

EIR request – environmental assessments and governance of Exploring Climate Cooling outdoor experiments

To: EIR@aria.org.uk

5 February 2026 at 13:13

Dear Sir or Madam,

I refer to your EIR response to myself dated 20 January 2026 regarding the “Exploring Climate Cooling” programme and its funded projects.

Under the Environmental Information Regulations 2004, please provide the following information:

1. Environmental Impact Assessments (EIAs) and risk assessments

For each of the controlled outdoor experiments you identified:

- Re-Thickening Arctic Sea Ice (RASi)
- Marine Cloud Brightening in a Complex World
- REFLECT
- BrightSpark – Cloud brightening with electric charge
- Natural Materials for Stratospheric Aerosol Injection

1(a) Any environmental impact assessment, screening assessment, or scoping report (draft or final) produced for the purposes of these projects, whether by ARIA, project teams, contractors or independent reviewers.

1(b) Any risk assessments or risk registers covering environmental and health impacts of the proposed outdoor work (including local marine/terrestrial ecosystems, air quality, and human exposure).

2. Criteria for “time-bound, limited in size, and dissipate within 24 hours or fully reversible”

2(a) Any internal or external documents that define or explain the criteria ARIA uses for the statement in your published programme description that all funded experiments will be “time-bound and limited in size, scale so their effects dissipate within 24 hours or are fully reversible”.

2(b) Any quantitative thresholds or modelling used to decide whether a proposed experiment meets those criteria.

3. Community engagement and consent

For each of the above projects:

3(a) Community engagement or consultation plans, including any communication strategies for local communities at or near proposed sites (e.g. in Canada, the UK, and the Great Barrier Reef region).

3(b) Any records of public meetings, workshops, focus groups or correspondence with local communities relating to these experiments (minutes, summaries, slide decks, briefing notes).

3(c) Any internal guidance or policy ARIA uses for determining what level of public engagement or consent is required before an outdoor experiment can proceed.

4. Oversight and governance

4(a) The current terms of reference for the oversight committee(s) responsible for governance of the Exploring Climate Cooling programme, including membership and decision-making powers in relation to outdoor experiments.

4(b) Any committee papers or minutes where the above outdoor experiments were considered, approved, paused or rejected, including any discussion of legal, ethical or ecological concerns.

5. IP Pledge and repository

5(a) The current full text of the “Future Proofing our Climate and Weather Intellectual Property Pledge”, including any Submission Guidelines and descriptions of the “Pledge Repository” referred to in the grant agreements.

5(b) Any ARIA-level policy or guidance explaining how this pledge is intended to operate in practice, particularly in relation to access for UK public bodies and the wider public.

I am not seeking the personal data of private individuals. Please redact names of junior staff where necessary. If any information is withheld, please specify the EIR exemption relied on and explain how the public interest test has been applied.

I would prefer the information in electronic form (PDF or machine-readable files such as CSV/Excel where applicable).

Yours faithfully,


[REDACTED]
[REDACTED]

2 April 2026

Dear [REDACTED],

Environmental Information Regulations 2004 ("EIR") Request

We are writing in response to your recent request for information to the Advanced Research + Invention Agency ("ARIA") dated 5 February 2026 in which you asked:

"Under the Environmental Information Regulations 2004, please provide the following information:

1. Environmental Impact Assessments (EIAs) and risk assessments

For each of the controlled outdoor experiments you identified:

- *Re-Thickening Arctic Sea Ice (RASi)*
- *Marine Cloud Brightening in a Complex World*
- *REFLECT*
- *BrightSpark – Cloud brightening with electric charge*
- *Natural Materials for Stratospheric Aerosol Injection*

1(a) Any environmental impact assessment, screening assessment, or scoping report (draft or final) produced for the purposes of these projects, whether by ARIA, project teams, contractors or independent reviewers.

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2. Criteria for "time-bound, limited in size, and dissipate within 24 hours or fully reversible"

2(a) Any internal or external documents that define or explain the criteria ARIA uses for the statement in your published programme description that all funded experiments will be "time-bound and limited in size, scale so their effects dissipate within 24 hours or are fully reversible".

