice[10].

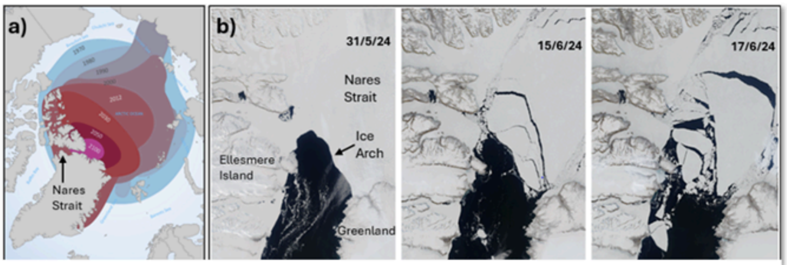

Figure 2. a) Map of the Arctic region, showing extent of permanent sea ice coverage against time (adapted from THE ARCTIC INSTITUTE). b) Satellite images from 2024, showing the break-up of the Nares Strait ice arch in under one month.

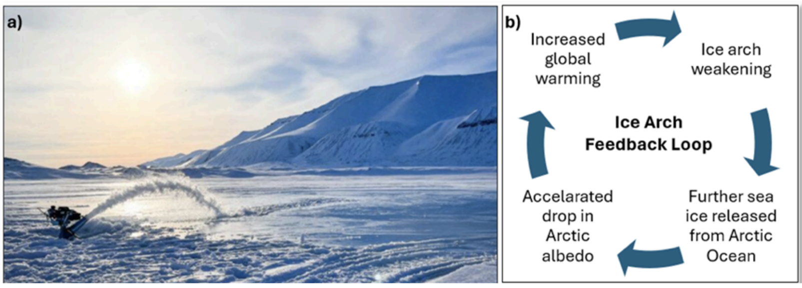

Figure 3. a) Arctic Reflections pumping sea ice onto a frozen lake surface in Svalbard 2024. b) Diagram of the Ice Arch Feedback Loop, which we seek to buffer.

Perhaps the best known ice arch is that of the Nares Strait, which is a 530 km x 35 km channel between Canada and Greenland (see Fig. 2). Typically, an ice arch forms annually at both ends of the channel, which has the natural effect of blocking the export of Arctic sea ice southwards, which would otherwise occur due to strong currents and the forces in the ice pack (Fig. 2b).

When formed, the ice arch in the Nares Strait typically lasts for around six months[11] before breaking apart, allowing the withheld sea ice to flush south. Approximately 95,000 km^2 of the Arctic Ocean's sea ice is lost through the Nares Strait during the annual open period, accounting for some ~11% of the ocean's total sea ice export[12]. The southern arch, or "ice bridge" plays a crucial role in maintaining the open water of the NOW Polynya (or Pikialasorsuaq), one of the richest ecosystems in the Arctic and vital sources of life. This area is essential for local indigenous communities, who have formed a Commission and recently published a report on the importance of the ice arch[13]. However, the Nares Strait ice arch has been forming less frequently and lasting for shorter durations in recent decades[14]. Before 2007, the arch lasted an average 177 days per year, but since then the average duration has decreased to 128 days per year[15]. Thinner ice arch thicknesses, resulting from less favorable formation and maintenance conditions[16], are less effective at holding back the surrounding glaciers [17] and the Arctic Ocean's sea ice[18].

The weakened state of the Nares Strait accelerates the depletion of sea ice within the Arctic Ocean. This depletion is further amplified by the Arctic Ocean's disastrous sea ice feedback loop, which includes effects such as increased open water causing larger waves, which breaks up even more ice[19]. In this study, it is anticipated that the maximum thickening required to stabilise an arch will be up to a few metres tall; this is much thicker than that needed for the regional application, but in line with previous ice island construction by oil companies[20]. This study will develop all the necessary components to determine if and how successful intervention in the detrimental ice arch feedback loop (Fig. 3b) can be achieved.

Scalability studies

In parallel to the above studies, we will investigate two methods to scale ice thickening techniques to large areas. One method will explore the use of underwater drones to automatically distribute a solution under the ice. The other method will seek to distribute water over larger ice areas from movable pumping platforms using high flow rate pumps.

2. Proposed activity of work (key metrics and milestones, dependencies and assumptions)

The project will comprise eight interlinked thematic work packages (**WP**s). Within each thematic **WP**, sub-packages will be led by the named institution. These sub-packages will support research into regional scale sea ice thickening and the targeted approach of ice arch strengthening. There will be significant dialogue and knowledge sharing within and across all **WP**s as shown in the Gantt Chart (Fig. 4)**.**

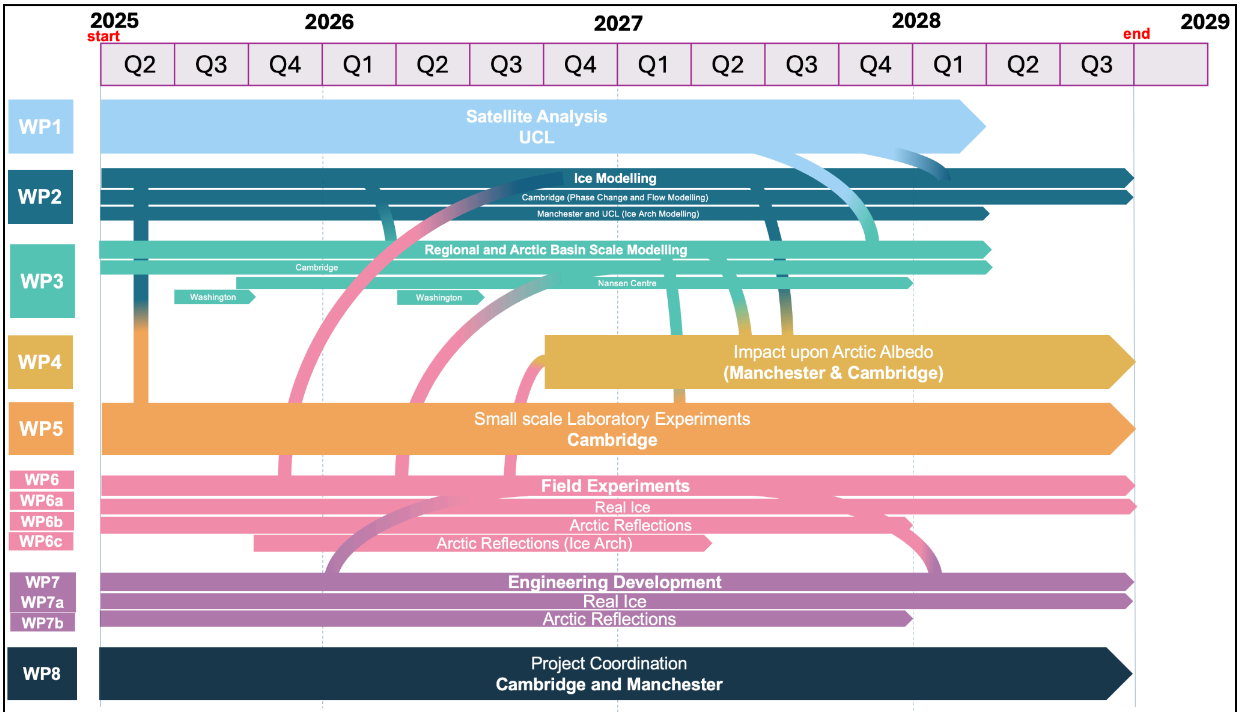

Figure 4: Gantt Chart showing the timelines and relationships between the different proposed work packages (WPs).

WP1 - Satellite Analysis: This WP aims to identify the most vulnerable areas of ice thinning that would benefit from ice thickening, providing crucial input for the modelling work. **UCL** will combine up to 30 years of sea ice thickness data from airborne and satellite measurements with sea ice drift data to calculate ice fluxes in both area extent and ice volume. This analysis will focus on regions such as the Canadian Archipelago and the Nares Strait, where ice arches form. We will use high-resolution satellite imagery to monitor the timing and location of ice arch formation and disintegration. Additionally, we will review data to identify areas in the Arctic, away from the ice arches, that are experiencing annual ice loss. This will help determine regions that could benefit most from winter sea ice thickening. The outputs from **WP1** will be shared as they become available to support the modelling work outlined in **WP2** and **WP3**.
Milestone/deliverable Month 9 (M9) – report on sea ice characteristics for input to regional model in ***WP3***
Milestone/deliverable (M36) – report highlighting target areas for Ice Thickening (Ice Arches and Regional)

WP2 - Ice modelling: Cambridge will use a suite of analytical and numerical models to enhance our understanding of how sea ice grows and strengthens when seawater is pumped onto its surface. This work will provide crucial input for the larger-scale modelling efforts of **WP3**. Building on initial modelling of ice growth[7] from water flow across the ice surface, Cambridge will develop models for water flow through snow. These models will help establish the areal extent of water coverage required based on snow depth, temperature, flow rate, and ice surface morphology. By developing end-member models of channel and radial flow, we aim to better predict the physical characteristics of sea ice that grows faster through seawater pumping. Informed by these findings, **UCL and Manchester** will use state-of-the-art finite element (FDEM) and mathematical modelling (utilising both discrete/granular and continuous properties) to better understand the structural integrity of ice arches as they are vertically thickened, and how this varies across different horizontal scales. This will be compared to satellite and in-situ observations from **WP1**. The output models from **WP2** will support and be informed by laboratory experiments in **WP5**, and the regional and basin-scale modeling in **WP3**.
Milestone/deliverable (M12) – report on initial modelling for Ice Thickening processes
Milestone/deliverable (M24) – report on sea ice mechanics from discrete/continuous FDEM model
Milestone/deliverable (M42) – report on modelling for Ice Thickening and structural integrity of ice arches

WP3 - Regional and Arctic basin scale modelling: This work package will determine the ultimate potential for ice thickening. Modelling the large-scale effects of Arctic ice thickening within climate models involves dealing with grid resolutions much larger than the scale of typical individual interventions. It also requires incorporating realistic operational scenarios and parameters. Therefore, we will use the outputs of our detailed ice modelling undertaken **(WP2)** in conjunction with the results from the small-scale laboratory

experiments **(WP5)**, and field tests **(WP6)** to inform the regional and Arctic basin model parameters. **Washington and Cambridge** will model the impact of re-icing using two fully-coupled climate models: the Community Earth System Model version 2 (CESM2) and the UK Earth Systems Model (UKESM). They will simulate sea ice flooding over specific locations and periods to assess its impact on sea ice and climate. This will include evaluating different scales of flooding (10,000 km² to 500,000 km²), optimal timing, and the effects of geographically variable flooding (e.g. starting further north early in the freeze-up season and moving southward over time). They will also quantify the impact on coastal sea ice, which is important to Arctic communities' livelihoods and coastal erosion. CESM2's sea ice component has been modified by the University of Washington team for sea ice flooding, following the CESM model used in [redacted] which flooded sea ice everywhere. Additionally, the impact of adding snow in spring as a potential sea ice restoration engineering technique will be modelled. The sea ice parameterization in UKESM is undergoing rapid improvements as part of the 5-year UKRI program in Climate Change in the Arctic-North Atlantic Region (https://canari.ac.uk/). This will allow for the incorporation of complex physics of sea ice and underlying water stratification to assess sea ice thickening impacts. Complementing this work, **Nansen** will seek to understand the overall impact and risks upon the Arctic Ocean of blocking Nares Strait for a longer period than currently observed. They will use the neXtSIM sea-ice model to simulate the impact on sea ice distribution across the Arctic basin. This task requires a much higher resolution than the fully coupled climate models can deliver and will benefit greatly from the advanced sea-ice dynamics of neXtSIM[6,19]. The modelling will provide crucial information on the dynamics of ice flow on a regional scale and how this may change in a warming climate. It will also allow us to identify the impact of blocking the Nares Strait in a warmer climate and understand how the ice flows further north. This will be key to determining the overall impact and benefits of the targeted approach.
Milestone/deliverable (M12) – report on initial modelling of Regional- and Basin-scale ice thickening
Milestone/deliverable (M24) – report on the evaluation of modelling ice flow through Nares Strait
Milestone/deliverable (M36) – final report on modelling of Regional- and Basin-scale ice thickening
Milestone/deliverable (M42) – report on modelling ice flow and Arctic ice state with a blocked Nares Strait

WP4 - Impact upon Arctic Albedo: Initial benefits of ice thickening in terms of albedo have been observed[27]. However, more work is needed to quantify the potential under differing conditions. Using the results of **WP2, WP3** and observations planned in **WP6**, we will calculate the potential change in Arctic albedo (and therefore global warming contribution) for a range of climate scenarios. In addition to the overall impact on areal extent of ice cover, we will assess the different levels of albedo of normal sea ice, flooded sea ice, and snow covered sea ice. This will help inform potential strategies, such as the best timing for pumping seawater onto sea ice to maximize climate benefits. **Cambridge** will oversee the impact of large scale intervention and **Manchester** will focus on ice arches.
Milestone/deliverable (M42) – report on impact of albedo of Re-Thickening of Arctic Sea Ice

WP5 - Laboratory Experiments: Initially **Cambridge** will conduct laboratory tests to validate the models developed in **WP2.** This will be critical for building our understanding of the evolution of the ice. We will then conduct a series of non-flow experiments to investigate the freezing of saltwater on top of fresh ice and the subsequent migration of brine. We will compare the evolving ice thickness and temperature profiles with theoretical predictions. These experiments will enable us to understand how the rate of ice accumulation from the underside of an overlying ice layer is affected by the introduction of artificial snow, and snow which has been flooded. Our final suite of laboratory experiments will investigate the flow of water through a snow layer on top of ice. The different processes of melting/freezing/dissolution will be investigated so that we can determine how to optimise the snow flooding process. The set up of the experiments will be informed by **WP2** and the results from this work package will feed back into the development of models in **WP2**.
Milestone/deliverable (M12) – Initial report on laboratory experiments
Milestone/deliverable (M42) – Final report on laboratory experiments

WP6 - Field Experiments: In order to get a better understanding of the behaviour of ice growth and melting beyond that which is possible by modelling and small scale laboratory experiments alone, field experiments will be undertaken. The experiments are designed to be as large as necessary to investigate issues such as fracturing of sheets of thickened sea ice, but as small as possible, using knowledge from previous field work. We propose two field test programs running in parallel, each lasting at most three winters (2025/26 to 2027/28), operating in different locations in the Arctic. This will mitigate the risk of disruption by local weather conditions, and increase the likelihood of successfully completing the field work, potentially even just after two winters. **Real Ice**, supported by **Arizona State University**, are proposing to undertake field experiments at Cambridge Bay (**WP6a**). **Arctic Reflections** will conduct work in the

Inuvialuit Settlement Region (**WP6b**) on general ice thickening, and on Svalbard (**WP6c**) on ice arch strengthening. These experiments will be informed by and inform our modelling work on ice growth (**WP2**). They will also help inform our larger scale modelling (**WP3**), our assessment of the impact on albedo (**WP4**), and our work on scalability (**WP7**).

In **WP6a** and **WP6b**, we aim to cover up to 1 km^2 in the first year, adapting in subsequent years. To observe results by the next melt season, the area re-iced must be large enough to minimise boundary effects which depend on local conditions. Further adjustments in the following year will be made based on the outcome of the results in the first year. In each location, we will measure net ice growth, melting, and the effect of salinity and snow, by pumping water on various test areas, using different methods, and comparing these rigorously with control areas (Fig. 1). We plan to learn, adjust and refine the ice thickening methods annually, so that the most effective ones can be given more focus. Furthermore, we will use a combination of manual and automated measurements during and after the tests. Measurements will include ice and snow thickness, salinity, density and temperature profiles. The automated tools will include six Ice Mass Balance buoys (for temperature profile and ice thickness) as well as tools for net radiation measurements and visual monitoring. For **WP6c**, determining how the thickened ice arch postpones its break-up is the key outcome.

Necessary permits will be obtained annually, including the required environmental impact assessments, to ensure up-to-date detailed plans are shared with relevant national, regional, and local institutions. Permissions have already been granted for the 2024/25 winter season in Cambridge Bay, which will offer a useful baseline for the subsequent winter seasons. In the other regions, contacts have been made, and the permit process has been initiated. To ensure a model of shared ownership with the local community, we will conduct community engagement activities that prioritise transparency, safety, and collaboration throughout the project. These will include outreach initiatives with Indigenous organisations, workshops, seminars, engineering demonstrations, and participation in community events.

We are committed to actively involving local representatives by offering roles such as guides, polar bear guard, and ice-thickening operators, to foster local employment and engagement throughout the project. For the ice arch strengthening work, a community outreach programme will be conducted in two phases, separate from field testing. This will help us understand the importance of ice arches, like those in the Nares Strait, to local communities and gather their perspectives on the advantages and risks to ice arch strengthening. In the first phase, we will build on initial contacts and conduct local interviews to build relationships and understand local concerns. In the second phase, we will implement a more extensive engagement programme. During this phase, we will also subcontract an ecological (desk based) research study to better understand the positive and negative effects of ice arch strengthening. The travel budget proposed for the project will support not only the team members conducting the experiments but also the visits and time spent developing and maintaining relationships with the local communities.

Milestone/funding stage-gate(M6) – Permits & local support obtained in each location for 2025/26 winter
Milestone/funding stage-gate (M18) – No barriers identified in previous winter, and permits & local support obtained in each location for 2026/27 winter

WP7 - Engineering Development: In parallel to **WP6**, engineering work will be undertaken by **Real Ice** and **Arctic Reflections**. They will investigate two different technological approaches and their potential for scaling up ice thickening to areas of approximately 1 million square kilometers. The technological approaches will build on a base of existing technologies, such as ice roads, but will differ from other commercial or emerging technologies due to the unique logistical challenges of the Arctic region, and the need to scale across a large area. Additionally, some components in standard designs will need to be modified to withstand the harsher conditions of the Arctic. Real Ice (**WP7a**) will focus on developing methods using a distributed solution which moves under the ice with underwater drones that automatically performs ice thickening operations. In Year 1 they will develop individual drone functions (such as underwater locomotion, ice perforation, and water pumping) and test these in the laboratory. In Years 2 and 3, up to four drones will be deployed in the Arctic to test scalability and robustness in real-world conditions. These tests will showcase increasingly sophisticated communication, navigation, and collaboration features, enabling the drones to autonomously perform ice thickening operations over larger areas. The drone prototypes will be developed in collaboration with **The Interdisciplinary Center on Sustainability and Climate**. Arctic Reflections (**WP7b**) will focus on developing methods to distribute water across a larger area of ice from larger pumping sites using higher flow rate pumps. They will also develop a method to move these simple, floatable pumping platforms safely and autonomously over the ice. Initially, movement will be achieved with amphibious vehicles. In subsequent years, a semi-autonomous hub & spoke model will be developed, with a centralised, sustainable energy supply hub, supporting and powering multiple mobile pumping platforms around it. Real Ice and Arctic Reflections will liaise with local

communities and institutions to gather views on the different approaches and obtain guidance on potential business and deployment models that would be of interest or acceptable. By pursuing two strategies within this work package, the chances of successfully validating the feasibility of scaling up within the project timeframe are materially improved. This work will be informed by the experience gained from the field experiments (**WP6**).
*Milestone/funding stagegate (M12) – Successful completion of design, delivery and testing/operation of first underwater drone before funding for manufacture of subsequent test drones (**WP7a**)*
*Milestone/deliverable (M36) – Successful design, manufacturing and operational test in Arctic conditions of the hub & spoke model, and a full feasibility study detailing a realistic pathway to scaleup, including the relevant operational parameters and required number of units for the ultimate ambition (**WP7b**)*

WP8 - **Project Management, Coordination and Synthesis:** This project involves a number of teams in different locations. Project management and coordination of the project activities and deliverables across the different work packages will be led by [redacted] One of the more challenging aspects of the project will be the fieldwork. Consequently, Real Ice and Arctic Reflections will meet regularly with [redacted] to review progress and proactively identify potential challenges before they arise, ensuring they can be effectively mitigated. The Advisory Group, already part established by the Centre for Climate Repair, will have regular meetings with the fieldwork teams to provide oversight and guidance. All team members will coordinate and agree on the broader engagement and communication of the project and its results. We will hold annual all-team in-person workshops in addition to regular project control meetings.
Milestone/deliverable (M3, M15, M27) – In person meetings of the whole team

3. Technical and non-technical risks/unknowns, and mitigations

The risks and mitigations noted below are key dependencies for the work packages.

1. Pumping of sea water onto sea ice doesn't lead to net increased thickness of ice. To mitigate, pumping will only be undertaken when air temperatures are sufficiently low and experiments will be monitored in real-time to ascertain growth or reduction during both freezing and melting seasons. The rate of pumping and timescales of relaxation in pumping activity will be factors investigated in order to ensure overall ice growth. The Team already has first-hand experience in successfully conducting ice-thickening experiments on Arctic ice, which were conducted in Nome (Alaska) in winter 2022/23 and in Cambridge Bay (Nunavut) and Svalbard in winter 2023/24 led by Real Ice and Arctic Reflections. Initial observations indicate increased thickness on the surface. However, overall *net* ice growth over the winter (especially in presence of snow) is not yet fully validated and quantified.
2. Artificially introducing material to the surface of existing sea ice could change the ecological and chemical environment of the surface, affect biogeochemistry, and impact carbon pump. Increase in ice thickness could also reduce the amount of sunlight that reaches the base of the ice thereby causing reduction in growth of microalgae. We will only utilise natural materials (seawater) present in the area to thicken the ice, significantly reducing environmental risks. We will collaborate with [redacted] regarding possible ecological and biogeochemical impacts of introducing new material to the ice surface and how timing, pumping rate and depth from which water is pumped could be designed to minimise risk. Ice will likely only be thickened by max 30% and any effect will last less than a season.
3. Export of ice is diverted rather than reduced through increased strength of ice arches. The impact of strengthened ice arches on the ice extent north of the Nares Strait will be a key aspect being investigated by the modelling work. During our field work, experiments will be focused to limited areas in a much narrower inlet or strait. The risk from our experimental intervention will be minimal.
4. Technical challenges within a given location, unfavourable weather, and a local authority might decide not to support field work in a given winter. The team is going to use multiple locations for the field work. These are supported by national technical and scientific bases and this will reduce the risks of technical, meteorological and logistical problems. We will incorporate time contingency into field work to help alleviate any issues arising from hold-ups. The use of locations in different regions also reduces the risk of societal challenges preventing any field work.

5. Local communities not supporting execution of field work in areas they own and control. The teams already have established ongoing relationships with the communities at the sites selected, which greatly helps increase the support for the work – one of the Real Ice team is now living in Northern Canada to aid with relationship building and planning. There is a formal permitting process which has been followed in the past and will be used in the future, to ensure work commences with local communities approval. These steps are to minimise the legal, regulatory and ethical risks associated with the field experiments. The project team already has an Ethics and Governance Advisory Group (see climaterepair.cam.ac.uk) including some indigenous people and social science experts to help guide the team in its work. We plan to expand this depending on advice from the current Advisory Group. Finally, we will continue to invest in community engagement, and also liaise with the ARIA team to coordinate with other funded projects.
6. Health/safety risks in the field (accidents due to extreme weather, wildlife, ice breakup, etc.). Prior to any staff working overseas, the project leadership will ensure staff have the following: have completed the appropriate training for the work they are undertaking; have all necessary PPE, H&S equipment; completed the appropriate risk assessments and methods statements to carry out their projects; health care assessment; any necessary vaccinations and/or medications; have met all institution/University travel office requirements (particularly regarding Covid-19, visa's and insurance).
7. Technology for Re-thickening Arctic Sea Ice found not to be scalable. Different technologies for re-thickening Arctic Sea Ice will be developed in parallel (see **WP7**).

4. The Team: The Team possesses a vast breadth of relevant knowledge and experience, with scientific discussions and collaborations among members having existed for a substantial length of time. All team members are passionate about *Re-thickening Arctic Sea Ice* and highly driven by the potential impact this project could have on mitigating the significant loss of sea ice coverage in the Arctic Ocean[2,3] . While most of the work will be UK-based, the team's international composition provides a valuable skill set. Its diversity allows for the inclusion of geographically varied perspectives, better reflecting the global nature of finding cutting-edge solutions to the climate problem. Further members and advisors will be continually sought to optimise the project's progress. Project lead [redacted] and deputy lead [redacted] are committing 40% of their time to the project. Key team members from Real Ice and Arctic Reflections are providing 100% of their time to the field trial aspects of the project. All postdoctoral researchers and PhD students involved are 100% allocated to this. Other university Co-Investigators will be providing between 5% and 15% commitment to the project.

[redacted]

[redacted]

(i) The Interdisciplinary Center on Sustainability and Climate: The group at Sant'Anna School of Advanced Studies has expertise in biorobotics and bionics, including the development of autonomous underwater systems, as well as smart systems inspired by the living world, and focuses its research in innovative solutions to issues related to sustainability and climate change. https://www.santannapisa.it/en/institute/biorobotics.

[redacted]

5. Conclusion This project proposal presents a now-or-never opportunity to help alleviate climate change. It provides the vital step towards determining the feasibility of large-scale sea ice re-thickening, offering a potential targeted, high-impact, low-risk climate intervention. We will address fundamental scientific questions, establish essential partnerships with local communities, and test innovative engineering technologies for re-thickening Arctic sea ice. Our fieldwork will be conducted in a small-scale, reversible manner, and will mimic existing natural processes, adhering to ARIA's oversight and governance principles. Depending on the success of the field, laboratory experiments, and modelling, the project aims to position the teams for scaling up seawater pumping for re-thickening of the Arctic's sea ice. This will include development of respective business plans, and raising of funds to make deployment a reality.

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StratoGuard - Global Monitoring of Geoengineering using Micro High-Altitude Balloons.

What do we want to do? Ultra-persistent, solar powered, micro-High-Altitude Balloons (mHABs), stationed primarily in the stratosphere, present a scientific and technological breakthrough in monitoring climate cooling mechanisms, over large scales, at high resolution and for long durations, whilst offering an extremely low regulatory barrier to world-wide operation and adoption. Many potential climate cooling technologies, such as stratospheric aerosols injection or marine cloud brightening, have a poor network of monitoring solutions; satellites lack the spatial, vertical and temporal resolution (e.g. estimations of SO_2 in the stratosphere have a resolution of +/-2km and revisit time of 2 per day[1]) to adequately measure the impact of any small-scale interventions in remote equatorial regions where interventions will likely be deployed[2]. Large scale measurements of stratospheric composition using the NASA ER-2 are extremely expensive ($3500/h)[3] and impractical over remote regions. Without a better baseline monitoring system, any active cooling interventions would have to be large scale, politically contentious and potentially risky[4] before their effects could be detected using current sensing systems.

[redacted]

Voltitude would like to use existing and intermittently occurring phenomena, such as volcanic activity, aircraft contrails, marine traffic, pollution and meteorological events (such as Saharan dust clouds) as pseudo sources of climate cooling technologies, as an ethically sensible stepping stone to future wider scale demonstrations of similar technologies, without meeting the same fate as other climate intervention programmes[5]. We cannot deploy geoengineering techniques until we can adequately monitor and model their effectiveness. There are already anthropometric and naturally occurring activities that alter the radiation flux of the world; volcanic activity[6] can present a similar cooling effect to a stratospheric veil and releases the same sulphur dioxide and potential subsequent damage to ozone. Equally marine and aviation traffic has been shown to affect the formation of clouds[7] to a similar effect as would be instigated by marine cloud brightening[8]. Monitoring of these effects in the short term allows development of technology while meeting the requirements for outside experiments as detailed in the thesis.

Voltitude would like to develop a novel low cost, light weight category (<4kg under the balloon), long endurance micro (<5m diameter) super pressure high altitude balloon capable of navigating for up to 30 days over an altitude range of 55-75kft. The ***Super-Pressure (SP) mHAB platform*** is presented in Figure 1 and Figure 2 alongside our existing Zero Pressure (ZP) mHAB. The platform will be capable of carrying a wide range of remote sensing, in-situ and dispensable payloads in the sub 2kg SWaP range. This project will deploy the University of Hertfordshire's Universal Cloud and Aerosol Sounding System (UCASS)[9] for in-situ measurement of aerosols targeting the Junge Layer (Stratospheric Aerosol Layer)[10] and Voltitude will combine our micro dropsonde with the UoH micro-optical particle sensor to produce a full column data of aerosols all the way to sea level, all in remote regions inaccessible to current sensing systems. Voltitude has also had extensive discussions with the proposed project 'INPUT:ACCESS' team, an airborne particle collector and research ARIA proposal by NOAA Chemical Sciences Laboratory. This is the same research team coordinating the Balloon Baseline Stratospheric Aerosol Profiles (B^2SAP) project, which is NOAA's

‘Earth’s radiation budget initiative’ project. The B^2SAP project uses other payloads which, if combined with Voltitude’s long endurance SP mHAB, could offer new research opportunities by collecting observation data from regions they cannot currently access on their existing B^2SAP short duration balloon systems. These include variants of the B^2SAP Frost Point Hygrometer (FPH) water vapour; Electrochemical Concentration Cell (ECC) ozone; and Portable Optical Particle Spectrometer (POPS) payloads.

The SP mHAB, combined with our current 5-day endurance ZP mHAB (a type of latex balloon), enables a low cost mHAB network of sensing platforms, offering a range of endurances and profiling capabilities. For example, our ZP mHAB latex balloon can drift at constant height to remote regions before profiling to sea level, over durations <5days, and our SP mHAB will be able to profile the stratosphere and dispense micro sensors before transiting back for recovery and reuse.

The proposed mission will be to launch from the UK during summer months and demonstrate navigation to the west coast of Africa using each navigation manoeuvre to profile the lower stratosphere with in-situ sensors, measuring aerosol concentration through the ‘Junge Layer’. Once over the region of interest, micro-optical particle sensors will be dispensed to profile the lower atmosphere and measure particulates entering the Atlantic from the Saharan dessert. This will be joined in the region by our short duration ZP mHAB system, which we operate out of Cabo Verde, to attempt aggressive profiling manoeuvres from high altitude to sea level, and back, using the ballast budget for profiling instead of navigation. This mission will demonstrate navigation to remote regions over long endurance while gathering stratospheric profile data from different volumes of air. The low-cost, long endurance mHAB system concept will unlock a ‘cube sat’ style capability in the stratosphere for the scientific community, using networks of mHABs which can be readily deployed from the UK for various measurements of geoengineering. We believe this could also act as a global warning system to detect and highlight rogue scenarios[11] from other countries – hence ‘StratoGaurd’.

Why is it important? The world is striving towards net zero, however current forecasts by the IPCC[12], make grim reading. 1.1°C of global temperature rise has already occurred, with climate effects directly attributed to this change. Limiting global increases to 1.5°C is possible, however an overshoot is likely which will still impact the climate in ways that may be irreversible including activating climate tipping points. As we become more aware of predicting these events, it is inevitable that an engineering solution may be grasped if these limits are exceeded, and climate change begins to affect the global order. The question is whether that reaction be last minute and ‘knee jerk’ (as is likely once political realities are applied) or should society prepare for this eventuality, if it is needed. The most credible, both in terms of technical feasibility, political ability, and implementable in a time span to be effective, will be a form of aerosol injection into the tropical tropopause[13]. It is vitally important that were this scenario[14] to play out an adequate method of monitoring the effects and measuring impacts relative to long term fiducial reference measurements[15] would be needed. mHABs are

Figure 3: Example heavy category HAB, after launch (left), fully inflated in the stratosphere (middle), and example station-keeping performance over many days (right).

the only solution that can be implemented within the current International Civil Aviation Organization (ICAO) regulations, and allow global reach at low through-life cost.

Balloon Technology Background: With advancements in the miniaturisation of electronics and improvements in electrical power efficiency, for many missions, there now exist lightweight payloads which do not require the lift capability of heavy category balloons, for example the Aerostar Thunderhead system in Figure 3 and Figure 6. Large HABs can offer extreme endurance, > 200 days has been demonstrated. Modern SP balloons have fine altitude control by pumping air into a ballonet, permitting the selection of specific wind layers to drift in. By changing altitude to hunt for desired wind drift directions, they can achieve accurate station keeping through an integrated drift vector which aims to remain below a desired station keeping radius. Common types of balloon systems and how they work are presented in Figure 4. This project will complete development of a small variant of a SP mHAB system which can mimic the amazing navigation and endurance capability of much larger, heavy category, SP HAB systems, and achieve through life cost 100x lower. SP mHAB have fine altitude control, accurate navigation and extremely long endurance. However, their dynamic range in altitude is limited to about 20kft in the stratosphere, i.e. 65kft ±10kft. ZP balloons offer multi-day endurance – these systems have more coarse altitude control and navigation is not as accurate, but they display extremely large dynamic range in altitude. Project StratoGuard will use a complementary network of SP and ZP mHAB to profile both the entire troposphere and lower stratosphere over remote regions using OPCs and dropsonde sensors. This will be in support of demonstrating climate cooling technology and monitoring methods, including the impact of stratospheric veils and marine cloud brightening.

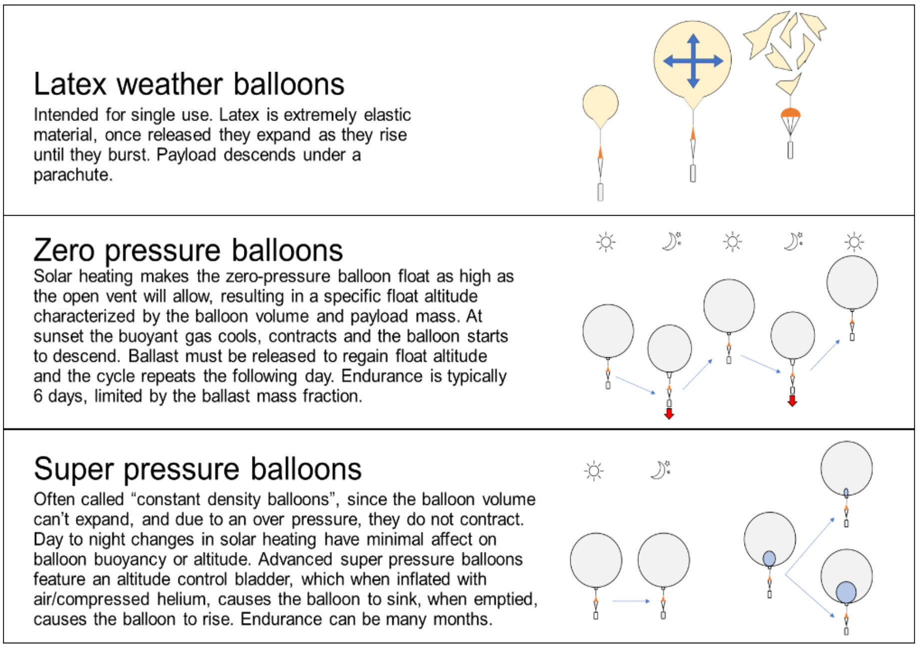

Figure 4: Common types of balloons and how they work.

Navigation and In-Situ Profiling

Balloons that can navigate between 55-75kft are able to access a diversity of wind tracks to allow year-round navigation in equatorial regions, with similar results over higher latitudes in summer months. This allows navigation to extreme remote areas, such as launching in the UK to transit to the west coast of Africa. Altitude changes require energy and in the case of a zero-pressure balloon this means using ballast or venting gas. As these are finite resources this limits endurance on top of the daily heating / cooling cycle so a choice must be made between endurance and profiling / navigation. The balloon navigation concept is presented in Figure

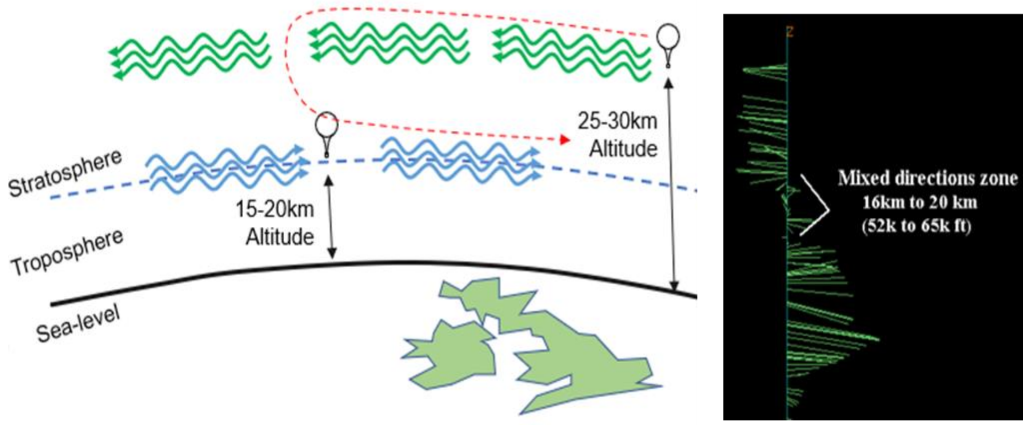

Figure 5: Navigation concept, in the light and variable winds of the lower stratosphere, just above the tropopause, a diversity of wind headings that rapidly change with small changes in altitude, can be selected by altitude controlling balloons to control drift direction and provide navigation.

Changing altitude ensures that balloon-borne in-situ sensors measure different air masses and move to new regions and new airmass.

Figure 6: Google Loon (note the internal ballonet)

Why hasn't it been done yet? High altitude long endurance navigable super pressure balloons are not new technology; however, the system trade space analysis shows that larger balloons are 'easier' to design, requiring lower material specification and battery/solar array performance while maximising payload mass fraction. The negative is that the envelopes become increasingly complex and expensive. These large balloons are produced on 100ft+ tables with intricate gore designs and quality control processes to maintain sufficient pressure without leaks to overcome the day to nighttime cooling without losing volume and descending (hence 'super pressure'). The Google Loon[16] project (Figure 6) successfully deployed a fleet of these balloons in equatorial regions with endurances above 250 days, with payload capacities of 25kg. [redacted] Ultimately it was not commercially viable, and these systems now live on only in a military capacity[17] as the Aerostar Thunderhead system.

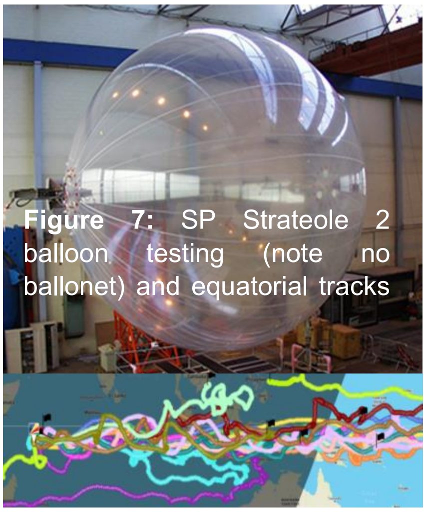

Figure 7: SP Strateole 2 balloon testing (note no ballonet) and equatorial tracks

Other scientific projects such as Strateole 2 have been extremely successful in deploying heavy category constant height super pressure balloons around the equator. These balloons, while successful, can only stay at a constant height. Not only does this mean sampling the same air mass over and over again with in-situ sensors, but there is no ability to move to new altitudes or control locations of overflight. They are also made with high performance biaxially tensioned materials (the skin takes the hoop stress directly as a monocoque as per Figure 7) and require a very high-quality threshold, a small defect will lead to an explosive failure. In contrast, a Google Loon balloon in Figure 6, uses a more puncture-resistant polyethene with shaped 'gores' where defects manifest as slow leaks rather than explosive failure.

All long-duration SP balloons are typically 'heavy category' (>6kg payload) and as such follow a much more stringent approval system, requiring authorisation from each country to enter its airspace. Conversely a light category balloon (<4kg under the envelope) used exclusively for meteorology is authorised to cross state boundaries[18] without prior approval other than the launch state (as per a normal radiosonde launch). Up until now it has not been possible to produce a small super pressure navigable balloon which meets this regulatory category. [redacted] No one has tried to make such a small navigable super pressure balloon. There are challenges in realising long endurance self-navigating mHAB within the light regulatory category. The opportunity is a low-cost system which can operate globally, without barriers. A global network would help accurately calibrate prediction models, and better understand the consequences using naturally occurring events[19], opening the door to large scale interventions with much higher confidence levels and provide UK institutions with an unprecedented data set and capability for further modelling. Furthermore, mHAB are more sustainable than heavy category HAB, and accurate navigation presents opportunities for recovery for responsible disposal of balloon envelop and payload reuse.

[redacted]

Envelope: Optimal mHAB envelope performance is the primary risk. Polythene envelopes used for zero-pressure mHABs are readily available at low-cost but cannot maintain any overpressure. This is traditionally overcome (as in the case of Google Loon) via a complex gore pattern and load wires to reduce hoop stress on the material and transfer it to the base. [redacted]

[redacted]

Effusion: Even ‘air-tight’ balloons lose gas through a process of effusion, compounded due to the small size of hydrogen molecules or helium atoms. In the stratosphere, effusion loss rate is slowed by extremely low ambient temperature, however, it is also proportional to the thickness of the skin material. There is a risk that the thin materials required to make an mHAB viable will not provide sufficient endurance due to the pressure being lost due to effusion. This is mitigated by early testing of candidate balloons and constant altitude flight testing in year 1. [redacted]

Micro-Compressor and Energy Budget: A compressor is required to fill the ballonets with air and allow multiple navigation manoeuvres or ‘profiles’ for in-situ measurements. Voltitude are experts in regenerative power systems having worked on the power systems for multiple high altitude solar powered aircraft and have extended this knowledge into high altitude ballooning to produce the highest energy density power system possible today. We have a longstanding relationship with [redacted] and the ability to manufacture our own custom battery packs within our facilities. A high energy power source still requires an optimised efficient compressor to work in the rarified air in the stratosphere. Voltitude has already prototyped and tested a micro-compressor candidate (Figure 9), although further optimisation is necessary. No commercial off the shelf compressor exists for this use case and at low enough SWaP.

[redacted]

Micro OPC: The micro OPC technology is the only candidate for including on a micro dropsonde. H[redacted].

StratoGuard Project Plan - All our projects follow project management best practice: we conduct weekly all staff stand up meetings, and each project has a bi-monthly progress review where sub-system managers and delivery channels are reviewed, with actions recorded and tracked and technical / commercial risk registers reviewed. When working with external collaborators our default is fortnightly progress reviews.
This way our collaborators are involved, informed, motivated and have strong influential voices into our projects.

The proposed 24-month project plan supports rapid prototyping and integration efforts to take advantage of early summer flight testing, all within the first 9 months of the project. This will support and inform a design optimisation process which will culminate in a demonstration in the second summer flight testing window. The summary project plan (Figure 10) highlights the modular programme with measurable key milestones.

This plan is reflected in a detailed task/resource breakdown under each work package with key interdependencies fully defined. Critical to each year within the programme is following a system engineering "V-cycle" approach to manage the design life cycle, leading to a yearly field trial campaign of the technical activities and allow the programme to pivot as the ARIA opportunity space develops. This approach allows balloon flights to be exploited in other projects, permitting flexibility in mission requirements and can accommodate alternative payloads from sister programmes. Management of technical risk is through early rapid prototyping and real-world test and evaluation, including stratospheric flights on pre-existing high-altitude balloons to inform decisions at engineering gate reviews.

[redacted]

The project is delivered through the following work packages:

WP1 Project / Engineering Management led by [redacted]
WP2 Field Trials, Logistics and Data Dissemination led by [redacted]
WP3 Platform Development led by [redacted]
WP4 Payload(s) Development and Integration (New Hire supported [redacted])

<u>Year 1:</u> Aim to demonstrate a long duration super-pressure envelope, perform atmospheric profiling mission with in-situ mHAB mounted sensor and qualify sub-systems.

Managed through WP1, early system requirements review, and preliminary design review will establish the specifications and configurations to be tested in this year's field trials. The specifications will come out of the SP mHAB optimisation [redacted] in WP3, culminating in MS1. After completing ground testing to the full over-pressure requirement, MS2, and after a critical design review, flight prototypes of the [redacted] balloon envelope will be manufactured and prepared for flight testing the in the stratosphere from Cabo Verde (CV), MS4. The Y1 flight tests, coordinated though WP2, will be without ballonet and compressor. These sub-systems will continue to be developed and optimised and undergo qualification testing in vacuum chambers, MS5, in preparation for integration with the [redacted] envelope in Y2.

In parallel to the SP mHAB envelope and sub-systems testing, WP4 focuses on integration of the in-situ OPC sensor for mounting on Voltitude's standard latex StratoSonde balloons. This will permit early testing and calibration of the OPC over the range of ascent and descent speeds expected of ZP mHAB performing full profiles of the entire troposphere and lower stratosphere. WP4 will also perform design, prototyping and ground-based calibration testing of the micro-OPC for integration with Voltitude's micro-dropsonde, this will be started in Y1 and include iterative optimisation of the [redacted] in preparation for constructing flight test prototypes in Y2. WP4 will also evaluate the feasibility of integrating other ARIA programme payloads from different projects ready for flight-testing in Y2.

<u>Year 2:</u> Aim to demonstrate a long duration navigable super pressure mHAB envelope, featuring ballonet and demonstrate novel micro-OPC dropsonde and support flights of other ARIA payloads

The Y2 cycle starts with a re-review of system requirements and design reviews to establish inclusion of lessons learnt and design improvements from Y1 into the configuration and specifications to be tested in Y2 field trials. This will include critical design review of the integration of the ballonet and micro-compressor into the [redacted] envelope, prior to assembly of a complete system prototype with OPC payload and dropsondes for the system's qualification test flight from the UK, MS6. This flight will attempt to navigate from the UK to CV, supporting a payload of balloon-mounted in-situ OPC and standard dropsondes.

Integration of the micro-OPC into dropsondes will continue under WP4 and will feature repeat real-world tests from standard latex StratoSonde systems over the UK, MS7, with validation data collected using the balloon-mounted OPC sensor for comparison. WP4 will also complete the integration of other ARIA programme payloads and ensure these are ready for field trials from CV under WP2, culminating in micro-OPC dropsonde and balloon mounted in-situ OPC comparison test flights from CV over the tropical Atlantic, MS8. The end of Y2 should have completed flight test qualification of the SP mHAB system including evaluation of its in-situ balloon-mounted OPC and micro-OPC dropsondes, with comparison test profiles provided by OPC sensors mounted on latex StratoSonde balloon systems. The legacy of project StratoGuard will be to have demonstrated the services available to other research projects of using low-cost SP and ZP mHAB systems in support of climate cooling experiments through the publication and sharing of the analysis and OPC sensor data in the project final report MS9. This might include the flight testing of other ARIA programme payloads.

Why we are the right team: The team at Voltitude have an outstanding track record for innovation and delivery. We are the design team behind the amazing Zephyr solar electric stratospheric aircraft, which is owned and operated by Airbus AALTO. Voltitude is exclusively owned by its employees, and is managed by Paul Stevens, former Zephyr Head-of-Design, and Steve Tate, former Zephyr Architect. We are joined in Voltitude by our most trusted team of design engineers who collectively have over 120 years of HAPS design, manufacturing and operational experience. Formed during the pandemic, Voltitude has grown to 12 full-time members of staff with a turnover ~£1 million/yr. Voltitude has created an environment of innovation where we are tackling the challenges facing the stratospheric industry.

[redacted]

As a team we are all passionate about working to address climate change and finding ways that mHABs can be used for scientific missions. As part of this journey, we invented the StratoSonde® long endurance mHAB balloon and micro-dropsonde system to provide weather data over Atlantic hurricanes (Figure 11). [redacted] While we have the passion and drive of a startup, our team is experienced in managing complex projects and following industry best practices. We are a very experienced multi-disciplinary team covering all engineering competency areas with support from our key collaborators. Geoengineering is something that, in our view, will be inevitable within the coming decades. Our current passion was providing mitigation to the effects of climate change through better weather forecasting of extreme events; however, we are excited to be a potential cornerstone of deploying real intervention strategies and provide the monitoring assurance that it is being done ethically, scientifically and responsibly.

ARIA funding for project StratoGuard will be hugely impactful for Voltitude, allowing us to commit to an accelerated growth plan, focusing on opportunities to train new scientists and engineers in mHAB design. To achieve this, we are seeking to employ talented people of diverse backgrounds and at varying points in their careers, including continuing and extending our year-in-industry (YIN) student programmes. Our industry has a gross under-representation of women and people of diverse or minority backgrounds which we see reflected in the demographics of students and graduates applying to work with us. We currently fund 2x YIN students each year, boosting our workforce by 20% and providing early engagement of diverse talent as students complete their education. We regularly work and collaborate with research institutions, f[redacted] [redacted]. We are the innovative bridge to ensure silos are broken down to deliver exceptional in-field demonstrations.

Team Bios: Our key team members and collaborators are:

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Consultants (sub-contractors) within project StratoGuard:

NOAA Chemical Sciences Laboratory: Expertise in ice nucleation and cirrus modelling. We will consult with NOAA CSL to gather requirements for monitoring of the Junge Layer and will share all data.

U[redacted]

[redacted]

Aerostar International Inc, Manufacturer of balloon envelopes and operators of Thunderhead balloons (ex Google Loon team). Voltitude collaborates closely with Aerostar due to their position as the leader in long endurance balloon design and construction.

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Towards Robust and Unbiased Validation of SAI Simulations (TRUSS): Advancing Ensemble Calibration for Reliable Geoengineering Impact Analysis

SECTION 1: Programme and Technical

Programme Alignment

This project aligns with ARIA's *Exploring Climate Cooling* programme by addressing a critical gap in the validation of Stratospheric Aerosol Injection (SAI) ensemble simulations. Many existing studies focus on ensemble means but often overlook the variability and uncertainties inherent in the data—key factors for evaluating the robustness of SAI models, especially at regional scales. Our research addresses this by applying advanced calibration methods, including Bayesian and machine learning techniques, to enhance ensemble reliability. By reducing uncertainty and improving model accuracy, we aim to provide more precise climate projections and assessments of both regional and global geoengineering impacts.

This approach directly supports ARIA's objective of advancing the predictability and effectiveness of climate cooling technologies, contributing to more informed climate policies and practical geoengineering implementations. The benefits of this project extend beyond academic research: by producing calibrated and validated SAI ensemble outputs, we equip policymakers with tools to better evaluate the viability and risks of geoengineering strategies. Our methodology presents robust, uncertainty-aware climate impact projections that reduce the risk of overconfidence in model outputs, fostering more cautious and effective climate policy planning. Ultimately, this makes our research an invaluable asset for future climate policy and global response strategies.

Description of Research and Methodology

Our project seeks to address the critical challenge of improving the reliability and interpretability of Stratospheric Aerosol Injection (SAI) ensemble simulations. The research aligns with ARIA's objective of advancing innovative approaches to mitigate climate change by refining climate intervention models, specifically focusing on improving the accuracy of SAI simulations. The project aims to develop a robust validation framework for SAI simulations through advanced post-processing techniques such as Bayesian ensemble calibration and machine learning-based corrections. By enhancing the reliability of ensemble outputs from established simulations, the project contributes to more informed and accurate assessments of SAI's potential as a geoengineering solution.

Ensemble simulations, such as those produced by the ARISE[1] and GLENS[2] projects, are critical in understanding the potential outcomes of SAI interventions. These ensembles provide multiple climate model runs that attempt to capture the range of possible outcomes given uncertainties in initial conditions, better sampling the long-term changes in oceanic conditions to provide a better constraint over the forced signal by more easily separating it from natural climate variability, thereby making attribution easier. However, much of the current research has focused on ensemble means[3,4,5], potentially underestimating the variability and uncertainty inherent in the results. This can mask important differences between individual ensemble members, leading to overconfident predictions about the efficacy or risks associated with SAI, especially at the regional scale. By exploring the degree of agreement between ensemble members and calibrating these outputs, we aim to improve the reliability and robustness of conclusions drawn from SAI simulations. This approach will not only enhance the validation process but will also provide more accurate assessments of the localized and regional impacts of SAI interventions, as well as allowing for more robust analysis of other SAI simulations with smaller ensembles (such as those under the GeoMIP[6,7] project, which normally only have 1 or 2 model runs) where the variability is undersampled, and of potential future SAI ensembles that include Perturbed Physics Ensembles (PPEs).

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Supporting Data

We will utilize data from the ARISE and GLENS SAI simulations to support our research, with additional observational data from satellite and climate monitoring networks for validation purposes. Previous published studies have demonstrated the effectiveness of Bayesian post-processing and ensemble correction methods in improving the reliability of weather forecasts[8,9,10,11]. This evidence underlines the scientific foundation of our proposed approach and provides a strong basis for improving SAI ensemble simulation accuracy.

Risk Mitigation Strategies

<u>Technical Risks</u>
Cross-Validation and Sensitivity Testing: To address the risk of inconsistent or unreliable outputs, comprehensive cross-validation and sensitivity analyses will be conducted for all calibration models. These practices will ensure robustness and applicability across various scenarios and datasets, minimizing the potential for model failures or biases in the results.

<u>Non-Technical Risks</u>
Stakeholder Engagement and Communication: A proactive strategy will be employed to engage policymakers and relevant stakeholders, ensuring that research findings are communicated in a clear and transparent manner. This approach includes providing evidence-based explanations of scientific assumptions, potential limitations, and the broader implications of the research. These efforts aim to build trust and encourage the practical adoption of findings, facilitating informed decision-making.

Overview of the Proposed Activity

This project focuses on enhancing the reliability of SAI simulations by addressing variability and uncertainty within ensemble outputs. The main research objectives (ROs) are:

- **(RO1)** Quantify and reduce uncertainty in ensemble outputs from SAI simulations (e.g., ARISE, GLENS).
- **(RO2)** Develop advanced calibration techniques to improve the predictive power and reliability of ensemble simulations, making these techniques available for future ensembles.

- **(RO3)** Validate the developed calibration techniques by comparing calibrated outputs with observational data and alternative simulations.
- **(RO4)** Utilize calibrated ensemble outputs for regional and local SAI impact analysis, simplifying the process by enabling teams to focus on aggregated outputs and their variability.

These objectives are covered through the following work packages:

WP1: Uncertainty Quantification and Calibration (Addresses RO1 and RO2)

This work package focuses on quantifying and reducing uncertainty in SAI ensemble outputs and developing calibration methods. We will perform detailed statistical analyses to understand the variability among ensemble members and quantify the spread and agreement within large ensemble simulations. Moreover, we will create and apply advanced Bayesian calibration and machine learning-based methods to refine ensemble outputs. This step ensures that ensemble data more accurately reflects real-world climate variability and conditions. The deliverable for WP1 is the production of calibrated ensemble simulations output with quantified uncertainty and reduced bias, forming a reliable basis for validation and impact analysis.

WP2: Validation (Addresses RO3)

This package is dedicated to validating the accuracy and reliability of the calibration techniques developed in WP1. We will validate calibrated outputs using historical climate data to ensure models align with observed trends and frequency of extreme events, as well as test the robustness of calibration methods by comparing calibrated outputs with other SAI simulation datasets. Furthermore, we will conduct sensitivity tests to evaluate how reliable the calibration techniques are under various conditions. This working package targets outputs in the form of reliable and validated calibration methods supported by observational data comparisons and sensitivity analyses. The deliverable for WP2 is a comprehensive publication detailing the reliability of pre- and post-calibration ensembles based on historical data.

WP3: Impact Analysis (Addresses RO4)

This work package focuses on using validated ensemble outputs for regional and local impact analysis. We will apply the calibrated ensemble data to understand potential future SAI impacts on specific regions (with a specific focus on Southeast Asia), identifying critical trends and outcomes relevant for policymaking and adaptation strategies. We will also assess and report on the variability within the calibrated ensembles to simplify interpretation for stakeholders. The key deliverables for WP3 are a set of comprehensive regional impact assessments that include quantified variability and support informed decision-making. Furthermore, we will generate detailed reports that present findings clearly, providing actionable insights for policymakers and researchers.

Key Metrics

- *Ensemble Variability Analysis*: Quantification of the variability among ensemble members using statistical measures (e.g., variance, agreement metrics). *Success Metric*: Reduced variability in calibrated outputs.
- *Calibration Accuracy*: Enhancement in predictive accuracy post-calibration using Bayesian and machine learning techniques. *Success Metric*: Significant reduction in prediction error rates compared to uncalibrated models.
- *Validation and Testing*: Comparison of calibration outputs with observational datasets (e.g., temperature) and alternative SAI simulations. *Success Metric*: Demonstrated accuracy and reliability of calibrated outputs, supported by cross-validation results against real-world data.
- *SAI Impact Analysis*: Delivery of robust and reliable results assessing the effectiveness of SAI in moderating climate change impacts. *Success Metric*: Consistent and reliable findings regarding the efficacy of SAI interventions.

The results of our project will be made available publicly through the release of code and results through open-access platforms such as GitHub.

Estimated Timelines and Key Milestones

The project is set to run for 36 months to comprehensively address the outlined research questions. The key milestones and specific activities are detailed in Figure 2.

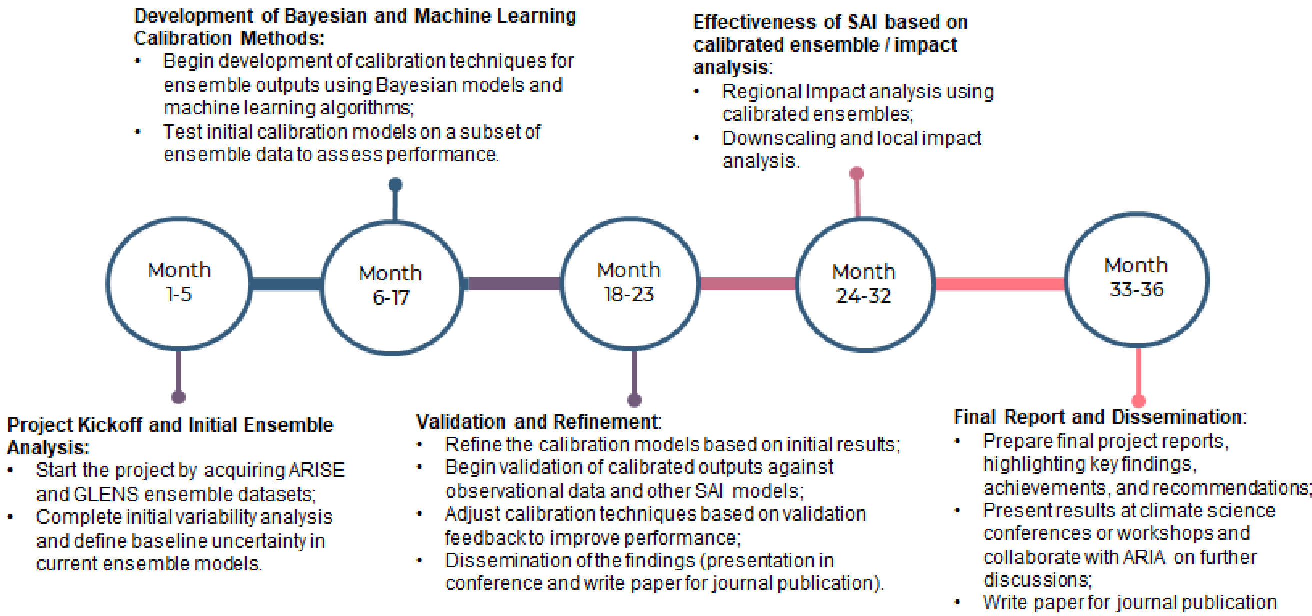

Figure 2. Estimated timelines and project milestone

Dependencies and Assumptions

The project relies on the availability of ensemble simulation data from the ARISE and GLENS projects. It is assumed that these datasets will remain accessible throughout the project timeline without significant delays in acquisition. This will be ensured by the project partners [redacted] who have reliable access to the datasets.
Successful execution of the project requires substantial computational resources to run machine learning and Bayesian models on large ensemble datasets, due to the complexity and scale of the analyses. Support from Institut Teknologi Sepuluh Nopember (ITS) has been secured, ensuring access to high-performance computing (HPC) facilities.

Mitigation Strategies

Recognizing the importance of uninterrupted data access and computational capacity, the team has developed proactive plans to address potential risks:

- *Early Data Acquisition*: Data collection will be prioritized at the project's outset to minimize any delays. Backup datasets from alternative climate data repositories will also be secured to mitigate potential disruptions.
- *HPC Resource Management*: Access to ITS's HPC facilities, including the NVIDIA DGX A100 system, will be organized with pre-planned usage schedules and contingency workflows. This approach will ensure continuous analysis, even in the event of unexpected challenges.

These measures are designed to safeguard the project's progress and maintain consistent analytical capabilities throughout the research period.

Ethical and Legal Compliance

This project adheres to all applicable legal frameworks and ethical standards for climate intervention research, ensuring transparency, safety, and global collaboration. The key aspects of our approach include:

1. Compliance with International and Domestic Laws:
   All research activities will comply with domestic regulations in the countries where data collection, analysis, or project activities occur. Specifically, we will ensure adherence to climate-related research policies, intellectual property laws, and data sharing agreements. The project respects international frameworks such as the Paris Agreement and UN Conventions on Climate Change, ensuring that the research aligns with globally accepted norms for climate intervention and geoengineering practices.
2. Data Use and Privacy:
   The project will utilize datasets from ARISE and GLENS, ensuring that access complies with licensing agreements and intellectual property rights. Data storage and processing will follow institutional policies for cybersecurity and privacy, safeguarding sensitive information.
3. Ethical Risk Assessment:
   The potential societal and ecological impacts of SAI simulations will be critically evaluated, with a focus on minimizing harm. For example, we will transparently communicate the scientific basis, assumptions, and limitations of the project to prevent misuse or misinterpretation of results.
4. Stakeholder Consultation and Public Engagement:
   The project will engage with policymakers, scientific communities, and relevant stakeholders to ensure alignment with societal values and needs. Open forums and workshops will be conducted to gather input and address concerns from the public and key decision-makers. Results, including negative findings, will be made available in an open-access format to foster transparency and informed debate.

Section 2. The team

The proposed project team brings together a multidisciplinary group of experts with deep experience in Stratospheric Aerosol Injection (SAI) simulations, ensemble calibration, and advanced statistical techniques, and computer science.

- [redacted]

[redacted]

Collaboration: Throughout the project, we will maintain active collaboration and discussions with leading scientists specializing in SRM experiments and ensemble calibration, particularly those cited in this proposal. This collaborative approach will ensure that our methodologies remain cutting-edge and aligned with the latest scientific advancements. We expect our results to be of great use for the validation of future ensembles, as well as downscaled products that might be produce in the next years.

Team Coordination: The project will use a collaborative platform to maintain regular communication among team members and ensure seamless integration of data analysis and model development. Regular bi-weekly meetings will be held to track progress, address challenges, and coordinate tasks. Collaborations with Exeter University and Cornell University will be managed through joint workshops and regular video conferencing.

Motivation and Suitability Our motivation stems from a collective commitment to advancing geoengineering research that accounts for both uncertainty and variability in model predictions. The team's combined expertise in geoengineering, machine learning, and statistical analysis positions them to tackle the unique challenges of SAI ensemble calibration. The PI's proven track record in handling large climate data sets and the collaborative experience of the team members ensures the project's success.

Section 3: Administrative Response

Regulatory, Legal, and Ethical Risks: The project involves handling large-scale climate data, which poses minimal regulatory risk. Data agreements will be secured to comply with privacy and data-sharing regulations. Ethical considerations include ensuring transparency in our calibration methods and results dissemination to policymakers and the public.

Intellectual Property (IP): The proposed methods will not depend on proprietary IP. Any developed tools or software will be shared as open-source to benefit the wider climate research community.

Budget: The project budget will cover personnel costs, HPC access, travel for conferences, and publication fees. A breakdown of costs includes:

- Personnel : PI, co-PI, postdoc, and research assistants.
- Materials : Laptops, cloud-based resources, etc.
- Equipment : Lab admin, maintenance, access to HPC, etc.
- Travel : Conferences and collaborative meetings.
- Others : Publication of paper in journals

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Global to Local Impacts of SRM Project (GLISP)

Advancing data accessibility and policy-relevant research

1. Programme and Technical

A. Concept

For the world to make evidence-based and equitable decisions about climate intervention, it must accelerate SRM (solar radiation modification) evaluation in the world's most climate vulnerable regions. Access to high-quality and relevant climate data is prerequisite for the evaluation of SRM and its impacts in the Global South. Data provision is currently underwritten by the goodwill and volunteerism of experts in the Global North, but this approach is reaching its limits. The proposed project would fill this gap by initially performing global statistical downscaling on relevant climate data sets and then creating an accessible data repository housed at the University of Cape Town (UCT). The repository of downscaled data would constitute a public good that would enable much more accessible SRM analysis across the Global South.

The proposed project would then demonstrate the potential of the repository and the downscaled data. It would convene a consortium of SRM experts from Asia, Africa, the Americas and Europe to conduct two global modelling pilot studies on a key global and regional climate impacts, with particular attention to potential regional tipping elements. Having single, authoritative, global studies on the impacts of SRM on key processes and sectors would be invaluable for developing the necessary evidence base to inform policy processes.

This project is proposed by a coalition that is uniquely capable of delivering such an ambitious programme of work. The Degrees Initiative (UK) has singularly transformed the global SRM research environment, and the Degrees Modelling Fund is the largest SRM research programme in the world, supporting 26 SRM research projects in 22 developing countries and emerging economies. Project data provision and downscaling would be managed by leading SRM scientists from the University of Cape Town (South Africa) and Cornell University (USA), and the data repository would be managed at the University of Cape Town, which is already well set up to do this.

B. Barriers, risks, and mitigation

Technical challenges in this project include building and supporting the required computational infrastructure. This requires (1) the computational hardware and related facilities and (2) software support for the storage architecture, modelling software and a user-friendly platform to make the data easily accessible. Both require engineers to support the data centre.

The existing infrastructure and expertise at the Climate Systems Analysis Group (CSAG) at UCT mitigates this challenge. Experienced software and hardware engineers already support a local data centre. Additionally, UCT has an efficient and user-friendly policy to accommodate additional data storage and provide access to the data downscale dataset.

A challenge in any modelling study is mitigating potential inaccuracies in the underlying climate models. Random biases, which often arise from the inherent unpredictability and complexity of the climate system, can vary from one simulation to another due to the sensitivity of the model to initial conditions and small perturbations. Systematic biases, typically due to the simplifications and assumptions made in the structure and parameterisations of Global Climate Models (GCMs), are consistent and repeatable errors that occur in the same way across multiple simulations. While random biases may not be removed by downscaling or bias correction, systematic bias can be reduced or removed using bias correction methods. To address this, we plan to include bias correction with our downscaling.

Non-technical challenges primarily revolve around the climate modelling and selection and validation of downscaling methods for climate data. Scientific decisions are needed to determine the most appropriate experiment design, including downscaling methods, especially for precipitation data, which will require validation using local observed data including rain gauge and satellite-derived data. Furthermore, the selection of specific agricultural and other impact models will require an understanding of available downscaled data and its temporal and spatial resolution. Although any advancement over current large-scale modelling will be beneficial, some variables, such as surface ozone and surface UV, might still rely on raw model output if challenges arise with downscaling these particular datasets.

To mitigate this, UCT has the capacity for both statistical and dynamical downscaling. Collaborations with the Coordinated Regional Downscaling Experiment (CORDEX), facilitated by [redacted] have connected the UCT team with a global network of downscaling experts.

It would be beneficial if the data repository remained accessible to researchers from the Global South following the three-year duration of this project. To facilitate this, Degrees will aim to explore external avenues for future funding from the 2nd year of the project onwards to help continue funding the post-doctoral researcher and the technical support expert costs at the University of Cape Town from year 4 onwards. Subsequently, most climate change modelling efforts would then transition to the CMIP7 cycle.

C. Proposed activity of work

We propose a project in three related work packages (WPs), all coordinated by the Degrees Initiative with partners from the USA and across the Global South. The first two WPs would conduct statistical downscaling and bias correction of key global SRM modelling datasets and create a repository for SRM research output. Together, these WPs would improve global access to regional-scale data, provide a foundation for modelling SRM impacts and reduce barriers to research, especially in the Global South. Scientists would be empowered to more easily and accurately understand how SRM might impact their regions which would act as an "output multiplier" for more and better SRM research around the world.

The third WP would convene a pair of global consortia of scientists for two studies modelling the effects of SRM on key policy-relevant climate impacts, such as health, agriculture or water availability, with additional attention to potential tipping elements. These would demonstrate the potential of downscaled data while producing new, policy-relevant science.

WP 1 – SRM information repository

We propose to create a repository of SRM research data and research output housed at the University of Cape Town and managed by a dedicated data technician. This repository will serve as an online, remote data analysis tool that does not require the user to download the data locally, e.g. a Jupyter Hub; a catalogue of all SRM research papers to provide access to a knowledge base often unavailable to researchers at institutions unable to pay article costs; and provide a structured platform to support the broader SRM community. Establishing the hub would represent a public good that acts as an "output multiplier" for SRM evaluation, enabling better and more accessible SRM research worldwide. One post-doctoral researcher will be employed at UCT over years 2 and 3 to support the creation of a repository of SRM research data, and to carry out the technical work in WP3.

WP 2 - Centralised global downscaling and bias correction

This work package will complete a statistical downscaling and bias correction of global climate data using a range of methodologies that have already been employed for future projections of climate change, and that will make the evaluation of the local impacts of SRM more reliable, robust and accessible in conjunction with WP1. The downscaling and bias correction methodologies include Ensemble Generalised Analog Regression Downscaling (En-GARD), bias-correction spatial disaggregation (BCSD, as used in the ISIMIP and NASA-NEX-GDDP-CMIP6 projects) and Multivariate Adapted Constructed Analogs (MACA). Most SD methods downscale only rainfall and temperature. However, this proposal will improve existing downscaled products, such as wind, humidity, and incoming solar radiation, which are required by many impact models, including those for agriculture, health, and renewable energy.

It will leverage current climate model outputs, including the new GeoMIP simulations, which are part of CMIP7 and the ARISE and GAUSS ensembles. The team will employ two post-doctoral researchers, one at UCT who will assist with the downscaling and the other at Cornell University to perform the downscaling based on GeoMIP data. Additionally, the project will provide funding for workshops to educate scientists about the use and limitations of downscaled outputs. The repository mentioned in WP1 will be used to share these outputs globally. The constant engagement with the Degrees Initiative's community will ensure that the downscaled and bias-corrected data can be validated in the regions that matter most, providing a "reality-check" that will allow for a robust, trustworthy product.

WP 3 - Global impacts studies

Degrees will convene a pair of global scientific consortia, each with members from Africa, Asia, and South and Central America to conduct two modelling studies on important impacts of global warming. Possible initial impact studies would include agriculture and food security, water security, extreme heat and heat exposure, health (climate-borne diseases and heat exposure) and biodiversity with additional attention to potential tipping elements. Such impact studies are reliant on downscaled and bias-corrected climate data, as opposed to the large-scale direct GCM output, to better capture the regionalised and local impacts of changes in temperature and hydrology that are context-dependent (i.e. they might depend on orography in a way that is not captured at the global scale), and therefore will greatly benefit from the output of WP2, which will provide a communal framework for worldwide impact assessments. These studies would represent a significant advancement in global SRM evaluation, offering an unprecedented level of granularity because of the downscaling and bias correction conducted in this project. The same post-doctoral researcher that was mentioned in WP1 will be employed at UCT to conduct the research for years 2 and 3 of the project, as the downscaled data will be produced during year 1. Having demonstrated what is possible and its impact on SRM evaluation, we would then seek further funding from other sources to continue studies on additional impacts. As such, any ARIA funding would leverage additional external funding.

D. Project timeline

Year 1 - Laying foundations and establishing infrastructure

1. Establish a data analysis hub at UCT/CSAG (Months 1 - 6)
    a. Procure computational hardware for the Climate Systems Analysis Group at the University of Cape Town.
    b. Install and configure hardware to create a high-performance hub for data analysis, processing and hosting.
    c. Recruit a qualified technician to support the CSAG analysis hub.
    d. Hire one post-doctoral research fellow specialising in statistical downscaling and data accessibility.
    e. Begin the downscaling and secure transfer of relevant datasets to UCT.
2. Begin statistical downscaling (Months 6 - 12):
    a. Complete statistical downscaling of relevant data sets.
    b. Testing and validation of initial results.

Year 2: Data processing and regional output development

1. Complete statistical downscaling (Months 1-4):
    a. Finalise downscaling of datasets and validate outputs for accuracy and reliability using bias-correction.
2. Enhance data accessibility (Months 1-12):
    a. Ensure the centre maintains high quality downscaled data for key regions including Southeast Asia, Latin America and the Caribbean, South Asia, and Africa.
    b. Ensuring the centre's data, including the research repository, is easily accessible.
3. Global pilot study (Months 1-12):
    a. Design and execute a pilot study focusing on a specific climate variable (e.g., precipitation trends or temperature variability) or sector (e.g. agriculture, health, water availability).
4. Create impact study repository (Months 6-12):
    a. Collect and curate 50 impact studies to begin building the SRM research repository.
5. Data access and usage analytics (Months 3-12):
    a. Establish tracking systems to monitor data access and usage.
6. Added value study (Months 6-12):
    a. Begin the analysis to quantify added value the downscaling brings over the raw GCM-scale data. Work closely with CORDEX in this study as they have similar questions.

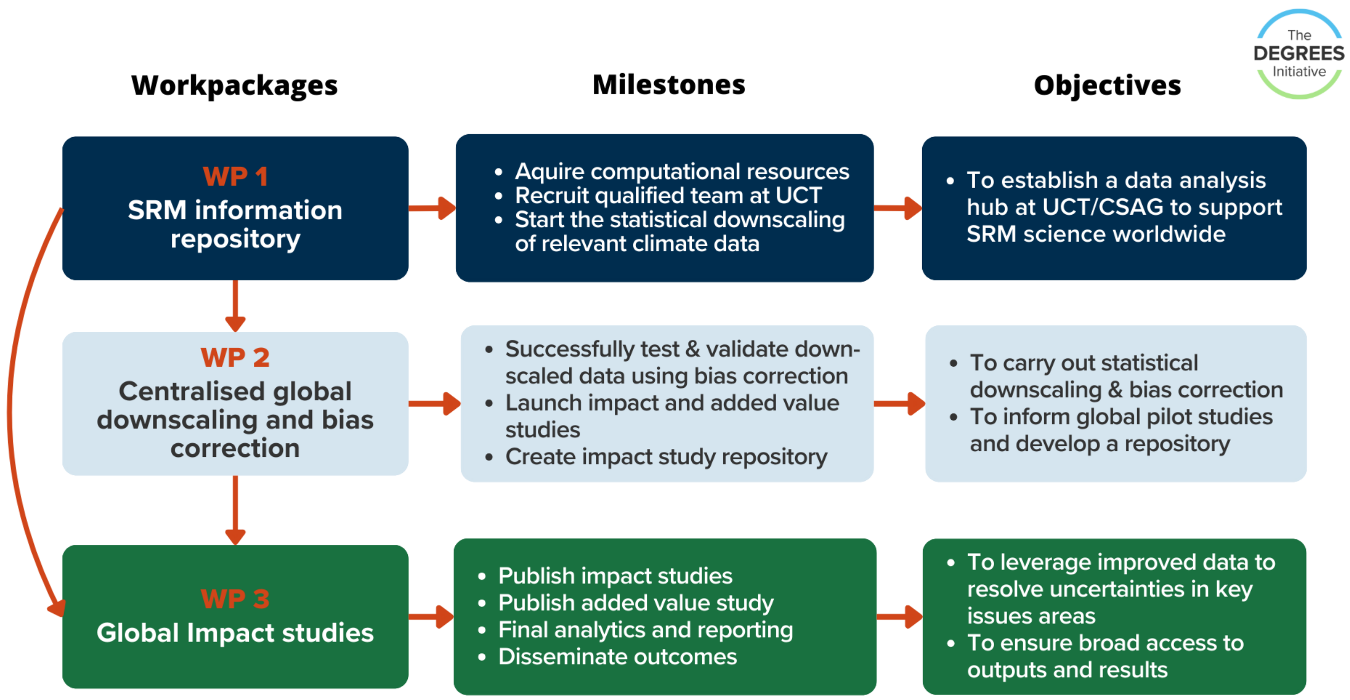
Year 3: Expansion, validation, and delivery

1. Maintain high-quality regional datasets (Months 1-12):
    a. Ensure datasets are continually updated, refined, and validated for priority regions.
    b. Collaborate with international partners to address emerging research needs.
2. Complete impact study repository (Months 1-8):

        a. Expand the repository to contain 100 rigorously reviewed impact studies, accessible via the research hub.
3. Complete global impact studies (Months 8-12):
    a. Complete analysis on chosen impact studies for write up in an international journal.
4. Complete added value study (Months 6-12):
    a. Complete analysis of added value for write up in an international journal.
5. Final analytics and reporting (Months 8-12):
    a. Analyse and report on data usage, identifying trends and areas for improvement.
    b. Develop a comprehensive project report summarising achievements, lessons learned, and recommendations for future initiatives.
6. Dissemination and stakeholder engagement (Months 6-12):
    a. Host workshops and webinars to share project findings and outputs.
    b. Engage with stakeholders to identify future collaborative opportunities and funding sources.

Metrics and milestones

Dependencies and milestones diagram



E. Regulatory, legal and ethical risks

To mitigate regulatory, legal, and ethical risks, we will adhere to the AGU (American Geophysical Union) Ethical Framework for Climate Intervention, ensuring that our practices align with the best available internationally recognised standards on SRM. These guidelines will serve as a benchmark for all our project activities, providing a clear framework for ethical conduct and decision-making.

To mitigate regulatory, legal, and ethical risks, UCT has several robust frameworks. These include obtaining legal certificates of compliance to ensure adherence to local and international regulations (https://uct.ac.za/about-uct-finance/compliance-certificates-and-bank-accounts). The Research Contracts and Innovation Department supports the navigation of legal complexities and securing necessary agreements and permissions (https://uct.ac.za/rci). Additionally, UCT's Office for Research Integrity oversees the ethical aspects of research, ensuring that all projects adhere to high ethical standards (https://uct.ac.za/research-support-hub/research-integrity).

2. The Team

F. The project team

[redacted]

Programme Director
[redacted]*, to be hired, 0.2 FTE*
Responsible for defining and shaping the overall project strategies, including establishing clear objectives, priorities, and deliverables that align with the overarching project plan. This role entails ensuring that the project vision is effectively translated into actionable plans and outcomes. Key responsibilities include overseeing the performance and progress of the staff scientist, providing guidance and support to ensure their work aligns with project goals, and serving as the primary point of coordination among various sub-contractors.

Staff Scientist - Project Manager
[redacted] *to be hired, 0.5 FTE*
The Staff Scientist will work closely with the Programmes Director to help deliver the project. Responsibilities include helping to coordinate the research between the universities, support the delivery of the workshops, as well as facilitating access to data and to cutting-edge techniques such as statistical downscaling.

[redacted]

Technical support expert - Information Repository Technician
[redacted] *to be hired, 1.0 FTE*
The Climate System Analysis Group at UCT has over the last 15 years built and administered a data centre, developing the expertise to support both the hardware and software components. However, this project will add an additional responsibility for the data centre with respect to technical support, particularly

in the hosting of a cloud-type environment for researchers to conduct analyses on the downscaled data, e.g. a Jupyter-hub. This requires access control and security, set up and administration of the hub environment, user support and developing online training materials on working on the hub. These responsibilities sit beyond those of the current technical support staff and would require a full-time technician able to support the new hardware and software infrastructure around the analysis hub environment.

Post-doctoral researchers - Downscaling Technicians

[redacted] *to be hired, 2.0 FTE*

Two post-doctoral researchers will be hired. One will be a 3-year hire to assist with the downscaling and bias correction in WP2 as well as address questions of added value. Added value could be assessed around climate metrics (e.g. extreme events), impact metrics (e.g. health, agriculture), tipping elements (e.g. West African Monsoon or glacier loss) or quantitative metrics (e.g. added value or fractional skill score metrics). The second post-doc will be a 2-year hire to conduct the global impact analysis of the downscaled data (WP3). This analysis will focus on impacts to various sectors and communities, for example agriculture, health, energy and water availability.

[redacted]

Post-doctoral researcher

[redacted] *to be hired, 1.0 FTE*

A post-doctoral associate will be hired for at least 2 years to perform the downscaling based on GeoMIP data, by firstly testing different downscaling and bias-correction methodologies for temperature and precipitation in collaboration with the other groups in the project and then performing and validating the downscaled data at the global scale.

Additional team members

The project suggests flexible work execution in two ways. First, contracting external support for downscaling may be beneficial. Project leads are currently discussing this with Carbon Plan, a US nonprofit providing climate data services.

Second, the selection of WP3 consortia members will depend on the chosen impacts. Where feasible, we will involve grantees and research collaborators from the Degrees Modelling Fund. They have expertise in with key climate impacts, including agriculture and food security, water security, extreme heat and heat exposure, health and biodiversity.

Potential members could include:

- [redacted].

G. Participating organisations

The Degrees Initiative

The Degrees Initiative is an NGO committed to placing the Global South at the centre of the conversation on Solar Radiation Modification (SRM). Our vision is a future where experts from every region of the Global South play a central role in SRM evaluation and governance. We work to transform the global landscape by building the capacity of developing countries through outreach workshops, research funding, and community-building activities that foster expertise and collaboration. Neutral on SRM, we focus on inclusiveness, academic excellence, and a commitment to mitigation, advocating for a more informed and equitable global dialogue on SRM.

Climate System Analysis Group, University of Cape Town

The Climate System Analysis Group is a climate research centre at the University of Cape Town. CSAG is a leading hub for climate research in Africa, with a strong emphasis on climate modelling and regional downscaling. It specialises in the development and application of advanced climate models to understand atmospheric, oceanic, and terrestrial processes. CSAG leverages state-of-the-art computational tools and datasets to generate high-resolution climate projections, which are critical for assessing climate variability and change at regional and local scales. CSAG is internationally recognised for its expertise in regional climate modelling and is involved in initiatives like CORDEX (Coordinated Regional Downscaling Experiment). Additionally, CSAG is concerned with generating robust, relevant regional climate change information while advancing understanding of the dynamics and processes driving the coupled climate system.

Cornell University

Cornell University is globally recognised for its research in climate science and expertise in climate modelling, downscaling, and SRM. With a robust track record of interdisciplinary research and innovation, Cornell combines advanced computational techniques with deep domain knowledge to address complex climate challenges. The university's researchers have pioneered scalable downscaling methods that bridge global models with local climate impacts, enabling actionable insights for policy and planning.

Additional organisations

As noted above, we will bring in additional organisations as appropriate into WP2 and especially WP3. Among these are Carbon Plan and the host institutions of the Degrees Modelling Fund grantees and research collaborators. This would demonstrate the value added of access to data, including downscaled, across the Global South.

H. Coordination and management

The Degrees Initiative would be the coordinator of the overall project, leveraging its extensive experience in transforming the global SRM research environment. UCT will lead WPs 1 and 2, focusing on the creation of an SRM information repository and the centralised global downscaling of climate data. The senior staff responsible for these efforts include [redacted] and the to be hired programme director at the Degrees Initiative, who will oversee the coordination between the participating organisations, and [redacted] and [redacted] who will lead the respective work packages. The leadership of WP3 will be determined later based on the topic chosen and the researchers recruited.

Additionally, we will coordinate with Degrees Modelling Fund teams, including those receiving funding through ARIA, to ensure they have access to the data and that we are informed of their research questions and requirements. For example, ARIA brought to our attention the concept note of [redacted] t[redacted], who proposes to research the impacts of SRM on the variability and dynamics of the West African Monsoon—precisely the sort of work that could benefit from the data that we wish to provide. Furthermore, this would provide the opportunity to compare dynamical and statistically downscaled data over the region, a task the UCT postdoctoral researcher could undertake.

I. Gaps in competency

The hiring of the data and analysis hub technician is crucial to the overall goals of the project. This skillset is not yet present at CSAG and would require a thorough hiring process including an interview and competence testing.

J. Motivation

This design of this proposal is informed by over a decade of engagement work on SRM in the Global South, plus extensive experience managing the Degrees Modelling Fund. It is shaped by the advice of Degrees' network of SRM experts in Global North and South in particular at a dedicated three-day convening at the Rockefeller Foundation Bellagio Center[i]. Last year, Degrees began a process of regionalisation, transferring coordination capacity to regional hubs across the Global South so that they can set their priorities and collaborate[ii][iii][iv]. These workshops brought together Degrees SRM modelling teams from across Africa, Southeast Asia and Latin America & the Caribbean to discuss what useful regional SRM research might look like in each context. At each of these meetings, scientists outlined key obstacles to advancing regional SRM research. Lack of access to data, and particularly downscaled local climate data, was one of the top concerns across the three meetings.

This view, shared by our network, is also echoed by cutting-edge scientific organisations. In 2021, a committee of the US National Academies called for, among other things, a system for data sharing and an international registry of SRM research[v]. Similarly, a committee formed by the UN Environment Programme (UNEP) recommended the promotion of reporting, transparency, inclusiveness and data-sharing[vi]. Finally, the leadership of the Geoengineering Model Intercomparison Project (GeoMIP) have regularly outlined the need for improved access to data for effective SRM impact modelling, particularly in the Global South[vii][viii].

3. Budget narrative

Degrees expects the 3-year proposal to cost £2,180,693 in line with the full cost summary template, including the ARIA calculation for indirect costs. As advised, with Degrees leading the bid, the costs for the University of Cape Town, Cornell University, and the costs for bringing in international expertise in workpackage 3 all constitute sub-contracted costs. Across each year the breakdown of costs is expected to be as follows:

Year 1	£694,523
Year 2	£863,835
Year 3	£622,335
TOTAL	£2,180,693

Given year 1 of the programme will commence with a significant outlay of hardware costs (£250,000) a prudent request would be for these committed costs to be repaid early in the project, or ideally in advance as it would significantly assist with cash flow. The situation will be similar for the hardware costs in year 2 (£100,000). The rest of the costs can be reimbursed through regular invoicing at the time period most convenient to ARIA. We have assumed quarterly stage gates in arrears for the rest of the costs. As such, the expected tranches of funding are as follows:

Initial payment	3 months	6 months	9 months	12 months	15 months	18 months	21 months	24 months	27 months	30 months	33 months	36 months	**TOTAL**
£ 250,000	£111,131	£111,131	£111,131	£211,131	£ 190,959	£190,959	£190,959	£190,959	£155,584	£155,584	£155,584	£155,584	**£2,180,693**

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[i] The Rockefeller Foundation, *Bellagio Center Opens Applications for 2025 Convenings,* https://www.rockefellerfoundation.org/insights/perspective/bellagio-center-opens-applications-for-2025-convenings/ [accessed 04 Oct 2024].

[ii] The Degrees Initiative, *Degrees holds workshop on regionalising SRM research in Southeast Asia,* https://www.degrees.ngo/degrees-holds-workshop-on-regionalising-srm-research-in-southeast-asia/ [accessed 04 Oct 2024].

[iii] The Degrees Initiative, *African scientists gather in Cape Town to develop collaborative SRM research*, https://www.degrees.ngo/african-scientists-gather-in-cape-town-to-develop-collaborative-srm-research/ [accessed 04 Oct 2024].

[iv] The Degrees Initiative, *Degrees holds research planning and regionalisation workshop in Latin America and the Caribbean,* https://www.degrees.ngo/degrees-holds-research-planning-and-regionalisation-workshop-in-lac/ [accessed 04 Oct 2024].

[v] NASEM. Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance. National Academies Press; 2021, pp. 174, 183.https://doi.org/10.17226/25762

[vi] United Nations Environment Programme (2023). p. 22 One Atmosphere: An independent expert review on Solar Radiation Modification research and deployment. Kenya, Nairobi.

[vii] Visioni, D., Robock, A., Haywood, J., Henry, M., & Wells, A. (2023). A New Era for the Geoengineering Model Intercomparison Project (GeoMIP). *Bulletin of the American Meteorological Society*, *104*(11), E1950-E1955. https://doi.org/10.1175/BAMS-D-23-0232.1

[viii] Visioni, D., Kravitz, B., Robock, A., Tilmes, S., Haywood, J. M., Boucher, O., & Muri, H. (2022). Opinion: The scientific and community-building roles of the Geoengineering Model Intercomparison Project (GeoMIP)-past, present, and future. *Atmospheric chemistry and physics Discussions*, *2022*, 1-44. https://doi.org/10.5194/acp-23-5149-2023

Eco-Gap: Ecological assessment of Geoengineering at the Poles

Section 1: Programme & Technical

1.1 Background & how this work is novel The use of geoengineering as a tool to actively cool the Earth is seen as a potential approach to "buy time" to allow for global decarbonisation. ***Eco-GAP will provide an assessment of the ecological impact of proposed polar geoengineering experiments using an independent, robustly empirical, risk assessment framework.*** There are several reviews on the potential efficacy of geoengineering interventions targeting, for example, solar[1,2], aerosol[3,4], and ice building[5,6]. There are also acknowledged challenges linked with the complex geopolitical issues associated with proposed interventions[7-9]. And, of course, concerns over the potential environmental impact on fragile polar ecosystems[10]. However, with perhaps the exception of iron-fertilisation[11,12], very few geoengineering concepts have included both modelling and experimental approaches to evaluate impacts and risks to the ecosystem; this is where Eco-GaP is unique and important. Additionally, recognising that the geoengineering space will likely continue to grow, Eco-GaP will develop an ecological risk assessment framework that can be utilised by funding bodies, governing bodies, environmental conservation organisations or geoengineering groups themselves to evaluate future proposed projects.

1.2 Objectives

Obj1. Design an Evaluation Framework (EF), with the necessary metrics, from which a robust and thorough assessment of potential ecological impacts due to geoengineering interventions can be established.

Obj2. Determine the physical changes that will occur in the ocean, sea-ice and atmosphere, and disentangle the geoengineering intervention impacts from the background and climate driven change.

Obj3. Using the outputs from Obj2; identify, test, model and predict shifts in biogeochemical parameters due to physical changes at both large and small spatiotemporal scales.

Obj4. Using outputs of Obj2 and Obj3; identify, test, model and predict shifts in the pelagic ecosystem due to physical and biogeochemical changes at both large and small spatiotemporal scales.

Obj5. Undertake a comprehensive Ecological Risk Assessment (ERA) of proposed geoengineering interventions to evaluate the scale, timeframe, scope and intensity of the potential ecological impact.

1.3 The challenges We aim to identify and assess the ecological impacts of the polar and marine related geoengineering interventions ARIA have selected for funding. This is a challenging task to fulfil: ideally, the parameters and interactions investigated would be well understood, constrained, and persist at a predictable steady state in polar ecosystems. In reality, many physical and ecosystem processes are not yet well observed or modelled, thus leading to major investigative programmes[13-17] and are in a state of stress and flux due to global climate change[18-21]. Consequently, identifying changes due exclusively to geoengineering interventions versus its confounding impact with global climate change, even at local scales, is complex. Thus, developing a holistic understanding of the ecological impact risk at multiple spatiotemporal scales and trophic levels is critical. We aim to elucidate and disentangle localised and global impacts of geoengineering interventions from climate change through highly advanced modelling and careful experimental design.

1.4 Project Management The project management structure of Eco-GaP is comparable to those utilised by similar-sized projects. This structure has proven to be effective in integrating scientific objectives with stakeholder involvement to produce results that break systemic barriers, enhance collaborations and interdisciplinary syntheses, and lead to high-profile publications and breakthroughs. It provides exceptional multi-sectoral penetration and decision-maker dialogue opportunities, and significant networking and training opportunities for Early Career Researchers (ECR). To promote equality, diversity and inclusion, Eco-Gap have united professionals from various sectors, backgrounds and stages of career development. Importantly, we have ECR representation at all levels of our project, including co-leadership roles for all WPs, and we strive for gender balance within the project. Project governance is based around a multi-layer, hierarchical, organisational structure, with clear responsibilities assigned to each layer. This robust management process achieves a seamless integration of the project's objectives along with enhanced dialogue – for project partners and stakeholders alike – with the expected transparency and equity. Scientific and managerial decision-making revolves around the Project Management Team (PMT), which consists of the Project Lead (A. Burson), WP co-leads, and the British Antarctic Survey's (BAS) in-house Research Development and Support Team (ReDs). Within ReDs, Eco-GaP will have a dedicated Project Manager who will assist in management tasks including keeping track of deliverables, milestones and maintenance of a risk register. The PMT will oversee communication with the collaborators, organise the annual project meetings as well as facilitate quarterly updates on project activities and deliverables, dissemination priorities, ethics, and other reporting requirements to ARIA. Additionally, Eco-GaP has dedicated resources with BAS's in-house communications team for support with project communications and outreach activities, including social media, website, and the stakeholder conference and summer school organisation. To ensure synergy between deliverables, WP and Task leads will organise team meetings as and when needed. Our annual project meetings (APM) will be in a hybrid format to ensure that all participants can equitably participate. In the spirit of inclusiveness, stakeholder groups and other ARIA projects will be invited to our APM.

1.5 Data Management Given the importance of our results to many stakeholder groups, the necessity for transparency, and the need for others to be able to replicate our findings, we will develop a comprehensive Data Management Plan (DMP) within the first 6 months of the project (WP5, M5.1). We have accounted for dedicated project time with the UK's Polar Data Centre (PDC), which will assist with DMP development. The DMP will ensure we adhere to international standards and best practices for collection, management, access and dissemination of our data. Data products generated will be publicly available in interoperable easy-to-access format. Data will be archived at the PDC (located at BAS) or Centre for Environmental Data Analysis (CEDA; for large volumes of model data, with archiving costs included), and there will be no limitations on sharing, reusing, or re-distributing our data products. A group workspace on the data analysis facility JASMIN will be used to share model data within Eco-GaP, and access will be granted to key outside collaborators. We abide by the TRUST (Transparency, Responsibility, User Focus, Sustainability, Technology), FAIR (findable, accessible, interoperable, and reusable) and CARE (collective benefit, authority to control, responsibility, and ethics) principles for data governance. To this end we will share modified model codes with public access coding platform GitHub.

1.6 Methodology and Work Package Description A diverse range of geoengineering interventions have been proposed as potential methods to mitigate climate change by cooling the Earth[22]. Polar regions have a disproportionate influence on the global climate[18], thus geoengineering projects there have the potential for far reaching impacts. It is important that effects and unintended consequences on the polar ecosystem (and particularly the polar marine ecosystem, where ARIA's proposed interventions are mainly based) are anticipated, understood, and quantified. We have designed five interdisciplinary, iterative, and self-reinforcing Work Packages (WP) with interlinked objectives, and milestones (see Fig. 1). At the top of Fig.1 sit the proposed geoengineering interventions. To constrain our empirical and modelling studies, we will first discuss with the ARIA-funded geoengineering teams the parameters of their proposed interventions in **WP1**. This is a critical step in ascertaining the necessary information to perform our assessment studies and develop a robust Evaluation Framework (EF) **(Obj1)**. During the development of the EF we will incorporate standard methodology for the development of monitoring systems for the marine environment by embracing best practice documents for evaluating Marine Protected Areas (MPAs), as well as international guidelines for biodiversity monitoring. Once a draft EF is completed it will be evaluated by an Independent Board of Advisors (IBoA) comprised of experts within key organisations (e.g. Scientific Committee on Antarctic Research, International Arctic Science Committee (IASC), Convention for the Conservation of Antarctic Marine Living Resources (CCMLAR), World Wide Fund for Nature) **(Obj1)**. Output of this evaluation will help facilitate WP1 in finalising the EF (WP1: dark blue box Fig 1.). The acceptance of the EF by key stakeholders, via WP5, is a crucial milestone for Eco-GaP, as well as for its use in the evaluation of future geoengineered interventions. The main programme of research is performed in WP2 to WP4, guided by the EF, which will quantify the ecological consequences of the proposed interventions in terms of physical, biogeochemical, and biological changes. **WP2** will assess physical changes in the environment caused by geoengineering interventions, directed by the EF. Within WP2, the physical changes will be contextualised from the perspective of the subsequent changes in the ocean, sea ice and atmospheric environs **(Obj2)**. The induced changes will be modelled at multiple scales, using several model platforms (e.g., UK Earth System Modelling (UKESM) at regional and fine scale modelling, ensembles, etc.). The outputs of this will be used to (i) direct the assessment of the associated changes in the biogeochemical environment and subsequently the biological response, (ii) provide physical and climatological impact risk information for the scientific synthesis report, and (iii) be an independent assessment of the efficacy of interventions, giving credence to our subsequent ecological assessments. **WP3** and **WP4** will respectively assess the biogeochemical and biological response of the projected physical changes predicted in WP2 models, both *experimentally,* using sea ice-growth tanks and controlled chemostat culturing facilities and *theoretically* using biogeochemical and pelagic ecosystem

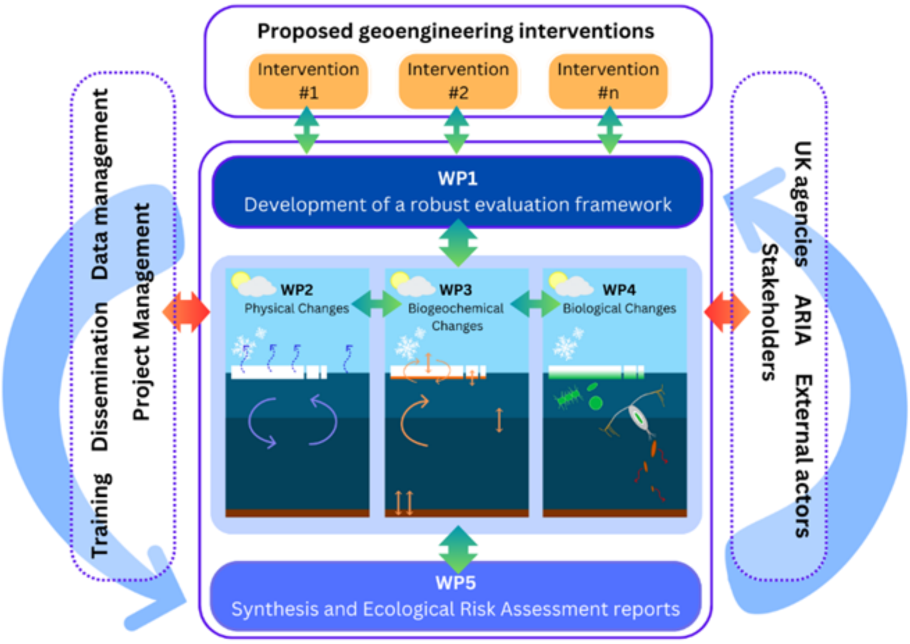


Figure 1: Schematic of WP interconnectivity and links to inputs and outputs

models **(Obj3 & Obj4).** Results of the experimental and modelling exercises performed in WP2-4 will be supplied to **WP5** (light blue box in Fig 1.) and synthesised**.** This synthesis will inform an Ecological Risk Assessment (ERA) report, that will draw on established methodology[e.g. 23,24], to evaluate the potential ecological impacts of the proposed geoengineering interventions and convey these in terms of risk **(Obj5)**.

WP1 Development of a robust evaluation framework (Objective 1)	
Inputs: Other ARIA projects, all WPs, IBoA	**Outputs:** WP2, WP3, WP4, WP5
Co-Leads: [redacted] (*Indicates an Early Career Researcher) **Participants/CO-I:** PDRA2*, co-leads from all WPs	

Overview: WP1 will develop a robust, science-based Evaluation Framework that underpins an independent evaluation of the physical and cascading ecological impacts on the polar marine environment associated with each ARIA-selected geoengineering intervention.

A recognised method for quantifying the effects of outside impacts on a marine ecosystem, such as a geoengineering intervention, is through the establishment of an Evaluation Framework (EF). A well-designed, scientifically robust EF allows for definitive conclusions (with quantified uncertainties) to be drawn on the cascading ecological impact across different trophic levels. The main objective of the EF is 1) identify key ecological components and associated environmental parameters that are most likely to be impacted by the intervention and 2) design observational experiments and modelling studies to quantify the ecological consequences of the proposed intervention.

WP1.1 Round Table assessment To initiate the drafting of the EF a series of round-table meetings will be held with the proponents of each assessed intervention. The aim of these meetings is to obtain a more complete understanding of (i) the intervention and its spatiotemporal domain, (ii) its expected environmental impacts and (iii) the magnitude of the intended perturbation and how it varies under different Shared Socioeconomic Pathways (SSPs). Co-leads of WP2 to WP4 will participate in the round tables to ensure their modelling and laboratory experiments can be better linked to each intervention. **(M1.1)**

WP1.2 Production of Evaluation Framework Using the outputs of WP1.1 we will co-design (with WP5.1) a step-by-step EF from which an interlinked and comprehensive understanding of physical changes (WP2), biogeochemical changes (WP3) and biological changes (WP4) caused by the intervention can be derived. The EF will include (i) defining clear and achievable objectives, (ii) determining the threshold and boundaries, as well as spatiotemporal limitations of the analysis, (iii) robustly selecting the ecological, environmental and pressure indicators to evaluate[i.e 25], and (iv) to identify/compile a baseline (control) dataset from which an assessment of the spatiotemporal impacts of the intervention can be assessed. Data availability, reliability and knowledge gaps will be key considerations when developing the EF. Once the draft EF has been completed it will be delivered to WP5.1 for evaluation by an Independent Board of Advisors (IBoA). This peer-review process is aimed at strengthening the EF, as well as ensuring the framework is flexible enough to be used for future assessments (beyond ARIA). Whilst the EF will remain consistent for the evaluation of selected ARIA-funded geoengineering interventions, the practicalities must be developed on a case-by-case basis. **(M1.2)**

<u>**Milestones**</u> **M1.1 (month 6):** Report on round table meetings for each intervention to be assessed. **M1.2 (Draft: month 8, Peer-Reviewed: month 12):** Delivery of the peer-reviewed Evaluation Framework.

WP2: The Global and Regional Physical Changes Associated with Geoengineering (Objective 2)	
Inputs: WP1, EF	**Outputs:** WP3, WP4, & WP5
Co-Leads: [redacted] **Participants/CO-I:** [redacted] PDRAs 3,4, & 5*, ESM Engineer, PhD_Oxford*	

Overview: WP2 focuses on diagnosing the physical changes associated with geoengineering interventions by implementing scenarios in global earth system models alongside high-resolution regional ocean-only models to isolate their impacts on sea-ice, oceans and climate. It will assess the physical impact of interventions, quantify their uncertainty, describe the mechanisms responsible and attribute the contribution of feedback processes. This diagnosis and assessment of impacts, uncertainties, and feedbacks supports the WP5 synthesis **(M2.4)**, and provides the physical forcing (boundary conditions) and mechanistic understanding required for the subsequent modelling and analysis of biogeochemical (WP3) and biological (WP4) impacts.

WP2.1 Implement Geoengineering Scenarios in UKESM and Regional Ocean models Driven by the WP1 prioritisation, WP2.1 will implement the WP1 geoengineering scenarios using ensembles of UKESM (United Kingdom's Earth System Model)[26,27] and high-resolution ocean-only regional simulations **(M2.1)**. It will ensure thorough testing of the impact of boundary conditions, model resolution and parameterisation, and other model set-up choices.

WP2.2 Track Global and Regional Geoengineering Impacts Across Earth System Components The UKESM is uniquely equipped with BAS developed water tracers[26,27]. This will allow for a detailed assessment and quantification of the water and climate impacts that are critical to understanding the changes and dynamics central to the proposed interventions[28,29]. As well as using this capability to trace directly where thickened sea ice, precipitation changes, and the oceanic freshwater goes, WP2.2 will also use a BAS developed water mass dynamic framework[30] to assess ocean circulation and property distribution changes in response to geoengineering scenarios. These approaches will quantify the responses of essential climate variables, including heat, sea ice and CO_2[e.g.31] to support WP5 reports. Additionally, an established high-resolution ocean model ACCESS-OM2-01[32] will be used to assess the impact of fine-scale processes (e.g. eddies, topography) unresolved in the UKESM, and feedbacks between climate components that may act to compensate geoengineering interventions **(M2.2).**

WP2.3 Attribute Simulated Changes to Geoengineering Interventions vs. Projected Climate Change Ensemble simulations of future climate projection(s) and the associated geoengineering simulations will enable robust estimation of causal processes, pathways of changes **(M2.3)** and attribution to intervention versus climate change[33,34]. Both storyline and probabilistic approach to attribution will be used[35,36] to establish causality information flow and infer crucial mechanisms[37].

Milestones M2.1 (month 24): Initial small ensembles of UKESM and high-resolution/ocean-only simulations to assess how geoengineering interventions affect the physical world and provide (global scale) data required for subsequent risk assessments and physical context for WP3 and WP4. **M2.2 (month 36):** Track and assess the impact of feedbacks between climate components that may act to compensate geoengineering interventions. **M2.3 (month 36):** Multi-method attribution and causality analysis for each intervention. **M2.4 (quarterly; final inputs month 42):** Provide a synthesis report summarising the potential physical changes associated with geoengineering actions.

WP3: Modelling the biogeochemical implications (Objective 3)	
Inputs: WP1, WP2	**Outputs:** WP4, & WP5
Co-Leads: [redacted]	
Participants/CO-I: [redacted] PDRA6*	

Overview: WP3 will investigate the sensitivity of biogeochemical cycling to geoengineering implementation in the polar regions[10]. The polar regions are important regions for driving global productivity and carbon cycling, both by direct supply of nutrients to the polar surface ocean, and by setting the nutrient signature of global-scale ocean circulation[38,39]. Using the outputs of WP1 and informed by the quantified outputs of WP2, WP3 will assess the biogeochemical impacts of geoengineering methods using experimental approaches, to determine the key drivers of biogeochemical change, and use observations to quantify changes relative to a baseline. Using established modelling frameworks, this work-package will quantify the sensitivity of biogeochemical variables such as nutrients and alkalinity, to geoengineered changes in an idealised system, e.g. fjord or two-basin ocean. WP3 will then provide a biogeochemical framework that will feed into WP4, identifying key potential bottom-up drivers of ecological impacts of geoengineering interventions **(M3.3)**.

WP3.1. Physical modelling of biogeochemical impacts of different scenarios. Use outputs from WP1 and WP2 to design and execute scaled laboratory-based physical models, either using seawater and/or sea ice incubations to reproduce resultant conditions following geoengineering implementation **(M3.1)**. For example, to reproduce sea ice thickening/albedo geoengineering methods and assess the changes to important drivers of biological production and inorganic carbon cycling, such as the flow of nutrients and alkalinity[e.g. 40,41]. Laboratory analyses will be carried out in BAS laboratories to calculate the distribution and fluxes of macronutrients, alkalinity and dissolved inorganic carbon (DIC).

WP3.2. Idealised modelling of biogeochemica impacts of geoengineering interventions*.* Idealised models are well-suited to this purpose because they allow for simple perturbations to key parameters/forcing of interest (i.e. phosphate, alkalinity and DIC) and efficiently allow for large numbers of model experiments. The MIT general circulation model (MITgcm)[42] presents a flexible and portable modelling framework and includes a range of state-of-the-art numerical schemes. We will investigate the implications for marine biogeochemical processes of two geoengineering scenarios: **i)** We will address biogeochemical impacts of physical changes in upwelling and mixing driven by benthic curtains using an ISOMIP-like (Ice Shelf Ocean Model Intercomparison Project)[e.g. 43] model with added carbon cycle model[44]. WP2 models will provide far-field conditions to drive the circulation and a simple carbon cycle model and far-field biogeochemical conditions will allow for quantification of the role of benthic curtains in modifying, e.g., surface nutrient supply and changes in productivity. Results will be calibrated against existing datasets to determine the geoengineering-driven anomaly. **ii)** A two-basin sector model of the Atlantic and Pacific with sea ice[45] and biogeochemical factors[e.g.46], designed as part of the BIOPOLE National Capability programme, will be used to consider the biogeochemical impact of sea ice interventions driven by stratification changes. We will use WP2 models to design the sea ice model parameter perturbations required to force geoengineering scenarios and guide the individual experiments. The computational efficiency of this configuration allows for the consideration of even longer (>100 years) timescales. **(M3.2)**

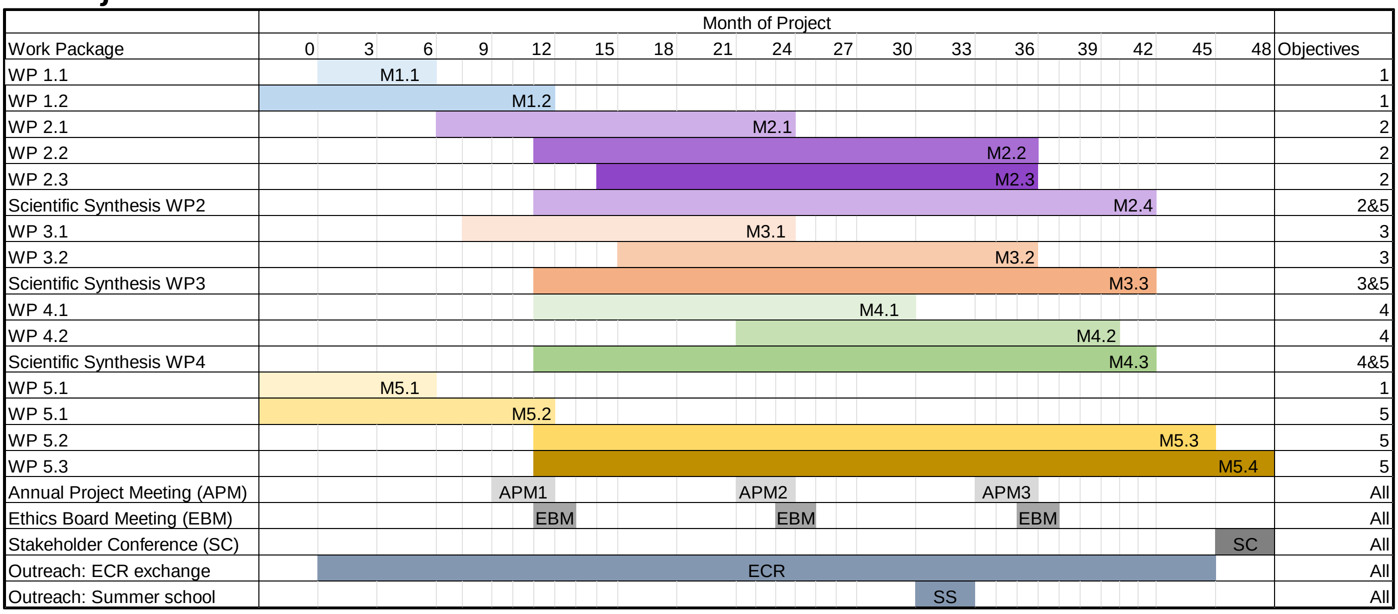
Milestones M3.1 (month 24): Develop capability for, and carry out, a set of sea ice thickening experiments, resolving fundamental nutrient exchange between ice and seawater during sea ice growth and loss. **M3.2 (month 36):** Deliver 3D idealised models with key biogeochemical tracers that can test the sensitivity of carbon and nutrients to proposed geoengineering methods. **M3.3 (quarterly; final inputs month 42):** Provide a synthesis report on the potential changes to nutrient cycles following geoengineering method implementation, and disseminate research.

WP4 Understanding the Biological Change (Objective 4)	
Inputs: WP1, WP2, WP3	**Outputs:** WP5
Co-Leads: [redacted] **Participants/CO-I:** PDRA7*, [redacted]	
Overview: WP4 will evaluate the potential impact of geoengineering interventions on the composition, functioning and resilience of pelagic polar ecosystems. We will focus on the plankton component, which underpins the biological carbon pump and is the base of the wider food web[47,48]. We will assess the individual and combined impacts of these interventions, including additive-synergistic and cascading effects. Using outputs from WP1-3, we will identify potential direct (i.e. habitat loss or degradation, species mortality or displacement) and indirect (i.e. altered food webs or predator-prey dynamics) impacts on community structure and biologically mediated carbon export. We will perform simulation experiments (using a combination of mesocosm incubation and modelling) where organisms will be exposed to environmental conditions reflecting pre- and post-geoengineering intervention scenarios. Findings will be relayed to WP5 and disseminated through scientific publications **(M4.3)**. **WP4.1 Laboratory mesocosm simulation of biological impacts.** Key marine plankton species will be cultivated-incubated and exposed to environmental stressors **(M4.1)** using multifactorial mesocosm experiments capable of supporting multivariable parameters and treatments under different environmental conditions (i.e. control versus geoengineering-intervention induced stressors such as changed light or nutrient conditions)[49-53]. Disturbances such as chemical pollution and physical barriers generated by the geoengineering interventions will also be addressed. Mesocosm experiments will be carried out in BAS climate-controlled laboratories. **WP4.2 Modelling biological impacts.** Models informed by WP4.1 outputs will be used to evaluate ecosystem impacts over larger spatial and temporal scales and to further explore the effects of individual and combined stressors[54] **(M4.2)**. The 2D ecosystem models will represent the spatiotemporal dynamics and food web structure of marine plankton under current and changed environmental conditions and will be used to assess impacts on biomass across trophic levels, species composition, network structure, predator-prey dynamics and their implications for ecological resilience and carbon export. **Milestones: M4.1 (month 30)** Perform experiments to investigate impact on and resilience of plankton community structure. **M4.2 (month 40)** Deliver a model-based analysis of the impacts of geoengineering interventions on plankton community structure, dynamics, resilience and carbon export. **M4.3 (quarterly; final inputs month 42)** Provide a synthesis report on the potential changes to plankton community and carbon export following geoengineering intervention.	

WP5 Synthesis and Ecological Risk Assessment reports (Objective 5)	
Inputs: WP1-4, IBoA, select BAS scientific experts	**Outputs:** WP1, ARIA, UK policy agencies
Co-Leads: [redacted] **and PDRA2*** **Participants/Co-I:** [redacted] Independent expert Board of Advisors (IBoA), all WP co-leads	
Overview: WP5 will work with WP1 to ensure that the design of the Evaluation Framework (EF), is suitable for the delivery of an Ecological Risk Assessment (ERA), synthesise the modelling and experimental results from WP2-4, and produce an ERA report of the proposed geoengineering interventions. Leads will ensure Eco-GaP addresses the three main phases of ecological risk[55], 1. problem formulation (Obj1), 2. analysis of exposure and effects (Obj2-4) and 3. risk characterisation with considerations of uncertainty (Obj5). **WP5.1 Support development of Evaluation Framework.** Once provided with an overview of the proposed geoengineering interventions, WP5 will consult with the IBoA, via roundtable discussion, to inform the development of the EF. The precise composition will depend on the proposed geoengineering intervention, but could include, for example, expertise on benthic communities, higher marine predators (such as birds and marine mammals), fisheries, and invasive species, as well as management and policy experts. The environmental /ecological issues raised during the roundtable discussion will be collated and used to inform the EF design **(M5.2)**. WP5 will also work with the ReDs and the PDC to develop the DMP **(M5.1)**. **WP5.2 Scientific synthesis of Eco-GaP programme.** The results from WP2-4 will be collated, interpretated and summarised to provide a scientific synthesis report for each geoengineering intervention **(M5.3)**. Importantly, the synthesis report will also identify uncertainties in analysis and results. The scientific	

synthesis report will be shared with the IBoA, as well as an expanded network of experts, if deemed necessary. Additional IBoA roundtable discussions will be held to incorporate input from a broad range of experts to yield a final scientific synthesis of the ecological impact which will ultimately inform the ERA. WP5 co-leads will meet regularly (minimum quarterly) with WP2-4 research teams to receive a steady input of modelling and experimental results allowing a progressive development of the scientific synthesis report, and associated sections of the ERA, with a consolidated effort in the final months.
WP5.3 Ecological Risk Assessment report. Utilising the scientific synthesis report and the input from the IBoA roundtable discussions, an ERA will be undertaken to evaluate the level of ecological risk associated with the proposed geoengineering interventions. This will include evaluation of the (i) likelihood (probability of impact occurring), (ii) magnitude (severity of the impact), (ii) duration (temporary, long-term, or permanent effects), (iv) reversibility (potential for recovery/restoration), and (v) significance (ecological importance). We will provide scaling metrics for these evaluation criteria and ultimately provide a final assessment of the ecological risk associated with geoengineering interventions to be weighed against the theoretical climatological benefit. The structuring of the ERA will begin immediately following the development of the EF and progress in stages as new scientific results are documented during regular meetings with WP2-4 research teams. Upon completion, the ERA report will be disseminated to ARIA, the geoengineering teams and relevant stakeholders as well as presented at the end of project stakeholders conference. The Polar Regions Department (Foreign and Commonwealth and Development Office) is well-placed to share WP5 outputs with international policymakers through the Antarctic Treaty Consultative Meeting (ATCM) and Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), thereby informing international thinking regarding potential issues with geoengineering solutions under the Antarctic Treaty System governance framework and associate environmental impact assessment system. Programme Advisor Hughes and Co-lead Cavanagh work closely with the Polar Regions Department as members of the UK delegations to the ATCM and CCAMLR. Project Lead Burson works closely with IASC and the UK Arctic Office (located within BAS) for dissemination to Arctic stakeholders **(M5.4)**
<u>Milestones:</u> M5.1 (month 6): Develop data management plan with PDC and ReDs support. **M5.2 (month 12):** Hold IBoA roundtable discussions to support development of the EF with WP1. **M5.3 (initial structuring from month 9, final conscripting month 40-45):** Scientific synthesis report of modelling and experimental outputs of WP2-4 **M5.4 (initial structuring month 9, final conscripting 45-48):** Development and completion of ERA report.Dissemination of ERA to relevant bodies.

1.7 Project Plan



1.6 Managing and mitigating risks

Non-technical risks: Due to the cascading and interconnective nature of this programme, the down-chain risks to later WPs should early WPs be delayed is significant. As much of the modelling and experimental design of WP-2-4 depends on development of an effective EF in WP1, access and willingness of participation with geoengineering project teams is paramount. To mitigate this risk, we will work closely with ARIA to ensure the geoengineering project teams are informed regarding the added value that ecological assessment of their proposals provides not only to them but also to ARIA. ***Technical risks:*** Other potential risks to early WPs include access interruptions of the NERC HPC platforms. As WP2 output will also inform the specific experimental questions evaluated in WP3 and 4, ensuring efficiency in the modelling stages is important. Should this occur, we would seek to utilise non-NERC HPC platforms as well as perform smaller scale computations within BAS. However, additional resources and modelling time may be required should the interruptions in access prove to be substantial. ***Regulatory, legal & ethical:*** Due to the sensitivity of geoengineering projects and potential ethical considerations they involve (e.g. local community and Indigenous community impacts), Eco-GaP, with the assistance of BAS's Communications and Research Development offices, will establish an "ethics board" who will identify, alert, and suggest mitigation strategies for, possible areas of concern. Because we are not proposing any field-based experimentation we do not anticipate regulatory or legal issues, but if any should arise BAS is well equipped with support staff to assist.

Section 2: The Team

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Grants [redacted]

G1. EU project – Past to future: Towards Paleo-informed future climate projections (P2F). EU framework programme for research and innovation, Horizon Europe (commencing in March 2025) (**Sime institute & WP lead**

G2. EU project – Tipping points in the Earth System (TiPES). EU framework programme for research and innovation, Horizon Europe, under grant agreement number 820970 (2019-2024) (**Sime WP & institute lead)**.

G3. EU project – Research and training network on understanding Deep icE corE Proxies to Infer past antarctiC climate dynamics (DEEPICE). EU framework programme for research and innovation, Horizon Europe, under grant agreement number 955750 (call: 2021-2024) (**Sime institute lead**).

G4. NERC Directed (**Co-I Sime**) 2024-29: Assessing ocean-forced, marine-terminating glacier change in Greenland during climatic warm periods and its impact on marine productivity: KANG-GLAC.

G5. NERC National Capability Single Science (**Co-I Sime**) 2024-28: UK Polar Research Expertise for Science and Society: PRESCIENT

G6. EU project – Marie Sklodowska-Curie Actions IF (**PI Fučkar**) Attribution of dynamic and thermodynamic components in extreme weather and climate events (2020-2023)

G7. EPSRC Impact Acceleration Account Fund (**PI Fučkar**) User-oriented information on tropical cyclones and water cycle extremes for the climate and disaster risk management (2023-2024)

G8. NIHR Research and Innovation for Global Health Transformation Call 5 (**Co-I Fučkar**) The Hospital Risk Insurance System for Kenya (2023-2027)

G9. Wellcome Trust (**Co-I Fučkar**) Climate Change Impacts on Early Childhood Health and Development: From Evidence to Action (2025-2027)

G10. NERC Addressing environmental challenges - highlight topic (**Co-I Fučkar**) Drivers and Impacts of Extreme Weather Events in Antarctica: ExtAnt (2024-28)

G11. CUPIDO II-RENEWAL, UKRI-FLF grant, (**PI, Manno**) 2024-2027: CalcUlating the strength of the Plastic pump In counteracting the Deep export of Oceanic carbon (CUPIDO) £0.55M

G12. NERC Directed (**WP Co-lead, Manno**) 2024-29: Assessing ocean-forced, marine-terminating glacier change in Greenland during climatic warm periods and its impact on marine productivity: KANG-GLAC £1.5M.

G13. UKRI Grant **(Co-I Manno)** BIOPOLE, Biogeochemical processes and ecosystem function in changing polar systems and their global impacts

G14. CUPIDO, UKRI-FLF grant, (**PI, Manno,** £1.2M) 2020-2024: CalcUlating the strength of the Plastic pump In counteracting the Deep export of Oceanic carbon (CUPIDO)

G15. Canada-Inuit Nunangat-UK Arctic Research Programme (CINUK) Inuit Qaujisarnirmut Pilirijjutit on Arctic Shipping Risks in Inuit Nunangat 2022-2025 **(Co-I Manno)**

G16. NERC grant 2017-2027 (**WP Co-lead, approx £350K to BAS**), PICCOLO, Processes Influencing Carbon Cycling: Observations of the Lower limb of the Antarctic Overturning

G17. PRESCIENT (NC-SS2), UK Polar Research Expertise for Science and Society, 2024-2029 **(Manno, WP leader)**

G18. Horizon Europe – OCEAN:ICE Ocean-Cryosphere Exchanges in ANtarctica: Impacts on Climate and the Earth System. (Nov 2022-2026) **(PI Meijers)**

G19. NERC LTSM2 – BIOPOLE Biogeochemical processes and ecosystem function in changing polar systems and their global impacts (April 2022-2027) **(WP Lead Meijers)**

G20. Horizon 2020 – SO-CHIC Southern Ocean Carbon and Heat Impact on Climate, (Nov 2019-2024) **(WP & institute lead Meijers)**

G21. NERC LTSM1 – ORCHESTRA Ocean Regulation of Climate by Heat and Carbon Sequestration and Transports (2016-2021) **(PI Meijers)**

G22. NERC LTSM1.5 – ENCORE ENCORE is the National Capability Orchestra Extension (2021-2023) **(PI Meijers)**

G23. NERC Large Grant “POLOMINTS: Polar Ocean Mixing by Internal Tsunamis” (2025-, £3.7M). **(Co-I Hendry)**.

G24. NERC Pushing the Frontiers Grant (2024-2027, £1M) “Silicon CycLing IN Glaciated environments (SiCLING)”. **(PI Hendry)**

G25. ERC Starter Grant (2016-2021, €2M) “ICY-LAB: Isotope Cycling in the Labrador Sea”. **(PI Hendry)**

G26. NERC-Conicyt Grant (2016-2019, approx. £680k) “"PISCES: Patagonian Ice field Shrinkage impacts on Coastal and fjord EcosystemS”. **(Co-I Hendry)**

G27. ERC H2020 Consortium Grant (2016-2019, in the theme “Blue Growth: Unlocking the Potential of Seas and Oceans”; approx. £91k to Bristol) “SpongGES: Deep-sea Sponge Grounds Ecosystems of the North Atlantic”. **(Co-I Hendry)**.

G28. Royal Society University Research Fellowship (2013-2021, £450k). **(PI Hendry)**.

G29. NERC Changing Arctic Ocean Strategic Science Grant (2017-2021, approx. £600k to Bristol) “The Changing Arctic Ocean Seafloor (ChAOS)”. **(Co-I Hendry)**.

G30. NERC Pushing the Frontiers Grant (2024-2027, £1M) “Silicon CycLing IN Glaciated environments (SiCLING)”. **(PDRA Jones)**

G31. RaCE:TRaX: Radium in Changing Environments: A Novel Tracer of Iron Fluxes at Ocean Margins. **(PhD Jones)**

G32. Diamond Light MG30572, MG32502 "Determining the composition and lability of glacially-derived iron-rich material from the West Antarctic Peninsula". **(Lead Jones)**

G33. Diamond Light MG36740 - “The composition and lability of iron-rich sediments from the West Antarctic Peninsula and East Greenland shelf”. **(Lead Jones)**

G34. KANG-GLAC (2024-29, £1.5M): Assessing ocean-forced, marine-terminating glacier change in Greenland during climatic warm periods and its impact on marine productivity. **(PDRA Atherden)**

G35. PICCOLO (2017-2027, £330K) Processes Influencing Carbon Cycling: Observations of the Lower limb of the Antarctic Overturning. **(PDRA Atherden)**

G36. DIAPOD (2017-2022, £701K): Mechanistic understanding of the role of diatoms in the success of the Arctic Calanus complex and implications for a warmer Arctic. **(PhD Atherden)**

G37. SPITFIRE Placement (2021, 5k). Using sediment traps to monitor the Southern Ocean zooplankton community. **(Lead Atherden)**

G38. DEFIANT: (NERC: ~£5 million): Drivers and Effects of Fluctuations in sea Ice in the ANTarctic (active) **(Coordinator Wilkinson)**

G39. PRESCIENT:(NERC: ~£11 million) UK Polar Research Expertise for Science and Society (active) **(Co-I Wilkinson)**

G40. TRaNSMIT:(EPSRC: £500k) A towable RF system for non-invasive sensing and measurement of Arctic sea ice thickness (active) **(Co-PI Wilkinson)**

G41. MOSAiC: (NERC: ~£300k): Seasonal evolution of Ku and Ka band backscattering horizon over snow on first-year and multiyear sea ice (completed) **(Co-PI Wilkinson)**

G42. Arctic PASSION: ~€15 million): Pan-Arctic observing System of Systems: Implementing Observations for societal Needs (active) **(Lead team Wilkinson)**

G43. EU PolarNet 2: (~€3 million): EU Polar Network 2 (active) **(Co-I Wilkinson)**

G44. KEPLER: (~€3 million): Key Environmental monitoring for Polar Latitudes and European Readiness (completed) **(CO-I Wilkinson)**

G45. ICE-ARC: (~€12 million): Ice, Climate, Economics – Arctic Research on Change. (completed) **(Coordinator Wilkinson)**

G46. EU PolarNet:(~€2 million): EU Polar Network (completed) **(Co-I Wilkinson)**

G47. Eco-Light: PI (NERC/BMBF: ~£1 million): Ecosystem functions controlled by sea ice and light in a changing Arctic (Eco-Light) (completed) **(PI Wilkinson)**

G48. MIZ:(ONR: ~$10 million): Emerging Dynamics of the Marginal Ice ZoneDRI (completed) **(PI Wilkinson)**

G49. SODA: PI (ONR: ~$10 million): Stratified Ocean Dynamics in the Arctic (completed) **(PI Wilkinson)**

G50. CARB-SEA (NERC global partnership seedcorn fund, £80k), **(project Co-lead and BAS lead Munday)**.

G51. POLOMINTS (NERC large grant, ~£3.7 million), **(Co-I and modelling contributor Munday)**

G52. C-Streams (NERC large grant ~£3 million), **(Co-I and BAS lead Munday)**

G53. NERC Highlight Topic Award. Drivers and Impacts of Extreme Weather Events in Antarctica. (2024-28). £3 million. British Antarctic Survey with Birmingham, Cardiff, Leeds, Reading and St Andrews Universities. **(Co-I Cavanagh)**

G54. UK Government Darwin Plus Funding Award. Evaluating climate change risks to Patagonian and Antarctic toothfish. (2023-26). £240,000. **(PI Cavanagh)**

G55. NERC Antarctic Logistics & Infrastructure. Research, Conservation and Leadership in Southern Ocean Ecosystems (CONSEC) (2023-33). British Antarctic Survey. **(WP Co-Lead Cavanagh)**

G56. PhytoFA:Phytoplankton in a Freshening Arctic, Rubicon Fellowship Dutch Research Council, (€200k) **(PI Burson)**

G57. NERC National Environtmental Isotope Facility grant £20k **(Co-I Burson)**

G58. Natural Environment Research Council (NERC) International Opportunities Fund: Coordinating International Research on Southern Ocean Ecosystems: Implementation of the ICED Programme. NERC International Opportunities Fund (IOF). £300,000 (completed). **(PI Cavanagh)**

G59. NERC National Capability Science Multicentre. BIOPOLE: How nutrients in polar waters drive the global carbon cycle and primary productivity (2022-2027). **(Co-I Hill)**

G60. NERC Pushing the Frontiers. KRILLGUARD: Safeguarding the future of the Southern Ocean (2024-2027). **(Co-I, institute lead, WP co-lead Hill)**

G61. NERC Antarctic Logistics & Infrastructure. CONSEC: Research, Conservation and Leadership in Southern Ocean Ecosystems (2023-2033). **(Co-I, WP lead Hill)**

Impact (I) [redacted]

I1. Record low Antarctic sea ice 'extremely unlikely' without climate change Press Release 20 May 2024 **(Sime)**
I2. Team heads for Antarctica to study global warming effects Press Release 8 November, 2023 **(Sime)**
I3. Past evidence supports complete loss of Arctic sea-ice by 2035 Press Release 10 August 2020 **(Sime)**
I4. Arctic sea ice loss in past linked to abrupt climate events Press Release 12 February, 2019 **(Sime)**
I5. Lee, J.J., Francisna Fernando, F., Desjonqueres, C., Gorgulu, N., Knudsen, C., Mealy, P., Shariq, A., Wu, J., **Fučkar, N.S.**, et al., 2024, Rising to the Challenge: Success Stories and Strategies for Achieving Climate Adaptation and Resilience, World Bank report https://www.worldbank.org/en/publication/rising-to-the-challenge-climate-adaptation-resilience
I6. The Telegraph, 25 July 2024, Everything you need to know about La Niña, the climate phenomenon behind this year's extreme weather, https://www.telegraph.co.uk/global-health/climate-and-people/what-you-need-to-know-about-climate-phenomenon-la-nina/ **(Fučkar)**
I7. **Fučkar, N.S.**, 17 May 2024, Extreme heatwaves in south and south-east Asia are a sign of things to come, The Conversation, https://theconversation.com/extreme-heatwaves-in-south-and-south-east-asia-are-a-sign-of-things-to-come-229832
I8. **Fučkar, N.S.**, 9 February 2024, Weather v climate: how to make sense of an unusual cold snap while the world is hotter than ever, United Nations Office for Disaster Risk Reduction, PreventionWeb, https://www.preventionweb.net/news/weather-v-climate-how-make-sense-unusual-cold-snap-while-world-hotter-ever
I9. Macintyre, H.L., Murage, P., **Fučkar, N.S.,** Hajat, S., Heaviside, C., Vardoulakis, S., Cordiner, R., Health Effects of Climate Change in the UK: 2023 Report, Chapter 2. Temperature effects on mortality in a changing climate, UK Health Security Agency, https://www.gov.uk/government/publications/climate-change-health-effects-in-the-uk
I10. Plastic reduces how krill remove carbon into deep ocean, Press Release 20 November, 2024 **(Manno)**
I11. Sea butterfly life cycle threatened by climate change Press Release 15 May 2023 **(Manno)**
I12. Microplastic found in Antarctic krill and salps Press Release 29 March 2023 **(Manno)**
I13. New kit enables study of microplastics in the ocean, 8 September 2022 **(Manno)**
I14. Universities Network: COP26 Images of Innovation Exhibition, 19 October 2021 **(Manno)**
I15. Plastic pollution and ocean acidification reduce Antarctic krill development 4 August 2021 **(Manno)**
I16. Krill provide a highway for ocean carbon storage 27 November 2020 **(Manno)**
I17. Krill swarms responsible for 'hidden' carbon storage 21 February 2019 **(Manno)**
I18. Sea butterflies repair shell damage from ocean acidification 25 January 2018 **(Manno)**
I19. EU policy briefing: The Changing Poles: how Antarctic and Arctic science helps to inform and prepare the EU for changes in sea level rise and the global climate (Brussels, Feb 2024) **(Meijers)**
I20. The Conversation article: Slowing deep Southern Ocean current may be linked to natural climate cycle – but that's no reason to stop worrying about melting Antarctic ice (June 2023) **(Meijers)**
I21. Is the climate crisis finally catching up with Antarctica? Finding the answer has never been more pressing – Guardian invited opinion article (Aug 2023) **(Meijers)**
I22. Changes in Atlantic currents may have dire climate implications for the next century – Guardian Invited opinion article (Feb 2021) **(Meijers)**
I23. Live interview BBC news: A23a iceberg encounter (Dec 2023) **(Meijers)**
I24. "Southern Ocean monitoring needed to predict climate change", invited interview on ABC Radio National Breakfast. (Aug 2023) **(Meijers)**
I25. Speaker at Cheltenham Science Festival 2024 **(Hendry)**
I26. Expert witness for cross-Whitehall round table discussion on UK Arctic policy (2022) **(Hendry)**
I27. Attendance at Arctic Circle Assembly, Reykjavik, invited speaker in 2021 & 2023 **(Hendry)**
I28. Lead author of IES environmental SCIENTIST article "Where warming land meets warming sea" (2021) **(Hendry)**
I29. Co-author of ECOmagazine article "New nutrient sensors provide icy insights" (2020) **(Hendry)**
I30. Co-author Grantham Institute briefing note "The Arctic and the UK: climate, research and engagement" (2020) **(Hendry)**
I31. Interview for BBC News on Arctic policy and climate change (2020) **(Hendry)**
I32. UN Ocean Decade Early Career Ocean Professionals International Workshop co-convenor (2022) **(Jones)**

I33. UK Arctic Expert: G7 FSOI (2023-2024) **(Wilkinson)**
I34. Policy Brief European Parliament OCEAN:ICE and Arctic PASSION (2024) **(Wilkinson)**
I35. Invited speaker: Future Collaboration by Research Vessels and Icebreakers, Japan (2023) **(Wilkinson)**
I36. Invited speaker: Arctic Circle Japan Forum, (2023) **(Wilkinson)**
I37. Various press releases associated with NERC:DEFIANT and EU:Arctic PASSION (2023-2024) **(Wilkinson)**
I38. Marine Working Group Fellow International Arctic Science Council (2020-2023) **(Burson)**
I39. Invited speaker *Author spotlight: recent high -impact authors from the Association for Sciences in Limnology and Oceanography journals* at 2019 meeting Puerto Rico **(Burson)**
I40. Imbalance in Phosphorus and Nitrogen Levels in the North Sea Caused by Environmental Policy 27 January 2016 Press Release **(Burson)**
I41. Member of the Scientific Committee on Antarctic Research (SCAR) Standing Committee on the Antarctic Treaty System (SCATS) (2024-28) **(Cavanagh)**
I42. Scientific Advisor on the UK delegation to the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), leading on climate change issues (2021-ongoing) **(Cavanagh)**
I43. Invited speaker and panellist: UK Government Bluebelt Symposium, February 2024 **(Cavanagh)**
I44. Co-author of climate change "report card" for the coastal and marine environment around the Polar UK Overseas Territories (2021) 10.14465/2021.orc02.pol **(Cavanagh)**
I45. Leading scientists warn of global impacts as Antarctic nears tipping points Press Release 15 June, 2021 https://www.bas.ac.uk/media-post/leading-scientists-warn-of-global-impacts-as-antarctic-nears-tipping-points **(Cavanagh)**
I46. Studies highlight fragility of Antarctic ecosystems 29 November, 2019 Press Release **(Cavanagh)**
I47. Krill from Space. Livestreamed presentation at COP29 15 November 2024 **(Hill)**
I48. Antarctic krill can lock away similar levels of carbon as seagrass and mangroves. Press Release 19 September 2024 **(Hill)**
I49. Enabling sustainable fisheries management in the Southern Ocean. Commended Entry, NERC Impact Awards, 2023. 11 April 2024 **(Hill)**
I50. Q&A: How might fishing be impacting the carbon cycle? Interview 26 January 2022 **(Hill)**
I51. Antarctic krill: Key food source moves south. Interview, BBC News, 21 January 2019 **(Hill)**

Responsible Research [redacted]

R1. Earth System Modelling summer school lecturer: https://deepice.cnrs.fr/deepice-events/ (DEEPICE AWI, Germany, 2023) **(Sime)**
R2. Winter school lecturer: https://deepice.cnrs.fr/deepice-events/ (DEEPICE Finse, Norway, 2022) **(Sime)**
R3. DEEPICE: Network of young researchers to unveil past climate change in Antarctica **News** 13 October, 2021 **(Sime)**
R4. Glasgow COP26: Invited panel member: Climate Risk & Tipping Points in the Polar Regions (Panel + Q&A, 2021) **(Sime)**
R5. University of the Arts COP26 event speaker/panellist: Ask a Climate Scientist: COP, Science, Culture and Politics **(Sime)**
R6. Engagement with multiple artists through ClimArts: https://www.climarts.org/ **(Fučkar)**
R7. Two bachelor and seven master students graduated, and supervision of two master and doctoral students, and two PDRAs**(Fučkar)**
R8. Climate Change and Our Power, Youth Forum, Oxford University Museum of Natural History, 2023 **(Fučkar)**
R9. Co-chair of the series of Oxford University Climate and Health Forums, 2021 **(Fučkar)**
R10. Climate Advice Sessions with the Lord Mayor of Oxford, 2019 **(Fučkar)**
R11. Podcast "Plastic in Antarctica", Pine Forest Media, https://podcasts.apple.com/us/podcast/5-plastics-in antarctica/id1748730442?i=1000660878643 **(Manno)**
R12. Podcast, "Ask the geographer" Royal Geographical Society Schools https://soundcloud.com/rgsibg **(Manno)**
R13. 2020 Creation of an animated video for general audience focus on the link between microplastic and climate change shared on YouTube https://www.youtube.com/watch?v=Ivm4H3Lpr8A **(Manno)**
R14. How Might Plastic Pollution Affect Antarctic Animals?. *Frontiers for Young Minds.* **(Manno)**
R15. Sea Butterflies Defend Their Homes Against an Acidic Ocean. *Frontiers for Young Minds* **(Manno)**
R16. Live stream event organized by the German Federal Ministry of Education and Research (BMBF) in partnership with the Intergovernmental Oceanographic Commission to talk about anthropogenic impact on impact the marine ecosystem. **(Manno)**

R17. COP26 UK Universities' Climate Innovation showcase https://www.strath.ac.uk/workwithus/cop26/innovationshowcase/livingonlandsea/zooplanktonplasticpump/ **(Manno)**
R18. Panellist at the INC-5 Intergovernmental Negotiating Committee on plastic pollution to develop an international legally binding instrument on plastic pollution, South Korea **(Manno)**
R19. Co-convenor RECOIL workshop: Reconciling Cross-platform Observations of Ice-shelf meLt. (September 2024, Copenhagen). **(Meijers)**
R20. Southern Ocean summer school convenor (May 2024, Corsica) **(Meijers)**
R21. Lead convenor Royal Society Discussion Meeting: Heat and carbon uptake in the Southern Ocean: the state of the art and future priorities (May 2022, London) **(Meijers)**
R22. "Oxygen Thieves". Invited chapter in: "Adventures in Climate Science". Woodslane Pty Ltd. (2023) **(Meijers)**
R23. Lead convenor: Workshop on Southern Ocean-cryosphere feedbacks (July 2023, Berlin)
R24. Invited speaker: European Data Week (May 2024, Genoa) **(Meijers)**
R25. Co-convenor of Arctic Science Summit Week (ASSW) Science Day, Edinburgh, 2024 **(Hendry)**
R26. Panellist for EDIA session at Challenger150 Meeting, London (September 2023) **(Hendry)**
R27. Member of Greenland Ice Sheet Ocean Science Network (GRISO) working group (2022-) **(Hendry)**
R28. Co-chair of Diversity in Polar Science Initiative DiPSI (2021- 2023) **(Hendry)**
R29. Honorary Secretary of Challenger Society for Marine Science (CSMS) (Sept 2022-) **(Hendry)**
R30. Net Zero Oceanographic Capability (NZOC) Work Package lead (2020-2021) **(Hendry)**
R31. Lead author of Ocean Challenge article "Equity at Sea: Gender and inclusivity in UK sea-going marine science" (2020) **(Hendry)**
R32. Mentoring networks for women in science, including mentoring junior researchers (via: mento International) **(Hendry)**
R33. Antarctic Science Ltd Board member (2012-); Treasurer (2017-2020); Chair (2020-) **(Hendry)**
R34. UK Polar Network: International Collaboration Officer: Arctic field training seminar series (2022), Social Media Officer (2022) **(Jones)**
R35. UK-Russa Arctic collaborations policy brief co-author (2021) **(Jones)**
R36. Net Zero Marine Planning policy recommendations for 25 % reduction by 2025, co-author (2022) **(Jones)**
R37. GEOTRACES Early Career Scientist Committee member (2024-) **(Jones)**
R38. National Oceanography Centre Environmental Advisory Group Postgraduate Representative **(Jones)**
R39. Creator and current coordinator of Fellows' On-going X-change (FOX), fellows alumni group within the International Arctic Science Council (IASC) (2023-) **(Burson)**
R40. Lead convenor: Workshop for IASC FOX contribution to International Conference on Arctic Research IV (July 2024) **(Burson)**
R41. Editor of the British Phycological Society's biannual magazine *The Phycologist* **(Burson)**
R42. Participant in *Skype a Scientist* programme 2021 **(Burson)**
R43. Capacity Building Fund Committee, Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) (2023-ongoing) **(Cavanagh)**
R44. Debate and Spokesperson Climate Change Masterclass, Grantham Institute, Imperial College (2021) **(Cavanagh)**
R45. COP26 (26th United Nations Climate Change Conference) Engagement Campaign, British Antarctic Survey Ambassador (2021) **(Cavanagh)**
R46. Cambridge Natural Environment Research Council (NERC) Doctoral Training Partnerships Training Committee, University of Cambridge (2019-ongoing) **(Cavanagh)**
R47. Leadership Programme for Women (2017) **(Cavanagh)**
R48. Lead author "The Important but Mysterious Antarctic Krill" - children's journal article 2023. **(Hill)**
R49. Scientific consultant "Krill: Superheroes of the Southern Ocean" - animated video 2021 **(Hill)**
R50. Challenge of Science Leadership course 2021 **(Hill)**
R51. Unconscious Bias Training course 2021 **(Hill)**
R52. Science Coordinator SCAR Kril Expert Group 2022-2024 **(Hill)**

A Responsible innovation Framework for assessing NOvel Spray Technology Research to examine local AlbeDo changes from Marine brightening and its mUlti-Scale impacts. (NOSTRADAMUS)

Section 1: Programme and Technical

1.1 Programme Alignment: Marine Cloud Brightening (MCB) and Marine Sky Brightening (MSB) are two of the most significant opportunities to increase the average planetary albedo and provide a mechanism for cooling the earth. The biggest technical barriers in any proposed MCB deployment are associated with the ability to produce aerosols at a high enough rate in an energetically efficient way and at the 'correct' size in a real world environment. We propose a programme for developing and testing spray technologies to deliver aerosol particles; their application for MCB and MSB; and a robust framework for testing both their effectiveness and wider environmental impacts through a stepwise, consultative and inclusive approach. We will follow responsible research and innovation best practice to deliver a limited area experimental environment to test and optimise the effectiveness of a range of spray technologies in increasing the local planetary albedo. We will use this to inform and challenge a multi-scale modelling prediction system to improve assessment of MCB and MSB schemes and quantify risks and threats of future deployment. We propose a closely coupled programme of laboratory studies, sprayer technology development, testing, and modelling to aid and develop small scale field trials. As identified in a recent review[1], these elements are essential next steps to assess the feasibility and risks of MCB and MSB, and test the veracity of current model predictions of large scale deployment effectiveness and impacts, necessary conditions before implementation is considered.

Field trials of MCB will emerge in the next few years to examine important cloud regimes in key geographical locations around the world. These need to be conducted transparently, objectively, and be acceptable to society. At present only one trial is underway, in a sub-tropical cumulus regime focusing on locally reducing sea surface temperatures around the Great Barrier Reef[2]. It is necessary to also examine other cloud types important for MCB, such as stratocumulus clouds[1]. Owing to practical constraints, such experiments are only possible for a limited number of case studies and cloud regimes. A multi-scale model approach is therefore a vital component for interpolation and extrapolating results to the global environment. Our proposed field experimental programme would provide: an independent evaluation environment for MCB and MSB technologies; a globally unique test of mid-latitude stratocumulus response to aerosol perturbations; UK spray developers with a testing location for their devices at modest cost compared to overseas deployments; a UK capability for testing other MCB projects within ARIA and beyond.

1.2 Research Objectives:

O1: Develop and test spray technologies capable of delivering sea spray aerosol particles at the necessary size distribution and rate, that can reliably operate in real world environments for extended periods.

O2: Conduct laboratory experiments on multiple particle populations to verify model predictions of cloud activation used to optimise spray technology for use in a range of cloud conditions.

O3: Deliver a real-world experimental framework to rigorously assess the viability of spray technologies for influencing local albedo change in clear and cloudy conditions, and examine cloud property changes

O4: Assess the local, regional mesoscale and climate-scale dynamical responses and impacts of a large-scale implementation of spray technology for MCB and MSB.

O5: Evaluate the wider risks and benefits of future development and use.

O6: Develop and manage a responsible research and societal engagement framework, building on well-established imperatives for socially desirable science and innovation, undertaken in the public interest.

1.3 Research Description: We envisage a set of coupled work packages (**WP**s) to address widely recognised research questions (**RQ**s)[1], conducting limited area field trials and determining impacts via ***predict-test-monitor-validate*** cycles, focusing on new approaches and validating the outcomes (see Fig.1).

Work package A (WPA): Effective Spray Generation of Aerosols (UoC, Archipelago, UoM); (O1, O2)

RQ1: *Can a robust sprayer be designed for use in the marine environment which delivers aerosol particles in an appropriate size range, at the requisite rate (informed by WPC) with reasonable energy use.*

The focus is to research promising novel droplet generation methods for MCB/MSB (Fig. 1) that may prove more optimal than current effervescent spraying technology. We aim to develop at least two of the following emerging spray techniques into efficient field deployable prototypes: 1) superheated atomisation[3,4]; 2) electrospraying[5,6]; 3) Rayleigh jets[5,6,7]; 4) bubble bursting atomisation[8,9]; 5) Powercloud spray system from inkjet technology developer Archipelago Technology. Only the superheated approach is developed elsewhere, by a close collaborator, Southern Cross University (SCU).

Spray technology development will proceed in three stages. *Stage A1* will develop each of the five methods in parallel at the laboratory scale with single nozzle testing including combinations so that the findings from one method can be applied to others. The methods that show most promise will progress to *Stage A2* where arrays of nozzles will be tested within wind tunnel facilities at UoC and the Manchester Ice Cloud Chamber (MICC). These experiments will examine whether aerosol particle size distributions change as a result of coagulation before scaling the technology further. *Stage A3* will scale up at least two of the technologies into prototypes for field testing. Prior to a stage gate review at **M32** or any outdoor trials, the prototypes will be tested indoors, in a large controlled environment such as a hangar or warehouse. This is a low risk approach to verify correct and safe operation of the entire spray generation system, including droplet dispersal and filtration before going out into the field.

The progression of each technology is dependent on evaluation against the following metrics: spray generation rate, droplet size range, overall power consumption and unit cost to achieve the target spray rates, filtration requirements, spatial requirements, robustness to marine environments, and manufacturability. The latest results from our chamber experiments and parcel modelling (**RQ2**) will provide metrics to evaluate and improve sprayer performance during laboratory scale development. Technologies that show no improvement over existing spray technology will not progress to the next stage; however, the risk of not producing new applications is low since we are pursuing multiple approaches. Impacts of sprayer performance will be tested in **WPC**.

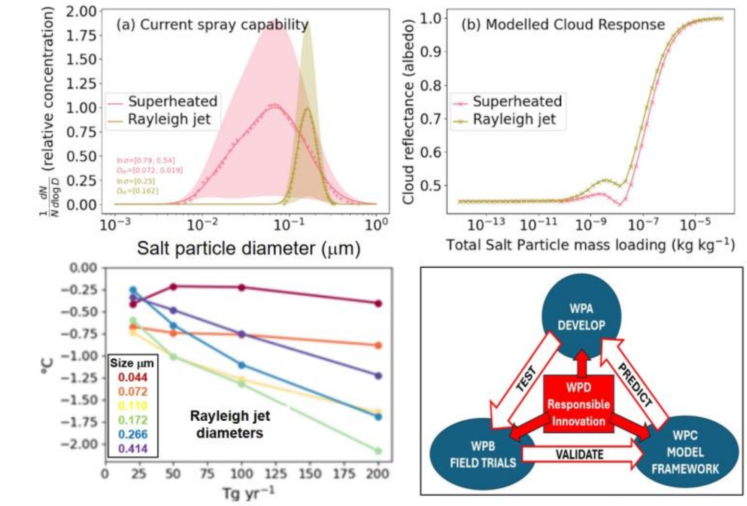


Figure 1. (a) spray number size distribution of two methods developed by UoC, the Rayleigh jet distribution is narrow and represents significant advance, (b) cloud albedo using the UoM parcel model two spray distributions including representative background aerosol populations. The reduction of cloud albedo seen in the superheated spray case is avoided for the Rayleigh Jet, (c) UKESM1 climate model simulations (Haywood et al., 2023) - the Rayleigh jet optimises the global mean cooling for significant injection rates.

Methods 1-4 will involve the use of engineering design consultants (UoC currently liaising with a potential subcontractor) for prototype(s) design. The design scale-up for method 5 will be undertaken by Archipelago and the manufacturing of a prototype for all methods will involve outsourcing to fabrication companies. We are working closely with SCU who have suppliers with relevant experience in engineering for marine environments willing to share knowledge to streamline development. We have already identified suppliers with capacity for manufacturing some of the main components for each technology, including for silicon-based nozzles .

Key outcomes: KO1: Single nozzle tests and stage one technology evaluations completed for at least two methods (**M6**) and for three further methods (**M18**); KO2: Multi-nozzle tests and stage two technology evaluations completed for at least one technique (**M18**) and for the remaining techniques (**M30**); KO3: First field trial capable prototype designed, built and fully tested indoors (**M30**) KO4: Second prototype tested indoors (**M36**); KO5: Continued testing (indoors) and refinement of prototypes and final design recommendation for full MCB/MSB deployment (**M60**).

RQ2: *Do models correctly capture the competition effects between aerosol particles of different sizes and composition during realistic cloud formation experiments?*

Whether injecting NaCl particles into the base of marine clouds will give the desired cloud response depends on how aerosol particles of different sizes and compositions compete for water vapour. If too many small particles are generated they may not be capable of growing into cloud droplets, on the other hand, large particles require a lot of water to grow and this can suppress clouds forming on smaller particles, and may also lead to drizzle. Understanding these competition effects is crucial to addressing **RQ1**[10]. Single particle experiments or use of cloud condensation nuclei (CCN) counters cannot test process-level models that predict the dynamic competition for water vapour that occurs in a real cloud with a mixed population of particles (e.g. Fig 1a-b). We propose to experimentally test this for the first time by comparing our process models, ACPIM[11] and PARSEC[12], to results from the UoM cloud and aerosol chamber. Findings will be directly fed into the multi-scale modelling framework (**WPC**, Fig 2), since PARSEC is embedded in the UK Met Office Unified Model (UM) via UKESM1 (**WPC**).

During the first 6 months we propose necessary upgrades to the MICC by fitting new state-of-the-art probes using customised inlets fabricated at the UoM. We will also build a standalone spray system for aerosol generation, based on known technology (Palas UGF2000) and ultrasonic atomisation that can generate realistic background aerosol size distributions with mode diameters in the range 40 to 250nm. This relatively low-tech development does not have the same potential for scale-up as the spray technology in **RQ1**, but it can produce variable particle size distributions and allows experiments to commence quickly. We propose to use two simple, single component aerosols for background activation experiments such as $(NH_4)_2SO_4$ and fulvic acid, which span observed atmospheric aerosol hygroscopicity. Aerosols will be generated inside the MICC, and we will perform cloud formation experiments, measuring the cloud drops. Experimental data will be used to drive the UoM cloud parcel model, ACPIM[11], developed to evaluate competition effects. We will experiment with external mixtures of both background aerosol and NaCl aerosol, evaluating against ACPIM and correcting biases. Findings from the experiments will be transferred to **RQ1** so that the correct droplet sizes and concentrations can be targeted. As the spray systems mature they will be deployed in the MICC to test their performance in competition with a background aerosol population.

Key outcomes: KO6: MICC upgrades (**M06**); KO7: MICC experiments evaluating single component aerosol ($(NH_4)_2SO_4$, organic acid) at 3 different mode sizes compared to ACPIM simulations using approximately 5 cooling rates (**M10**) KO8: addition of external mixtures of NaCl particles of different sizes with feedback to spray development (**M18**); KO9: external mixture evaluation using new spray technology in MICC (**M24**); KO10: refinement of spray technology during MICC tests (**M30**).

Work Package B (WPB): Field Trials (UoM, UoC, UoL) (O3; O4; O5; O6)

RQ3: *How can a UK based experimental test bed for examining spray technology applications for marine atmospheres which is transparent and objective be established and delivered?*

RQ4: *Will different spray technologies perform as expected in an operational environment?*

RQ5: *Can local albedo changes induced by an evolving spray plume be detected, perturbations to microphysical properties be observed, and results correctly predicted in cloud-free and cloudy conditions?*

We propose an experimental test bed that will be used to validate (i) spray performance in real world conditions and (ii) model tools that predict aerosol mixing through the boundary layer, impacts on the surface albedo and responses of the cloud. The WP is deliberately cautiously staged, with a formal stage gate review at **M32** to externally evaluate the effectiveness, safety, and risks before any field experiments are carried out. It will develop in close synergy with our responsible research and innovation[13] (RRI) framework (**WPD**) and be regularly examined by our management team and key stakeholders (Part 2: Governance). A second stage gate at **M42** is possible to allow re-evaluation after the initial experiment.

Stage B1 (M1-M32): identification of field location, safety and risk management framework development: Identification of an optimum field location will be made in year 1 based on the likelihood of representative conditions and operational considerations. A coastal, land-based location will: reduce cost; allow ready access to technical support for ease of servicing/modifying; facilitate space and power for sprayers and instrumentation. In the case of the second field experiment, the background CCN concentration should be as close to 100 cm^{-3} as possible to represent clean, marine conditions[14] where cloud albedo response is sensitive[15] and ideally an airfield for small aircraft within range. Initial investigations suggest the Weybourne Atmospheric Observatory (north Norfolk), for example, provides a very promising location for the first stage field trials having sufficient power, space, hard standing, an adjacent grass airstrip for UAVs, and easy access from Cambridge.

A Technical, Safety and Risk Management Framework will be developed synergistically with the RRI Framework (**WPD**), guided by the technical consideration decision tree (Fig 2) and funding approval decision tree (Fig. 3) in the ARIA Programme Thesis. Our framework will be a living document that, alongside a technical progress report and the RRI Framework (**WPD**), will form the basis of the Stage Gate review (**M32**) and acceptance via the ARIA evaluation process ahead of any field trials. This will include the plans, safety documentation and technical, regulatory and environmental assessments of risk and mitigation plans.

Importantly, Box 1 summarises the size of the particle generation sufficient to examine the effectiveness of the sprayers but not to cause regional impacts and these scales bound the size of our experiments. We will begin with low emission rates ($\sim 10^{14}$ s^{-1}) lasting only a few minutes, evaluating outcomes and risks at each stage as we scale in a stepwise manner to approach target rates of $\sim 5\times10^{16}$ s^{-1} lasting up to one hour to examine cloud interactions. Our experiments involve real time monitoring so that they can be

BOX 1: TARGET SPRAY RATES FOR SAFE, CONTROLLED BUT MEASUREABLE

A spray rate of 1×10^{15} s^{-1} injected into a 1 km deep boundary layer with a mean wind speed of 10 ms^{-1} will yield concentrations of 100 cm^{-3}, equivalent to a marine background only 10 km downwind.

To examine cloud perturbations, distance scales would need to be 30-40 km to allow the plume to mix through the depth of the boundary layer. A spray rate of 5×10^{16} s^{-1} would lead to 300-500 cm^{-3} at these distances, with plume widths of less than 3-4 km.

rapidly terminated. Our Framework documentation will include wider safety assessments such as near field exposure, discussions with landowners, and government compliance (eg Environment Agency, SEPA). A risk assessment and Environmental Impact Assessment will be carried out, though we anticipate risks are very low given that the volumes of filtered seawater are of the order of 5-6 l/min or 300-400l over a hour long experiment and spraying will be done in offshore wind conditions. Drafts of the framework will be regularly presented to ARIA, our Advisory Board, and to Key stakeholders (see **WPD**) and recommendations incorporated into the document which will be made publicly available online.

Key outcomes: KO11: Locations selected for the two field deployment (**M18**) KO12: Technical, Safety and Risk Management Framework developed (**Draft M24; Acceptance Stage Gate M32**)

Stage B2 (M32-M48): Testing Effective Distribution of Spray Aerosols in the Atmospheric Boundary Layer. Generation of large aerosols or near-field coagulation may produce giant CCN that may preferentially activate, suppressing activation of background aerosol[16] and/or initiating drizzle[17]. Rapid evaporation of water from the spray may inhibit mixing[18], and although initial experiments[19] and modeling[20] suggest this effect may be modest, confirmation via field observations is necessary. Spray generation and mixing will be tested in this first field trial. Field scale spray systems (**WPA**) will be deployed alongside the current SCU spray system for comparison in a 40 day field experiment (**M38**). Atmospheric monitoring of the marine boundary layer will include use of radiosondes, a wind profiler, radiometers and a ceilometer as well as in-situ observations of the background aerosol, temperature and humidity. Operational models (Met Office's Unified Model (UM) and Numerical Atmospheric-dispersion Modelling Environment (NAME) will forecast plume direction, altitude and dispersion width. Plume evolution will be observed by scanning aerosol and Doppler lidars. A UAV mounted aerosol instrument will examine the aerosol size distribution development in the plume (100nm-10μm diameter) and UAV borne radiometers will monitor any resulting changes in the local planetary albedo. These observations will constrain and validate our models of physical and thermodynamical plume evolution, mixing and impact on albedo. Large Eddy Model (LEM) simulations will be used to interpret the observations (**WPC**).

Key Outcomes: KO13: Assessment of performance of spray technologies (**WPA**) in real world conditions to inform final stage-gate review (**M42**). KO14: Data stored in a publicly available repository (**M42**).

Stage B3 (M42-M60): Determination of Clear Sky Albedo and Cloud Responses to Aerosol Injection into the Boundary Layer: Responses of clouds to changes in aerosol are highly uncertain. Introduction of aerosol into a cloud system may change drizzle, cloud thickness, entrainment and diurnal cycle of cloud, all of which interact with each other in complex ways. LEM and Cloud Resolving Model (CRM) tools have been used to investigate these interactions but critically have yet to be tested against observations of an aerosol injection on a scale large enough to assess cloud responses. The second 40 day field study (**M48**), will seek to investigate cloud responses and test the LEM and CRM cloud simulations (**WPC**). A new Frequency Modulated Continuous Wave (FMCW) mobile cloud radar and micro rain radar will be added to the Stage B2 observations. The FMCW radar is capable of high resolution scanning and retrieval of droplet size distributions and so offers a powerful way of examining the plume interaction with cloud. These observations will deliver the necessary constraints to validate model predictions and target improvements. At the scales envisaged large aircraft fly too fast to adequately resolve the plume features though small, slower aircraft may be deployed.

Key Outcomes: KO15: Public report on field trial outcomes (**M60**); KO16 Publicly available data archive (**M60**).

Work Package C (WPC): Modelling (UoE, FMI) (O4, O5)
RQ6: *How accurately can model predictions of MCB/MSB, optimised using information from sprayers, be represented across a range of scales?*
RQ7: *What are the regional and global impacts of MCB and MSB?*
In WPC we will assess the regional dynamical and climate scale responses and impacts of a large-scale implementation of spray technology for MCB and MSB. An essential part of our ***test/monitor/validate*** strategy is the use of models to extend the necessarily limited number of observations at local scales (**WPA**, **WPB**) to additional meteorological regimes and to larger spatial scales. This will be achieved through a seamless multiscale-framework (Figure 2). We will utilise:-

i) Parcel models: The UoE cloud parcel model (PARSEC)[12], and the UoM bin microphysics model (ACPIM)[11] are state-of-the-art size dependent cloud models that serve as the benchmarks for the development of droplet activation parameterisations in climate models. PARSEC is already operational within the UM, and whilst too computationally expensive for decadal simulations, can be used for shorter (up to 1 year) process-orientated UM simulations. PARSEC can track aerosol growth and evaporation for specific bin sizes explicitly in global

climate simulations allowing competition effects to be quantified for regions with different background aerosol and updraft regimes for comparison against idealised chamber experiments (**WPA**).
ii) ***LES models:*** The Met Office NERC Cloud model (MONC)[21] multi-moment bulk microphysics model and the UCLA Large-Eddy Simulation (UCLALES) coupled with the Sectional Aerosol module for Large-Scale Applications (SALSA)[22] bridge the gap between microphysical processes and larger scale models (Figure 2). iii) ***Nested models:*** The Nested Unified Model with Aerosol and Chemistry (NUMAC)[23] can be used to assess the impact of plume concentrations at surface level, visibility, deposition etc. that cannot be resolved with climate models. iv) ***Earth System Models:*** UKESM1 is a well-respected climate model that can be used to assess the dynamical impacts of MCB/MSB[24].

Scale	Model/ Resolutn	Application	Utility
Earth System Model	UKESM /120km	Sprayer size distribution as input to parameterised or explicit activation schemes	• Enables estimation of scaled-up climate impacts for MCB and MSB. • Allows assessment of large-scale climate impacts. • Allows future scenarios to be performed that use MSB/MCB to combat impacts of climate change. • Haywood, J. M. et al., doi:10.5194/acp-23-15305-2023, 2023.
Nested Model	NUMAC /5km	As above, but can resolve clouds at 5km resolution	• Reasonably realistic representation of clouds at updraft velocities and variability resolved • Aerosol plumes explicitly represented. • Can predict the evolution of plumes from field trials • Gordon, H., et al., doi:10.1029/2022MS003457.
Large Eddy Simulation (LES)	MONC EUCALES SALSA /1m	Explicit representation of turbulence and activation and aerosol size distribution	• Primary tool for assessing/validating field-trials • Scale-appropriate for assessing impacts on clouds at a local scale • Sectional aerosol schemes allow explicit representation of aerosol size distribution and microphysical interactions. • Brown et al., 10.48550/arXiv.2009.12849; Tontilla et al. doi:10.5194/gmd-10-169-2017
Parcel Model	PARSEC & ACPIM /1µm	Explicit condensation and evaporation of water vapor on aerosols, particle activation and droplet growth	• Primary tool for investigating aerosol activation into cloud drops. • Bin microphysics schemes allow explicit representation of condensational growth of aerosols and cloud droplets. • Can predict water vapour competition effects and the size dependent CCN-activity of aerosol particles • Heikkinen et al., https://doi.org/10.5194/acp-24-5117-2024; James et al., https://doi.org/10.5194/acp-23-9099-2023

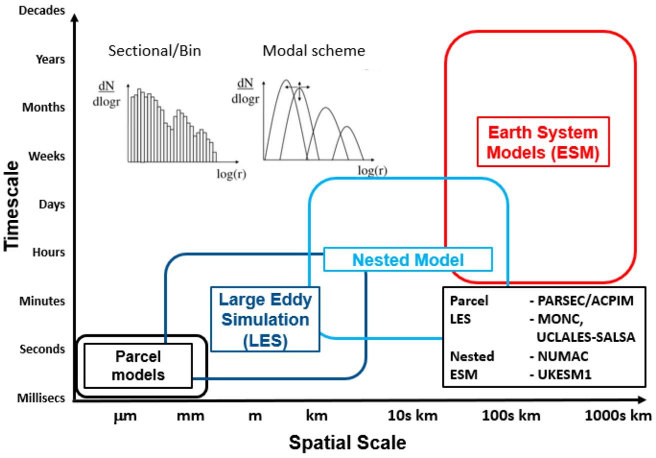


Figure 2. Left Panel): details of the specific models that are proposed. Right Panel): models and their spatial scales and schematic of sectional and modal aerosol size distributions.

MONC and UCLALES simulations will be performed using the observed aerosol size distribution from the sprayers and appropriate meteorological boundary conditions to simulate the aerosol plume and impacts on cloud development, microphysical and radiative properties (see **WPB**). Synergistic NUMAC model simulations and UKESM1 coupled simulations will investigate a number of scaled up deployments. These will include centring the NUMAC grid on i) the UK, ii) the Namibian stratocumulus cloud deck, iii) the Caribbean ocean, iv) the N. Atlantic Ocean, and v) the Indian Ocean. These simulations will use the sprayer-derived aerosol size distribution (**WPA/WPB**) which can be explicitly modelled in terms of emissions (Figure 1c) and will use the standard activation scheme[19] and that developed from emulation of the PARSEC model to facilitate accurate simulation of cloud droplet number response to spray injection on climate timescales. UKESM1 simulations, which are fully coupled to a dynamical ocean, will allow assessments of dynamical feedbacks, and the local and remote cooling impacts for each of the regions where sea-salt aerosol is applied. This is critical in understanding climate impacts should any deployment be successful in cooling a limited area of the ocean as inhomogeneous spray deployments have been shown to lead to very inhomogeneous climate responses[24,25]. Particular foci will be on the effectiveness of MCB/MSB in ameliorating climate extremes, tipping points and climate change-induced wildfire, hurricane development, Amazon die-back, sea-ice loss, and changes in the Indian monsoon as appropriate. Other areas may be investigated.
NUMAC simulations are unable to provide climate projections, but the superior resolution provides a realistic and more detailed representation of the impacts on cloud properties and precipitation for any potential deployments. Air-quality (sea-spray contributes to the PM2.5 and PM10 pollution targets adopted by the UK and internationally) will be impacted by extensive sprayer deployments and could lead to some deleterious impacts if deployed around populous regions. Similarly, visibility could be very strongly impacted[24]. Simulations can adjust deployment strategies to take account of e.g. location, time of year, meteorological conditions etc. Time-slice NUMAC simulations will be run for future scenarios through to the end of the century utilising various future Shared Socioeconomic Pathways (SSP) and GeoMIP scenarios.

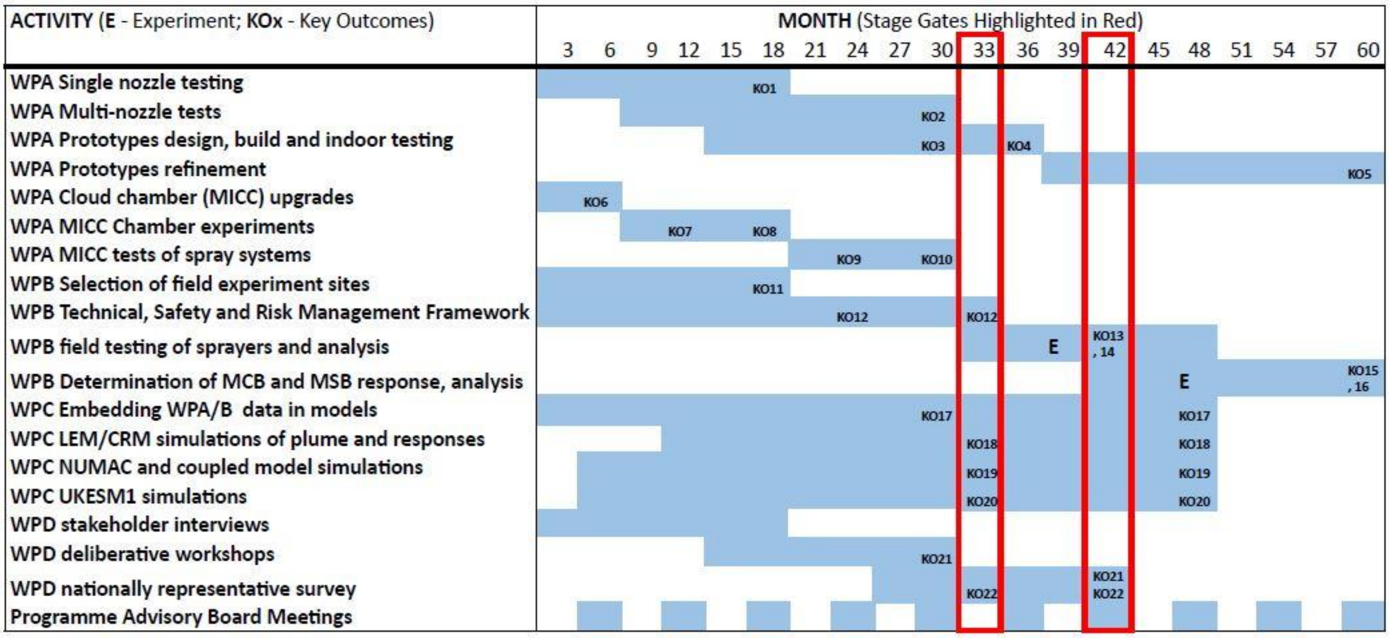
Key Outcomes: KO17: Spray characteristics embedded into models (**M30; M42**) KO18: Simulations of aerosol plume and impacts on cloud evolution and radiative properties (**M32; M48**); KO19: Reports on impacts of sprayer deployments if applied to key regions optimised in **WPA** for MCB and MSB on simulations of cloud, visibility, air-quality and further optimisation/improvement (**M32; M48**) K020: impacts of optimised sprayer deployment for MCB and MSB under various future climate scenarios (UKESM1-climate) (**M32; M48**)

Work Package D (WPD): Responsible Innovation and Societal Engagement (UoM) (O6)
R6: *How can MCB/MSB field experiments be conducted responsibly and under what societal pre-conditions?*

We build on well-established imperatives for science and innovation that it is socially desirable and undertaken in the public interest, by seeking to (i) "anticipate" the impacts of MCB/MSB field experiments; (ii) "reflect" on the uncertainties and ambiguities of research; (iii) "engage" in meaningful two-way engagement with society; and (iv) "act" on its findings to inform the trajectory of MCB/MSB research and innovation in the project and more broadly[13,26]. We will facilitate "upstream" societal engagement to address these aspects in advance of significant research activities to help avoid sociotechnical lock-in to undesirable pathways. **WPD** will elicit perceptions of, and preferences for, MCB/MSB experimentation pathways through (1) semi-structured interviews with diverse experts and stakeholders from across academia, government, civil society, and industry (**M1-18**), (2) qualitative deliberative workshops with socio-demographically diverse members of the public[27] (**M15-30**), and (3) a quantitative nationally representative survey of the public (**M27-41**). The work will include consideration of key ethical concerns known to pervade SRM research, including 'moral hazard' or 'mitigation deterrence' (the pursuit of MCB/MSB may distract from efforts to reduce greenhouse gas emissions) and 'slippery slope' (research and experimentation may lead to undesirable deployment)[28].
In tandem with the project's technical stage-gate process (see **WPB**), **WPD** will develop and apply a social stage-gate process to ensure that responsible innovation is addressed prior to MCB/MSB field experiments taking place (M38, M48). Building on earlier frameworks, this will include consideration of risk management, regulatory compliance, clear communication, impacts review, and stakeholder and public engagement[13]. This forms part of our wider commitment to the ARIA Programme Oversight and Governance measures, which will include regular engagement with the Independent Oversight Committee (IOC) and our own independent oversight and advisory group (IOAG) (see **Management and Governance of the project**).
These tasks will be carried out by a dedicated responsible innovation and societal engagement Postdoctoral Research Associate and supported by the work package lead.

Key outcomes: KO21 Synthesis of the stakeholder interviews and public workshops and survey on the responsible conduct and societal preconditions for MCB/MSB field experiments (**M30**), that are peer reviewed (**M41**); KO22 a social stage-gate process for ensuring that responsible innovation is addressed prior to MCB/MSB field experiments taking place (**M33**, **M42**).

1.4 Timelines and Key Outcomes



1.5 Synergies: In **WPA**, the work being undertaken by UoC is also costed in the proposal being developed by SCU. If both proposals are funded, there is no need to duplicate the UoC costs. It is planned that use of the sprayers for field experiments will be at different times to save on infrastructure and sprayer costs, and so that practical experiences from different field trials can be shared across the two teams. Where possible, we will use as much of the SCU back-end equipment that has already been demonstrated during their previous field trials (e.g. filtration, pumps, and generators) to provide cost savings, reduce risk, and streamline development. Planned use of the MICC chamber in other proposals is either to test new particle types or work on SAI and there is no overlap with the more comprehensive competition experiments planned here. **WPB:** There is considerable synergy between this proposal and that of SCU. Examination of aerosol injection into the marine boundary layer and its effects on radiation and clouds needs to be carried out at a number of small, experimental scales to test cloud responses under different meteorological and cloud microphysical regimes. The SCU proposal is very complementary, focusing on subtropical Cu clouds, which will respond very differently. Further, we provide a UK testbed and a legacy capability for the UK. This proposal would benefit from the ARIA proposal led by Girdwood to develop a drone based platform for MCB, but we limit reliance on UAVs in this work to sub-cloud aerosol and can use pre-existing instruments if necessary. A part of **WPC** is complimentary to some NERC proposals submitted to the recent SRM call but the work is not focused on assessing the wider impacts of sprayer development that are at the heart of **WPC**. **WPD** is likely to have synergies with potential cross-programme social science proposals through its wider responsible innovation activities and its expert, stakeholder and public engagement activities in particular. Cross-cutting ethical concerns are likely to arise in other funded technical projects with which we will engage.

1.6 Overall project risk and mitigation: The main risk to the project is that a field location for testing (**WPB**) cannot be found (unlikely) or cannot be developed due to a lack of public acceptance or stakeholder requirements that cannot be addressed. The **M32** stage-gate ensures that we are not committed to large field costs until the field site and associated social acceptance and regulatory compliance is approved by the ARIA process. This alleviates substantial financial risk since the field costs are approximately £4.5M, 40% of the total budget. Even if the field trials cannot be delivered, the project will deliver a large number of successful outcomes since the spray development and optimisation (**WPA**), the impacts of its regional and global implementation (**WPC**), and the development of a technical (**WPC**) and RRI plan (**WPD**) would have all been delivered. We have discussed other specific risks along with their mitigation in the relevant **WP**s.

<u>Section 2: The Team</u>

2.1 Details of Project Team

[redacted]

[redacted]

[redacted].

[redacted]

2.2 Third Parties and Sub-Contractors: Nozzle design assembly and manufacturer will need to go to tender. Cambridge Design Partnership has been identified as a potential subcontractor. Initial costings have been provided, but at least two other potential subcontractors will be approached in line with the procurement policy of the University of Cambridge. Contractors may well be used to provide some of the field logistics infrastructure. Archipelago will use two subcontractors, both of whom it has worked with extensively.

2.3 Management and Governance of the project Overall project management will be the responsibility of the project management group (PMG). It will meet quarterly (twice in person; twice online) to review WP progress, budgets, the risk register, engagement with local community groups and other stakeholders, data quality assurance and availability, and communications. Chaired by the PI [redacted], it will include the Partner leads, [redacted] (RRI lead), the NCAS Communications lead ([redacted] and the Project Manager. The PM will work alongside the PI and will be responsible for operational management, including ensuring that records of all meetings are publicly available and reporting is timely and transparent.

Our data management and stewardship will follow the FAIR Principles. It will be made publicly available promptly and will have clear and full metadata. The atmospheric observations during the field trials will be carried out through the NCAS Atmospheric Measurement and Observation Facility (AMOF). AMOF Data is made available through the Centre for Environmental Data Analysis (CEDA). Laboratory and model data will be made available through host institution servers. All data will be signposted through the project website.

Project Governance will be guided by the ARIA Exploring Climate Cooling Programme Oversight and Governance document. The PMG and PM will work closely with the ARIA leadership and its Independent Oversight Committee (IOC), providing regular updates and meeting reporting requirements. We will set up a project specific independent oversight and advisory group (IOAG). It will meet twice yearly to provide critical feedback to the PMG, drawing on the ARIA Governance measures. It will aid the development of the Technical, Safety and Risk Management Framework (**WPB**). It will appraise the project approach to RRI (**WPD**), which is guided by the UKRI AREA Responsible Innovation Framework and the Oxford Principles for Geoengineering Governance and examine engagement with the wider public and key stakeholders. [redacted] has already agreed to sit on the IOAG and we will advertise for other members. IOAG views will be cascaded to organisations' senior management teams, the ARIA Leadership and the ARIA IOC.

NCAS Communications will work with the communications teams from the partner organisations across the project to build a unified communications strategy; assign roles and responsibilities; coordinate regular meetings; develop a communications calendar and digital content (incl. web design/hosting, campaign branding); evaluate/optimise communications; develop a community-building stream to enable effective KE.

2.4 Motivation We are extremely motivated by this project. Substantial action to reduce carbon emissions is essential and SRM is not an alternative to that primary goal. Equally, we are aware that rapid interventions may help avoid harm until carbon reductions can be ramped up. We believe that MCB is one of the most likely schemes to make a difference on a decadal timescale. We are convinced that small scale field experiments are a necessary next step in developing the knowledge needed to predict how the atmosphere responds to MCB perturbations and wish to ensure that independent assessment of technology is at the core of the approach. The project also provides key team members with a unique opportunity to use their combined skills and knowledge in a broad range of areas which will be incredibly fulfilling.

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Marine Cloud Brightening in a complex world – moving beyond the Twomey effect

[redacted]

Section1: Programme and Technical

Aim. Advance the technical feasibility, social license and scientific understanding of efficacy and risks of Marine Cloud Brightening (MCB). By undertaking the next generation of outdoor experimentation enabled through the development of technology, methodology, numerical modelling, governance, and engagement.

Programme alignment. Anthropogenic climate change is increasing the global temperature, with serious consequences already observed in marine, terrestrial, and human ecosystems. A prominent example is the increase in frequency and severity of marine heatwaves leading to mass coral bleaching events which now threaten coral reefs globally. Aerosol emissions, through their light scattering properties and interactions with clouds, constitute the largest negative anthropogenic forcing in the global radiative energy balance[1]. It follows that deliberately leveraging aerosol-cloud-radiation processes is the basis for several proposed methods to actively cool the earth, including the marine cloud brightening and marine sky brightening (MSB) techniques. The extent of uncertainty in the magnitude of these forcings[1] highlights the need to better constrain the numerous atmospheric processes which are impacted by a change in composition and quantity of aerosol loading[2]. Understanding how MCB impacts these complex interactions (see Fig. 1A) can only be achieved through a program of real-world experimentation on clouds, combined with adequate, high-resolution numerical modelling of the underlying processes [2, 3]. To evaluate the benefits and risks of various MCB implementation scenarios, it is necessary to extend real-world experiments sufficiently to capture the impacted processes and conduct numerical modelling over multiple scales to not only consider local effects, but approach regional impacts that are inherently difficult to constrain[3].

Background. Building on over 30+ years of theoretical study, Southern Cross University (SCU) and partners have advanced MCB research from theory and laboratory studies to outdoor experiments[4] measuring *in-situ* with aircraft the cloud microphysical response to perturbation (Fig. 1 B&E). In our nozzle laboratory we refined the effervescent atomisation technique[5] to create aerosols at MCB relevant sizes with number production rates and energy efficiency which enable outdoor field testing to occur[4, 6]. From 2020 to 2024 we successfully scaled up outdoor field-testing prototypes from 100 to 640 nozzles and developed the Aerosol, Radiation, and their Interactions Experimental Laboratory (ARIEL) spraying system. ARIEL can produce up to 10^{15} s^{-1} sea spray aerosol (SSA) in three distinctly different aerosol size spectra to tease out the influence of competing cloud processes and direct radiative responses (Fig. 1C).

A series of 'point source' perturbation experiments over the Great Barrier Reef (GBR) have been completed to evaluate the sensitivity of trade wind cumulus clouds to the artificially generated SSA. We have demonstrated a key underpinning hypothesis of the MCB concept, that supplying additional cloud condensation nuclei (CCN) can, for a given cloud liquid water content, decrease the cloud drop effective radius (Fig. 1D) and increase the droplet number concentration (Fig. 1E). These initial shifts in cloud microphysical properties are those proposed by Twomey[7] (Fig. 1A) and are expected to result in a predictable initial albedo increase for the cloud (1st aerosol indirect effect). While the resulting albedo increase can be calculated[8], it has not yet been measured explicitly during our field experiments due to their limited scale. Beyond the initial Twomey effect, MCB is expected to result in a series of adjustments to cloud properties (2nd aerosol indirect effects; Fig. 1A) which may further increase, or conversely reduce, the net radiative forcing. Both the sign and magnitude of these interacting effects are influenced by the concentration, composition, and size distribution of the artificially generated aerosol as well as that of the background aerosol, the prevailing atmospheric conditions, and the nature of clouds present. Understanding these interlinked processes sufficiently well to estimate their respective importance and cumulative impact on radiative forcing is key to accurately predicting the efficacy and risks of MCB for a given atmospheric and meteorological situation.

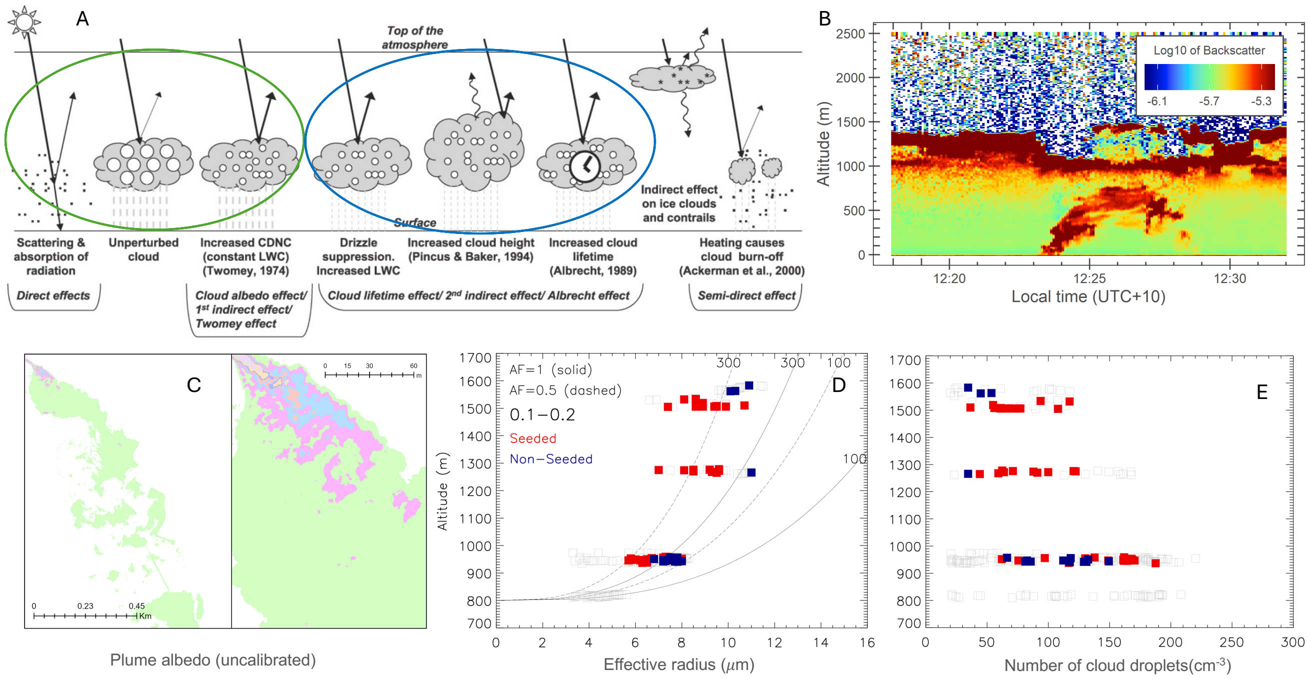

__Figure 1:__ (A) Aerosol-cloud-radiative processes[9], green circle represents MCB effects measured in past campaigns (C-E), blue indicates effects targeted in this proposal. (B) LiDAR measurement from a sampling vessel of the ARIEL produced MCB plume lifting into a cloud layer at ~ 1000m cloud base altitude. (C) uncalibrated albedo of MSB (direct effect) from the aircraft mounted hyperspectral camera (still in processing), vessel is in upper left corner. (D&E) Within-cloud results demonstrating the Twomey effect.

Why the GBR? Low cloud over the GBR consists of stratocumulus, shallow trade wind cumulus, and cumulus of greater vertical development, with the latter two classifications being more common during our field campaign periods in summertime[10]. Our work has shown that meteorology and clouds in the GBR region play an important role in coral bleaching events[11, 12]. Corals experience bleaching due to a combination of both heat and light stress[13-15]. Modelling[16], field observations[6], and our previous MCB experiments (Fig. 1B-E) demonstrates that sky and cloud albedo over the GBR is sensitive to aerosol perturbation. Hydrodynamic modelling indicates that the unique shallow semi-enclosed bathymetry of the GBR lagoon provides an ideal case study, where application of MCB at a regional scale could lead to significant sea surface temperature reductions[17]. Implementation over as little as 10% of the GBR would be effective in reducing ocean temperature and mitigating coral bleaching. Evidence that MCB could meaningfully alter the trajectory of live coral cover on the GBR over the coming decades[18] makes this a promising application of technology to actively cool the earth. Our work on the GBR has proceeded under federal regulatory approval and with effective governance mechanisms in place[19, 20]. The Australian public supports further research, and is 'accepting' of cloud brightening on the GBR with 63% supporting (69% within region), and 14% rejecting this intervention in a national survey[21].

Advancing the state of the science. A challenge of measuring albedo change in cumulus cloud fields is that the perturbation does not necessarily affect the entire cloud at once and can progress in individually impacted clouds at different rates and locations (Fig. 2). We propose to address this challenge by employing an upscaled experimental approach. By including 2-3 MCB spraying vessels and increasing the output of the next generation of ARIEL, we will aim to achieve a degree of homogenisation of the enhanced CCN concentration within an area of approximately 10x10 km. By utilising two sampling aircraft we will measure the albedo change in a more uniformly perturbed region of cloud and begin to examine experimentally the microphysics induced changes to whole-of-cloud structure with time (1-2 hours) that result in the 2nd aerosol indirect effects (Fig. 1A).

We will apply a state-of-the–art lagrangian cloud model (LCM) [22, 23] coupled to a large-eddy simulation model[24] for high resolution MCB simulations. The LCM relies on individually simulated computational particles, each representing an ensemble of identical hydrometeors (aerosols, cloud droplets, rain drops), where process rates are determined from first principles. The use of individually simulated particles allows the physicochemical properties of the sprayed and natural aerosol to be directly described, a prerequisite to investigating the effects of MCB on clouds in the required detail. Within the two-way coupled LES-LCM framework, we can investigate the interactions of dynamics, aerosol, and cloud microphysics essential to quantifying aerosol indirect effects on clouds and radiation, e.g., the turbulent transport of sprayed aerosol to the cloud base (see. Fig. 1B), their subsequent activation determined by the cloud's updraft, as well as the turbulent mixing of the cloud with its environment and the subsequent effects on the number and size of cloud droplets and evolution of the cloud properties over time.

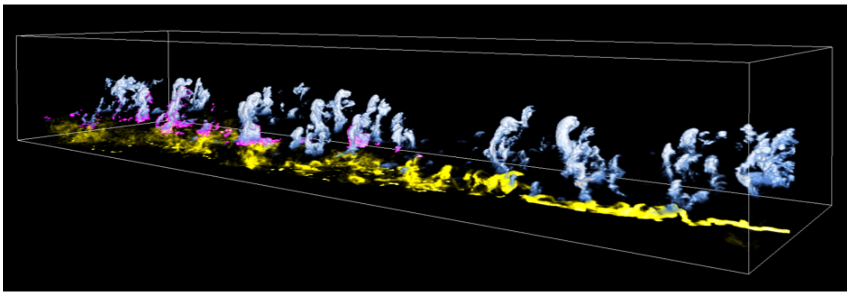

Figure 2: *LES-LCM model results of a single MCB spraying vessel (at far right) in a shallow cumulus cloud field with wind right to left. White = cloud, Yellow = MCB aerosol, Magenta = aerosol impacted cloud.*

ACCESS-EMS-GBR is a convection-permitting, coupled atmosphere-ocean model of the GBR that has been configured to undertake assessments of MCB using simulations at local to global scales. The model consists of a regional atmosphere configuration of the Australian Community Climate and Earth System Simulator (ACCESS), coupled for this project to the CSIRO Environmental Modelling Suite (EMS) hydrodynamic and biogeochemical model of the GBR. The resulting coupled model represents aerosol-cloud-radiation interactions, atmosphere-ocean heat feedbacks and subsequent impacts on the underlying coral reef, making it ideal for assessing the impacts and risks associated with MCB applied to the GBR and wider region. Higher resolution convection-resolving simulations are also achievable, and wider insights into potential benefits and pitfalls of MCB beyond the GBR application can also be derived.

Work detail. We propose activity across five work streams (WS A-E) each consisting of work packages.

WS.A Proposed technology development. To support the next phase of MCB research it is necessary to increase the total output of ARIEL and construct additional units. The most important improvement is to increase the number CCN produced per unit energy required. It is also desirable to decrease the total footprint of the system to allow operation on smaller and less costly vessels. Two shipping containers of ARIEL are each fully occupied by 3 sizable air compressors (total 6) that supply the large quantity of compressed air required (Fig. 3C). The requirement for compressed air is responsible for most of the energy, space, and weight of the overall system. The current technique achieves ~66% of the SSA within the target size range (Fig. 3A). We aim to improve the current system by targeting a reduction in the gas to liquid ratio (and hence energy) while improving output. In parallel we will investigate alternate technologies which may remove the need for compressed air entirely while also improving the size distribution (Fig. 3B).

WP.A1 Nozzle tech development (UoC & SCU, yr 1-3). Five alternative technologies to atomise the seawater will be developed and tested for size specificity, production rate, and energy efficiency. These include; superheated water[25-27], electrospray[28], Rayleigh jet breakup[29, 30], bubble formation from pressurised air[31], and Powercloud derived from Archipelago's proprietary Powerdrop ® technology. Several of these techniques are already showing promise of improved energy efficiency and size mono-specificity (Fig. 3B). Initially these methods will be developed and tested in parallel at the nozzle development facilities. SCU's dedicated facility includes two sizes of non-recirculating wind tunnel developed specifically for MCB nozzle testing. There is custom designed industrial plant to supply high pressure air, water, and heat. The key objectives are to establish the resulting aerosol size distribution, the degree to which it can be manipulated, the production rate, and energy efficiency for each technology. The leading two technologies will move to the prototype stage (internal performance stage gate). Spray characterisation results will inform WP.C2.

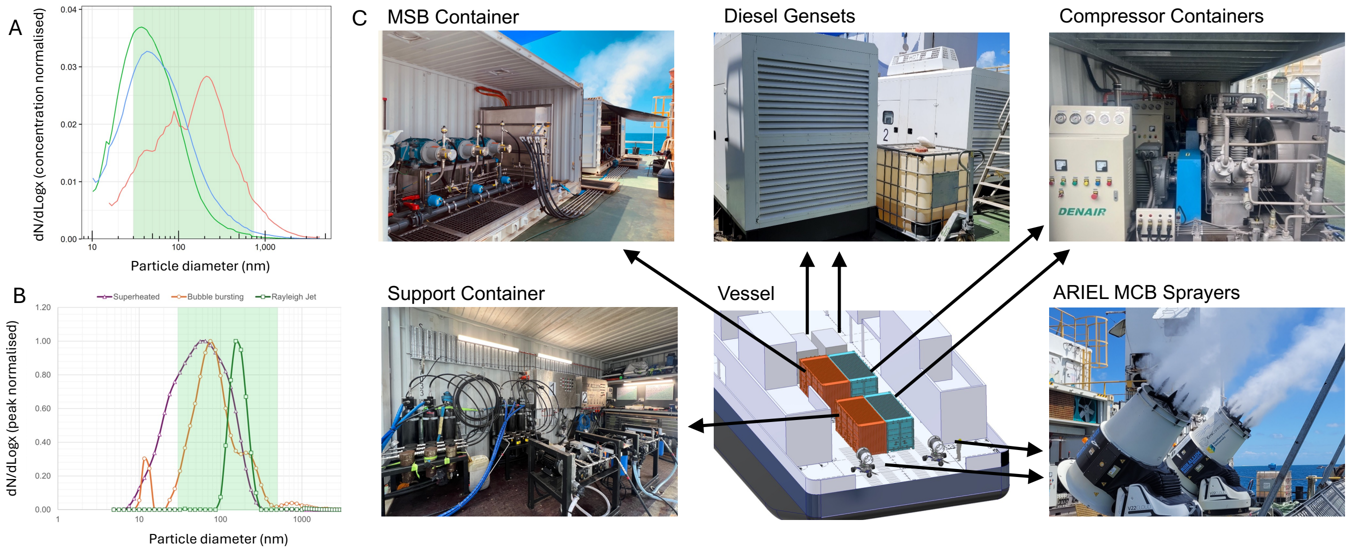

Figure 3: *(A) Field measured size distributions for the 3 sprays currently produced by ARIEL. (B) Alternate spray technologies showing improved fraction in the target range (green shading). (C) ARIEL components.*

WP.A2 Prototype development and testing (UoC & SCU, late yr 1 – yr 3). In this stage we will undertake the engineering design for an overall system of sufficient scale to achieve production of 0.5-1x10^{16} CCN s^{-1}, targeting ~10x increase on the current ARIEL output. The design phase will confirm the viability of upscaling the most promising water atomisation techniques to field testable prototypes and determine the process inputs, feasibility, safety, and environmental considerations. Following the design phase review (stage-gate) prototypes will be manufactured for field testing. This process will involve engineering design consultants and certifiers to ensure safety and regulatory compliance. The prototypes will be tested in WP.B2.

WP.A3 Prototype upscaling and manufacture (SCU & UoC, yr 4). Based on the outcome of WP.B2 field testing (stage-gate) a technology prototype will be selected for the manufacture of 1-2 additional systems. The final number of sprayers (target 3) will be dependent on performance and informed by modelling undertaken in WP.C1 to support the experimental planning. The system selected may be the existing ARIEL technology if new prototypes prove unable to outperform the existing system or are found to be unreliable or impractical for operations at sea. ARIEL was improved iteratively over multiple field campaigns and the expectation is that there will be improvements to new prototypes following each round of field testing.

WS.B Fieldwork. Ahead of the proposed outdoor field experiments we will refine and test our methodologies for tracing the generated aerosol plume in the atmosphere and for quantifying the cloud microphysical and albedo response. In later stages, preliminary outdoor experiments on land and at sea will provide opportunity for real-world testing and refinement of the improved ARIEL prototypes prior to design finalisation and multiple unit manufacture. The major MCB perturbation experiment will consist of a multi-spraying-source field campaign in which we aim to validate model predictions and explicitly measure the response of cloud albedo, and the extended series of cloud physics impacts illustrated in Fig 1A.

WP.B1. Methodology development (SCU & UNSW, yr 1-2). All but two methodologies required for the proposed fieldwork are now well refined to practice including; logistics, vessel fit out and operation, ARIEL reliability, methods to manipulate the size and salt composition of the spray, use of drones[4, 32-34], aircraft sampling operations[6], ground based remote sensing[34], and satellite observation of the perturbations. Methodology for tracking the plume without the addition of any chemical tracer has been developed and allows apportionment of the relative contributions of diesel exhaust and sea salt aerosol. There is, however, no independent validation as yet. The hyperspectral camera is mounted to the aircraft and acquiring data (Fig.1C) but the methodologies for retrieving cloud microphysical properties, calibrating albedo, and altitude for each pixel requires further development. We propose to further refine these two techniques in a low-cost manner during test flights with the aircraft, targeting aerosol plumes resulting from container ship exhaust.

WP.B2 Prototype land testing (UoC & SCU, late yr 2 / early yr 3). Initially the prototypes will be tested on land (stage-gated). This will serve to iron out any initial engineering issues, and confirm the performance of the design by sampling the produced sea spray aerosols downwind while monitoring of the engineering parameters of seawater flow and energy consumption. SCU has developed proven methodologies for such land-based testing. This work may be in undertaken in conjunction with the U. Manchester (UoM) team.

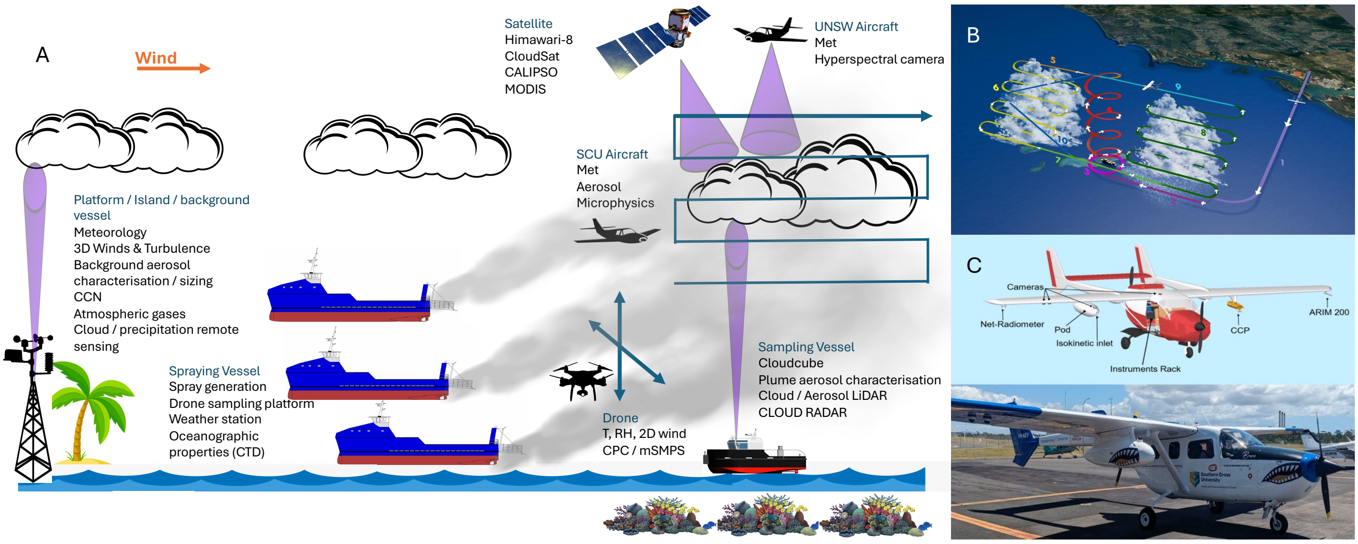

Figure 4: *(A) The proposed major field campaign strategy. (B) Flight sampling strategy for aerosol and cloud physics sampling of upwind (background) and downwind (perturbed) cloud. (C) The SCU aircraft[6].*

WP.B3 Prototype sea testing (SCU, UoC, QUT, UNSW, late yr 3). Following the land-based testing, an iteration of engineering improvements is allowed for, prior to the Australian sea trials. These trials (stage gated) will serve as a smaller precursor to the major field campaign. It will consist of a single spraying vessel and a sampling vessel to operate downwind for characterising the SSA plume and remote sensing of cloud properties (a simplified version of the strategy illustrated in Fig. 4A). SCU has developed a small portable 8’ x 8’ containerised laboratory “CloudCube” that can be loaded aboard a vessel for this purpose. This fieldwork will offer the opportunity to compare and contrast the impacts of up to three different MCB technologies on cloud (ARIEL + prototypes developed in WP.A2). It will provide proof of concept demonstration for methodologies developed in WP.B1 prior to the major field campaign in yr 4 (WP.B4).

WP.B4 Next generation MCB field experiment (SCU, QUT, UNSW, UoC, late yr 4). This (stage gated) package delivers the major advancement in MCB research that our proposal is focused around. The field campaign strategy is illustrated in Fig. 4. It involves multiple spraying vessels (target of 3) operating in the optimum configuration informed by the outcomes of the high-resolution modelling in WP.C2. By operating multiple higher output systems together, we will have advanced the engineering aspects of MCB one step closer to potential implementation. The comprehensive measurement campaign will improve our process understanding of the multiple interconnected atmospheric and cloud microphysical implications of MCB.

WS.C High resolution modelling of aerosol and cloud processes. We will undertake high-resolution, large-eddy numerical simulations with Lagrangian cloud microphysics (LES-LCM)[22]. This computational tool will assimilate data from previous outdoor experiments into a numerical modelling framework, aid in the interpretation of results from past and future campaigns, and allow us to plan and predict outcomes of multi-vessel spraying scenarios and optimise sampling methodologies for the planned field campaign.

WP.C1 Model validation and hindcasts (LMU & SCU, yr 1-2). Our team is unique in that we have collected a wealth of field data on MCB which is yet to be incorporated into a numerical modelling framework, the LES-LCM is the most appropriate state of the art tool for this purpose. To validate the model and interpret past results a major objective is to conduct simulations of selected days during past field campaigns (hindcasts). For this, reanalysis data, and/or the modelling output from WP.D1 will provide the synoptic conditions that determine the development of the boundary layer and its clouds. The measurement campaigns will provide detailed information on the background aerosol, while sprayers will be added using the specifications from past lab studies and measured in WP.A1 (e.g., the size and number of sprayed aerosols). We expect that the large-scale conditions vary during the field campaigns (e.g., wind direction, background aerosol), therefore we plan to produce at least one simulation for each condition.

WP.C2 Informing fieldwork planning and interpreting results (LMU & SCU, yr 2-5). A primary purpose of the modelling will be to guide and augment observations. Our simulations will identify regions of cloud most susceptible to the MCB aerosols e.g. where to target observations for the Twomey effect and for cloud water adjustments (Albrecht effect), cloud lifetime, and cloud fraction effects (Fig. 1A). Our simulations will give a baseline on how strong these effects are expected to be in relation to background variability and indicate under what atmospheric, meteorological and spraying conditions they will be statistically discernable. The simulations will augment the field collected data by providing process-level insights that will support the interpretation of the observations. The modelling will also allow us to gain insight into (a) the impacts of negative buoyancy due to the evaporation of sprayed seawater droplets, which may limit the vertical transport of the sprayed particles, and will vary for different spraying technologies and atmospheric stability (b) the potential collisions of sprayed particles close to the sprayer where concentrations can be very high (Brownian coagulation), which reduces the number of sprayed particles reaching the cloud base, (c) the potential losses of very large sprayed particles to the ocean due to sedimentation, and (d) how the sprayed aerosol is distributed within the boundary layer[35].

WP.C3 Alternate scenarios (LMU & SCU, yr 5). Financial, technical, and meteorological constraints will limit what we can test in the field. Therefore, we will use our simulations to test how clouds would respond to increased or lowered spraying rates, alternative distributions of sprayed aerosols, spaying geometries and strategies, different conditions of background aerosols, and multiple meteorological situations. This will inform the design and assessment of future MCB implementation strategies and scenarios for WP.D1&2.

WS.D Understanding efficacy and risks of implementation. This workstream is focused on gaining insight into potential implications of MCB operated at a sufficient scale to derive regional benefit. Since LES-LCM is limited to geographical domains of ~ 20x20 km, and it is infeasible to directly test MCB under all variations of atmospheric condition, the broader evaluation of benefit and risk will use a larger domain model in which some processes are parameterised. We limit our focus in this work stream to address the key questions of scalability, efficacy, and risks of the most apparent concern, being those to regional weather, precipitation patterns, the marine and terrestrial environment, and atmospheric chemistry.

WP.D1 Simulating MCB impacts and efficacy (CSIRO & SCU, Yr 1-3).

We will use observations from field studies (WS.B) and insights from the high-resolution cloud microphysics modelling (WP.C1-2) to better represent aerosol indirect effects on cloud. A key consideration in determining the efficacy of MCB is the importance of the aerosol direct and indirect effects on the radiation budget. ACCESS-EMS-GBR includes detailed aerosol[36, 37] and cloud microphysics[38] schemes that explicitly represent aerosol-cloud interactions and radiative effects. The model also includes a mechanism to represent sea spray aerosol emissions for MCB and can therefore be used to quantify the direct and indirect impacts on cloud, precipitation and radiation at implementation scales which are unachievable in the high-resolution modelling. Various sea spray injection MCB scenarios will be explored to identify the optimal scenario in terms of emissions parameters, timing and location, to maximise the cooling response while minimising resources and costs. Model performance will be benchmarked against the LES-LCM.

WP.D2 Quantifying risks of MCB (QUT, CSIRO & SCU, yr1-3).

The coupled ACCESS-EMS-GBR model will also be used to assess the risks associated with MCB, including the potential for precipitation changes. An increase in cloud droplet number concentration can suppress rainfall in low-level cumulus clouds[6, 16] or enhance precipitation in deep convective clouds[39, 40], highlighting the complexity in aerosol-cloud-precipitation interactions. While the scale of any future sea spray injections for the GBR are not currently expected to seriously impact precipitation, long-term changes could influence flooding and/or drought in north-eastern Australia and therefore stakeholder concern and diligence require a detailed risk assessment. A series of control and perturbed simulations will be conducted at convection-permitting resolution to explore the impacts of sea spray injections on precipitation over the north-east Australia region. Impacts on atmospheric composition via altered aerosol pH, altered heterogeneous and aqueous-phase reactions and altered oxidative capacity, will also be assessed.

Supplementary chemical transport modelling will be conducted, supported by experiments to be undertaken in the QUT atmospheric chamber using nozzles developed in package WP.A1 with seawater samples collected from representative ocean regions and types. These experiments, combined with the modelling, aim to assess whether the addition of sea spray aerosol at levels necessary for effective MCB, will significantly impact secondary atmospheric chemistry in pristine regions.

WS.E / WP.E1 Governance and social license. Working with federal regulators from the outset, SCU and partners have conducted a total of five MCB field campaigns. Each incremental improvement in technology, scale and scientific ambition has been subject to permitting approval by the Great Barrier Reef Marine Park Authority, following review of the outcomes of the previous iteration. In this manner our research is progressed in responsible steps with appropriate monitoring, risk minimisation, regulatory oversight, indigenous consent and involvement, and societal support. Critically, this progress has occurred and would continue under ARIA within a fully transparent, federally legislated regulatory framework which includes public and indigenous community consultation[20]. We have supplemented this external oversight through multiple levels of internal governance arrangements, including an independent risk review group, and our own community and traditional indigenous owner engagement, including community reference panels. We propose to continue similar arrangements to be determined in consultation with ARIA. This WP allocates time of the leadership team to comply with ARIA principles for outdoor experiments by continuing the aforementioned engagement and governance activities, with the goal of continuing to build societal support to explore MCB as a potential intervention to mitigate coral mass bleaching events in the GBR[41] (yr 1-5). We are not requesting direct funding for social science or governance research, but rather will continue to collaborate with our now established network of social, legal, ethics, and regulatory scientists.

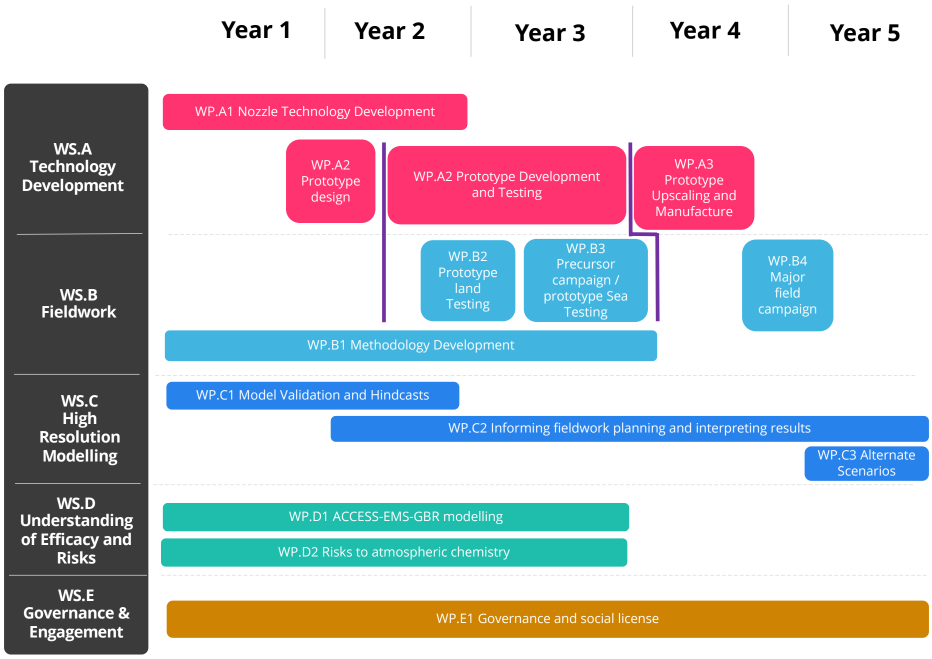

Figure 5: *Project timeline. Purple lines indicate suggested stage gates.*

Infrastructure. The ARIEL system was developed by SCU to produce CCN for MCB research. It is the result of multiple iterations of engineering development and proven to run robustly under harsh conditions at sea (300 MCB and 140 MSB operating hours). "Bruce" is a Cessna 337 aircraft that SCU has developed specifically for MCB research[6] and has recently been fitted with a NVIR+SWIR hyperspectral sensor to map cloud albedo and microphysical properties in high spatial resolution. UNSW operates a piper Seminole research aircraft to which the hyperspectral sensor will be transferred for this work. The partners operate a comprehensive suite of meteorological, aerosol, and cloud microphysics instrumentation well suited to delivering this project. ARIA investment in our project effectively leverages on an $AUD 36m investment by the Australian Government and other funders over the last 4 years, including $AUD ~6m of new infrastructure, including our nozzle development facility. High performance computing in WS.C&D will be conducted on infrastructure to which we have access in Australia and Germany.

Linkages and benefits to the United Kingdom. This program of work has been developed in consultation with the team involved in the UoM led proposal. The scopes are complementary and we intend to work collaboratively amongst the two teams. The UoC contribution and costing of £1.84m including overhead is duplicated in both proposals. Our nozzle development work will be informed by the cloud chamber physics studies at UoM. Modelling, cloud chamber experiments, nozzle development, and fieldwork in the UK will benefit from access to existing and future real-world datasets and transfer of critical knowledge and experience developed during the previous Australian RRAP project. SCU has agreed to support outdoor experiments in the UK under the UoM led proposal by providing ARIEL (or its upgrade), technical staff to operate it, and researchers to contribute their expertise in outdoor MCB field experimentation. CSIRO are also able to offer their expertise in the regional modelling system identified for use in the UoM proposal.

Risks. The primary technical risk is that we are unable to significantly improve the output efficiency of ARIEL. This risk is mitigated by the parallel investigation of multiple alternate atomisation technologies with encouraging preliminary results (Fig 3B). Failure to achieve the output target, while discouraging for implementation scales, is mitigated because the primary science objectives of this project can likely be met using multiple copies of the existing ARIEL system. The modelling in WP.C2 will provide further clarity on spraying outputs required to meet objectives. Contingency for a *force majeure* event affecting the major field campaign is provided through the data collection in the preliminary campaign (WP.B3). Sufficient campaign length is planned to allow for weather and other interruptions. There is a small risk of an extended aircraft unavailability due to maintenance issues, this is mitigated by some redundancy in sampling with the 2nd aircraft, drone-based, and remote sampling capabilities. There is a risk of losing our existing indigenous, community, or regulatory support, although this is mitigated by our strong track record and continued program of engagement. There is a risk that the increase in scale of the major field experiment could trigger additional time-consuming regulatory processes (e.g. Assessment under Australia's EPBC Act[42]), this is considered unlikely given the highly transient nature of any potential impacts. Further mitigation is provided by the modelling in WS.C&D which will provide input to the regulatory and governance risk assessment processes on the potential impacts of the outdoor experiments.

Deliverables. Improved spraying technologies for MCB, publications disseminating all aspects of the R&D. Documented community and indigenous engagement including publications on best practices adopted in MCB for the GBR. Indigenous involvement in co-design and delivering the research. International governance engagement including with the developing world (e.g. through SOLAS, The Alliance for Just Deliberation on Solar Geoengineering, Carnegie Climate Governance Initiative, and other scientific, NGO, and government organisations). Knowledge transfer to other ARIA funded projects and international involvement in field campaigns. Publicly available field campaign datasets.

Section 2: The Team

Our team brings together a discipline specific mix of senior, mid, early career, and student researchers, supported by an experienced professional, technical, and administrative staff. [redacted] The team are highly motivated to work on this project because of their passion for atmospheric, cloud physics, and ocean sciences, but also because it is apparent to us that current global action on climate change is insufficient to save some of the world's most precious ecosystems including the Great Barrier Reef.

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Section 1: Program and Technical

S 1.1: Project Title:

Exploring Geoengineering's Effects on the Dynamics and Thermodynamics of Monsoon and Precipitation Extremes

S1.2: Aims and Background

Precipitation is a critical component of the Earth's climate system, essential for sustaining ecosystems and supporting agricultural productivity. However, climate change is projected to significantly alter global precipitation patterns, particularly during monsoon seasons. Numerical models indicate an increase in both the intensity and variability of precipitation as a result of climate change (Lee et al, 2021). According to the Clausius-Clapeyron (CC) equation, atmospheric moisture content is expected to rise 6 to 7%, which contributes to an increase in precipitation by up to 3% globally for each degree Celsius of surface temperature rise (Allen and Ingram 2002). This phenomenon is not uniformly distributed; climate models exhibit regionally distinct projections of moisture increases under the CC framework with enhancement of regional extreme precipitation of CC or even super-CC scaling (>7% per °C) (Allan et al., 2013; Martinez--Villalobos and Neelin 2023). Additionally, alterations in atmospheric circulation patterns driven by warming will further modulate the intensity and distribution of extreme precipitation events (Pfahl et al., 2017).

Our recent findings, Byju et al. (2024) suggest that as atmospheric temperatures rise, the dynamics governing monsoon precipitation and extreme weather events will be fundamentally altered for the Indian Summer monsoon precipitation. Specifically, there may be a reduction in the contribution of dynamic components influencing precipitation, while thermodynamic factors and nonlinear interactions complicate precipitation characteristics. Studies showed that geoengineering could lead to a reduction in temperature, but the response to precipitation would be regionally different. Such changes in precipitation would be critical for regions like India, where even slight changes in monsoon precipitation can significantly impact the socio-economic conditions. For example, Krishnamohan and Bala (2022) found that stratospheric sulphate injections in the Northern Hemisphere can lead to a reduction in precipitation over the Indian region by more than 20%, potentially resulting in permanent drought-like conditions. This raises some important questions: How will these critical physical factors (dynamic, thermodynamic and nonlinear causes of precipitation) evolve if human interventions aimed at cooling the Earth are implemented? How is it going to impact the extreme precipitation patterns? And, which component of precipitation is going to be impacted the most after the termination of Solar Radiation Management (SRM) interventions? Can we expect any seasonality changes?

The main aims of this project are to:

1. Conduct a comprehensive assessment of geoengineering's impact on monsoon and precipitation extremes across India and the UK—factors directly influencing agricultural practices and food production and economy.
2. Elucidate how the factors influencing precipitation frequency, intensity and seasonality such as atmospheric dynamics, thermodynamics, evaporation processes, and nonlinear physics are altered due to geoengineering interventions.
3. Investigate how these changes manifest in the precipitation and moisture budget terms following the termination of such interventions.

Background

The ongoing warming of the planet significantly influences precipitation patterns and extremes, which is a critical consideration when evaluating geoengineering strategies aimed at cooling the Earth. Research indicates that climate change exacerbates these patterns, leading to a scenario where wet regions become wetter and dry areas experience increased aridity (Donat et al., 2016). Specifically, models suggest that under the Shared Socioeconomic Pathway (SSP) 5-8.5 scenario, many regions will experience more intense monsoon precipitation compared to the SSP2-4.5 scenario. This trend is attributed to an increase in the frequency and intensity of extreme daily events associated with climate change (Krishnan et al., 2016).

Research identified enhanced vertical moisture ascent, referred to as the vertical dynamic component, as a primary driver of extreme precipitation events (Pfahl et al., 2017; Sudharsan et al., 2020; Kaagita et al., 2024). This vertical motion is often linked to local convection or low-level convergence, which elevates atmospheric moisture levels. The resulting latent heating further intensifies upward motion, promoting condensation and heavy rainfall. While thermodynamic factors may contribute to an overall increase in future precipitation patterns, dynamic processes are critical at local scales (Pfahl et al., 2017), particularly in enhancing ascent velocities and moisture content in regions such as the Asian monsoon area (Pfahl et al., 2017). Similar findings have emerged from studies in the UK, where an extreme winter event in 2014 was linked to stronger vertical motions that increased atmospheric moisture and promoted convection (Oueslati et al., 2019). A recent analysis by Byju et al. (2024) reveals that the vertical dynamic component accounts for over 70% of extreme precipitation intensity during wet monsoon months across much of the study area within historical data. However, projections indicate a reduction of 10-35% in this component's contribution to extremes from near-future to far-future scenarios, particularly under high-emission SSP5-8.5 conditions (Figure 1). This decline is associated with a fractional decrease in extreme vertical velocity during significant events, likely due to increased tropospheric stability resulting from warming.

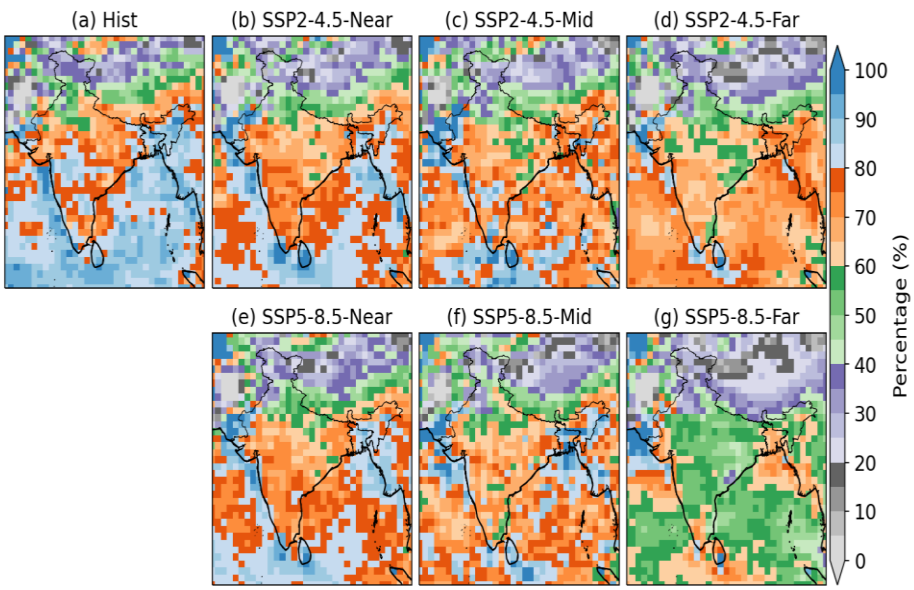

Figure 1: *Spatial map showing ensemble mean percentage contribution of Vertical Dynamic component to extreme precipitation (a) for the historical time period 1995-2014 (Hist) (b-d) for SSP2-4.5 scenario near (2021- 2040), mid (2041-2060) and far (2081-2100) time period (e-g) for SSP5-8.5 scenario. Vertical Dynamic component is the major contributor for extreme precipitation, with global warming its effect is found to be reducing irrespective of increase in intensity of extreme precipitation. (Figure is adopted from Byju et al, 2024).*

Geoengineering has gained attention as a potential approach for mitigating climate change impacts. However, it is crucial to thoroughly investigate the ramifications of geoengineering methods on hydrological cycle (Tilmes et al., 2013; Ricke et al., 2023), and their broader societal implications, particularly concerning agriculture. Current research indicates that while geoengineering strategies may effectively mitigate climate change impacts, they could also present significant drawbacks (Irvine et al., 2010, Parson and Keith, 2024). The nature and magnitude of these drawbacks are contingent upon specific geoengineering approaches. Additionally, uncontrolled termination of SRM interventions could lead to rapid climatic changes (Irvin et al, 2017).

Climate modelling studies available in this area are mainly focused on stratospheric aerosol injection (SAI), which is a proposed method to inject reflecting aerosols into stratosphere, which lead to a reduction in global and tropical precipitation (Ferraro and Griffiths, 2016). Several recent studies (e.g., Tilmes et al., 2018) indicate that planned simultaneous injections at multiple locations can effectively help maintain large-scale temperature metrics in a nearly stable state. The Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) experiment involved the injection of sulphur dioxide (SO_2) at various latitudes with an adaptive feedback-control algorithm (Tilmes et al., 2018), revealing that such injections suppress tropical precipitation, particularly affecting monsoon regions in India and the Americas (Kravitz et al., 2019). In contrast, Arctic aerosol injection is thought to have a lesser impact on tropical climates due to its shorter aerosol lifespan and smaller coverage area. Studies have indicated that both tropical and Arctic injections could decrease precipitation over monsoon regions in Asia and Africa (Robok et al, 2008). Specifically, research has shown that Arctic geoengineering and the resulting inter-hemispheric temperature difference can shift the Intertropical Convergence Zone southward, altering precipitation patterns in the Northern and Southern Hemispheres (Nalam et al., 2018). However, differences in injection intensities between tropical and Arctic SAI experiments complicate the assessment of their respective contributions to climate changes. While thermodynamic and nonlinear terms contribute to a decrease in global mean precipitation under Arctic SAI, dynamic terms may counteract this effect (Sun et al., 2020).

Studies shows that Indian Summer Monsoon (ISM) is sensitive to geoengineering (Bala et al., 2008) and to the location of aerosol injection, as interhemispheric differences in forcing and related temperature variations can lead to significant reductions in precipitation (Krishnamohan and Bala, 2022; Roose et al., 2023; Xavier et al., 2024). A recent study by Tilmes et al. (2024) shows that even in the GLENS simulation, where the large-scale temperature metrics remain unaltered, several factors such as upper tropospheric warming and circulation changes can lead to a weakening of the monsoon precipitation. Although the proposed geoengineering methods, such as SRM, Marine Cloud Brightening (MCB), and Cirrus Cloud Thinning (CCT), may lead to planetary cooling, their impacts on the processes controlling ISM will vary. Given the complexity of the Asian monsoon system and its numerous feedback mechanisms, establishing clear cause-and-effect relationships remains challenging. Nevertheless, considering that a significant portion of the population depends on the ISM for sustenance, these studies carry substantial regional implications—not only for solar geoengineering outcomes but also for intermediate climatic conditions during its implementation.

Studies have shown that while SAI may effectively moderate temperature increases, it also tends to reduce the frequency and intensity of extreme precipitation events. Ji et al. (2018) shows that the response of extreme precipitation to different geoengineering scenarios varies. While stratospheric aerosol injection is more efficient at decreasing extreme precipitation in tropical areas, solar dimming proves to be more effective in extra-tropical regions. Bal et al, (2019) shows that solar geoengineering can significantly compensate for the change in seasonality, peak precipitation timing and duration associated with enhanced warming. Several such studies also show that regional variability of precipitation responses to geoengineering is significant (Pinto et al., 2020; Obahoundje et al., 2022) but it is not uniform (Simpson et al., 2019). For Indian region, Tilmes et al. (2024) show that SAI can help reducing the monsoon extreme precipitation events relative to the SSP8.5 scenario in GLENS simulations. Study also shows that at the termination of geoengineering interventions, climatic conditions such as temperature, precipitation, winds, and moisture would abruptly revert to what they would have been under a global warming scenario (Bhowmick et al., 2021). This potential shift must also be considered when implementing methods aimed at cooling the planet.
Overall, while the proposed methods of geoengineering can cool the planet and negate some ill effects of climate warming, it carries complex implications for global and regional precipitation and requires careful consideration of the undesirable side effects, even after the termination of the method. The impacts of geoengineering on extreme precipitation can be multifaceted and can lead to both reductions and increases in precipitation extremes depending on the method used and the regional climatic conditions. Further, the relationship between warming/cooling and extreme precipitation is complex due to the interplay between dynamic and thermodynamic factors. **Utilising moisture budget decomposition methodologies as applied in our research article Byju et al. (2024), we aim to explore existing SRM methods while identifying necessary adjustments to current geoengineering proposals. Most importantly, understanding the basic science of causes of precipitation extremes and how it is modified due to warming/cooling effects is the motivation for this project.** The proposed project will offer valuable insights into regional variations and potential climate extremes hotspots, thereby providing policymakers, researchers, and stakeholders with meaningful information for decision-making processes on Geoengineering processes.

S1.3: APPROACH AND METHODOLOGY

Moisture budget analysis

Our primary objective of this proposal is to understand how the changes in atmospheric condition leading to a change in precipitation pattern. To address this, we can decompose the anomalous precipitation into different moisture budget components into dynamic, thermodynamic and nonlinear components. We believe that this will help us to identify the potential area where the changes stem from. Based on our recent article published (Byju et al, 2024; and the references in it) about the moisture budget changes in a warming world, changes in moisture balance in the atmosphere can be approximated by the following equation: -

$$P' = E' - \langle \overline{\omega} . \partial_p q' \rangle - \langle \omega' . \partial_p \overline{q} \rangle - \langle \omega' . \partial_p q' \rangle - \langle \overline{V} . \nabla q' \rangle - \langle V' . \nabla \overline{q} \rangle - \langle V' . \nabla q' \rangle + Res \quad \text{- - - - -Eq (1)}$$

where the angle brackets (< >) denote the mass integration through the entire atmospheric column, and primes (‘) denote the change in the monthly values relative to a reference period. P is precipitation, E is Evaporation rate, ‘ω’ is vertical pressure velocity, u and v are zonal and meridional wind vectors, and q denotes specific humidity. 2nd and 5th term on the RHS is the dynamic terms, which are the climatological circulation (vertical and horizontal) advecting anomalous moisture and is referred to as thermodynamic component. The 3rd and 6th term represents the advection of climatological moisture by anomalous circulation, which is termed as dynamic component. The 4th and 7th components are the nonlinear cross component depicting the anomalous moisture advection due to both circulation and specific humidity changes. Finally, Res represents the residual term.

By applying this equation, we will gain insights into the physical components that are most sensitive to climate intervention methods resulting in anomalous precipitation. Furthermore, analysing changes across different regions and distinct geographical contexts, while utilising various climate model data for different geoengineering approaches, will enhance our understanding of the sensitivity of these interventions.

Seasonality changes

Understanding whether the warming or cooling of the planet will lead to changes in seasonality is crucial, as these changes can significantly impact local ecological and social processes. Seasonality changes can be assessed using matrices that include dimensionless relative entropy, dimensionless seasonality index, timing of the peak rainy season, and duration of the peak rainy season (Feng et al., 2013).

At each grid point, relative entropy ($\bar{D} = \sum_{m=1}^{12} \bar{p}_m \log_2 (\bar{p}_m / q_m).$), which measures the deviation of the precipitation probability distribution (p_m) from a uniformly distributed precipitation (q_m), quantifies the concentration of precipitation during the peak precipitation season each year. The seasonality index (S), calculated as $S=D*R/R_{max}$ is derived by taking the product of relative entropy (D) and mean annual precipitation (R), normalised by the spatial maximum annual precipitation (R_{max}). Additionally, seasonality can be further decomposed into 'timing' ($\mathrm{C} = \frac{1}{\bar{R}} \sum_{m=1}^{12} m \bar{r}_m$, represents peak precipitation timing during the peak precipitation period) and ’duration’ ($\mathrm{Z} = \sqrt{\frac{1}{\bar{R}} \sum_{m=1}^{12} |m - \mathrm{C}|^2 \bar{r}_m}$, indicates the peak precipitation period duration), where ‘r_m’ is monthly precipitation and ’m’ is months.

By employing this method, we anticipate that we will effectively capture the impact of geoengineering methods on changes in seasonality, including peak precipitation timing and duration, as a result of the enhanced warming of the planet in both the present and future. Furthermore, we will also investigate whether cooling interventions lead to significant changes in seasonality that could affect society.

Data

A comprehensive analysis of the precipitation changes is proposed here by using existing GeoMIP model simulations. The Geoengineering Model Intercomparison Project (GeoMIP6) is a coordinated effort to understand the potential impacts of different geoengineering techniques on the Earth's climate system (Kravitz et al., 2015). Model data can be downloaded from Earth System Grid Federation site (https://esgf-index1.ceda.ac.uk/projects/esgf-ceda/).

GeoMIP primarily focuses on SRM techniques, which aim to reduce incoming solar radiation to counteract global warming. These techniques include stratospheric aerosol injection, marine cloud brightening, and cirrus cloud thinning. A wide range of climate models, including global climate models (GCMs) and Earth system models (ESMs), participate in GeoMIP. This diversity helps capture a range of potential climate responses to geoengineering. It explores a variety of geoengineering scenarios, such as different deployment strategies, intensities, and durations. This allows for a comprehensive understanding of the potential range of outcomes.

We will also use data from models participating in the Coupled Model Intercomparison Project phase-6 (CMIP6) under historical, intermediate (SSP2-4.5), and high-emission (SSP5-8.5) scenarios to investigate characteristic changes in precipitation, extremes and seasonality.

We can identify extreme wet months, defined as those months with total precipitation values exceeding the 95th percentile of historical precipitation for each month at each grid point. The 95th percentile could be determined using the model's historical precipitation data from 1965 to 2014. We will focus exclusively on the grid points where precipitation values exceed this extreme wet threshold. At these selected grid points, we will analyse the moisture budget terms, calculating anomalies relative to the historical mean from 1995 to 2014, in accordance with the IPCC AR6 report.

S1.4: Work Plan

Stream 1: Assess precipitation pattern over India and the UK

Objective: Understand the changes in precipitation patterns and moisture budget components over India and the UK.

1) Historical changes in precipitation and moisture budget

Given the significant climate changes observed over recent decades, it is important to examine past variability in moisture budget components related to excessive precipitation. First, we will analyse historical changes in precipitation patterns and corresponding moisture budget in both India and the UK using CMIP6 historical simulation model data. Here, we also expected to get an insight on region wise (tropical versus midlatitude) response of climate change to different components (dynamic, thermodynamic and nonlinear) of precipitation including the extreme.

2) Changes under different climate change scenarios

Utilising CMIP6 scenarios (SSP24.5 and SSP58.8), we will analyse future changes in precipitation patterns and moisture budget components. This analysis will help assess the sensitivity of large excess precipitation events to different emission scenarios and warming levels. Additionally, we will explore the differential impacts of global warming on tropical and midlatitude regions, with a particular focus on precipitation extremes and moisture budget dynamics. We have already carried out similar analysis over Indian monsoon (Byju et al, 2024), but the understanding of these factors over the UK in the midlatitude region must be carried out.

Overall, the outcomes from Stream 1 will be utilised to compare and analyse the physics of precipitation changes linked to geoengineering interventions in Stream 2.

Stream 2: Assess the impact of Geoengineering methods in precipitation pattern

Objective: To quantify the impact of various geoengineering methods, specifically Solar Radiation Management techniques, on precipitation and large excess precipitation events. How the cooling of planet Earth modulates the dynamics and thermodynamics of precipitation? How it behaves after the termination?

To achieve this, we will utilise GeoMIP simulation data to assess changes in hydrological cycles resulting from different SRM techniques. Advanced statistical and data analysis techniques will be employed to decompose anomalies in precipitation extremes across various scenarios. By comparing the results from Stream 1 (historical and warming scenarios) with the changes in moisture budget components analysed using GeoMIP, we will identify how the dynamics and thermodynamics are changing? And, which component of the moisture budget has the largest impact on precipitation change? We will also analyse the changes in moisture budget terms at the termination of the interventions. This comparative analysis will help us analyse regional variations and potential hotspots for climate extremes because of the implementation of Geoengineering methods.

Stream 3: Analyse the changes in precipitation seasonality

Objective: Analyse the changes in seasonality, timing and duration of precipitation due to Geoengineering interventions and after the termination.

Climate change not only impacts annual precipitation accumulation but also alters the spatial and temporal distribution of precipitation, including the timing and length of peak precipitation periods. In this project, we will evaluate changes in seasonality using indicators such as annual precipitation totals, dimensionless relative entropy, dimensionless seasonality index, timing of the peak rainy season, and duration of the peak rainy season (using the methods discussed in Feng et al., 2013). This evaluation will involve comparing results from various geoengineering climate simulations against historical and warming scenario simulations. Ultimately, this analysis aims to enhance our understanding of potential seasonal changes induced by the planetary cooling through various geoengineering methods. We will also study how the seasonality would be altered at the termination? This would help us to identify potential hotspots for drought or flood situations under the implementation of geoengineering interventions.

Section 2: INVESTIGATORS

[redacted] will serve as the **Principal Investigator (PI)** for this project. [redacted] will dedicate full time to this project, overseeing overall coordination and execution to ensure that research silos do not form. [redacted] will lead the work program for Stream 1 and Stream 3, significantly contribute to Stream 2.

[redacted] will act as the Geoengineering Expert for this project. [redacted] This project proposal is a collaborative effort with The Energy and Resources Institute (TERI). T[redacted] dedicate 0.3 Full Time Equivalent (FTE) to lead the work program for Research Stream 2, supervise the PDRA, while also contributing to Stream 1 and Stream 3.

[redacted] will serve as the Co-PI for this project. [redacted] will dedicate 0.8 Full-Time Equivalent (FTE) to this project, where [redacted] will make substantial contributions across all three research streams.

[redacted] is engaged with the Climate Change and Air Quality Programme of The Energy and Resources Institute (TERI) as Director. [redacted] experience and expertise on climate change can be utilised for the proposed project.

[redacted] experience and expertise could be beneficial for the proposed project.

All the team members will be responsible for writing high quality peer reviewed articles related to the project.

Section 3: Administrative Response

S3.1 Budget details

Total requested budget is £116020.0 only : Please note that VAT is not included here. A detailed budget is provided as Full cost summary in excel format submitted along with this application.

Description	***Amount in GBP (£)***
Labour	*69600*
Material	*500*
Equipment and Facilities	*20000*
Travel	*6000*
Other	*6000*
Indirect Costs	*13920*
Total	***116020***

S3.2 Intellectual property declaration

This project will leverage publicly available climate datasets such as CMIP6 and GeoMIP6, as well as open-source software like Python. Further, the project will leverage the expertise and computing resources of TERI.

[redacted] will adhere to the terms of our collaboration agreement to ensure the protection of intellectual property rights.

S3.3 Conflicts of interest Statement

To the best of our knowledge, there are no conflicts of interest associated with this project. The project team members have no financial, personal, or professional interests that could potentially compromise the objectivity or integrity of the research.

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