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3(a) Community engagement or consultation plans, including any communication strategies for local communities at or near proposed sites (e.g. in Canada, the UK, and the Great Barrier Reef region).

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3(c) Any internal guidance or policy ARIA uses for determining what level of public engagement or consent is required before an outdoor experiment can proceed.

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5(b) Any ARIA-level policy or guidance explaining how this pledge is intended to operate in practice, particularly in relation to access for UK public bodies and the wider public."

Response to EIR request

We have responded to each element of your request below. In total, ARIA has provided you with over 400 pages of documentation alongside this letter. As noted below, more documentation relating to ARIA's Exploring Climate Cooling programme will be produced and published on ARIA's website in due course. ARIA would encourage you to visit the [Exploring Climate Cooling programme webpage](#) to keep up to date.

Separately, thank you for confirming that you do not seek the personal data of private individuals. Where we do not reasonably believe that the identity of individuals concerned is already in the public domain, we have redacted that in line with regulation 12(3) of the EIR.

1(a) Any environmental impact assessment, screening assessment, or scoping report (draft or final) produced for the purposes of these projects, whether by ARIA, project teams, contractors or independent reviewers.

At present, assessments have been finalised for one outdoor experiment: Re-thickening Arctic Sea Ice (RASI). Further details about this project (including the community engagement survey, research licences and the Nunavut Impact Review Board's screening reports) can be found on ARIA's website: [Exploring Climate Cooling | Re-thickening Arctic Sea Ice](#). Relevant extracts of ARIA's website can be found at Annex 3 of our letter dated 20 January 2026. For your convenience, we have provided copies of the community engagement summaries, Nunavut Impact Review Board's screening reports, scientific research licences and letters from the project teams confirming their completion of ARIA's CEO conditions at **Annex 1** to **Annex 8**. Please find enclosed at **Annex 9** a copy of the Environmental Impact Assessment conducted in relation to this project.

The preparations for other outdoor experiments being funded by the Exploring Climate Cooling programme are only in preliminary stages, and no other outdoor experiments have yet been approved by ARIA in relation to this programme. As such, ARIA does not hold any other documents relating to this element of the request. When finalised, Environmental Impact Assessments, community engagement summaries and other governance documents relating to each project will be placed on ARIA's website: [ARIA | Exploring Climate Cooling](#).

1(b) Any risk assessments or risk registers covering environmental and health impacts of the proposed outdoor work (including local marine/terrestrial ecosystems, air quality, and human exposure).

At present, risk assessments have only been finalised for the RASI project. Please find enclosed at **Annex 9** a copy of the Environmental Impact Assessment conducted in relation to this project.

No other risk assessments covering the environmental and health impacts of the proposed outdoor experiments are yet held by ARIA. However, when other risk assessments are finalised by the projects, they will be provided to ARIA and placed on ARIA's website: [ARIA | Exploring Climate Cooling](#).

2(a) Any internal or external documents that define or explain the criteria ARIA uses for the statement in your published programme description that all funded experiments will be “time-bound and limited in size, scale so their effects dissipate within 24 hours or are fully reversible”.

Details of the framework used for outdoor experiments in the context of ARIA's Exploring Climate Cooling programme can be found in the programme's thesis. A copy of this thesis is enclosed at **Annex 10**. In particular, we draw your attention to the descriptions on page 6, the figure on page 7, and Appendix A on page 19. You will note that this document specifically explains the rationale behind the criteria and sets out a flowchart that is to be used to establish whether a proposed experiment meets those criteria. As the experiments proposed by project teams are different, pursuing different scientific goals and being undertaken in different locations and environmental contexts, the application of the criteria must be project-specific. However, in any event, the *“magnitude of the intended perturbation should be limited so that it is within the bounds of known and benign natural phenomena (or anthropogenic phenomena that are considered harmless), so that there is precedent for the size of the effect that will be produced”*.

Further information can be found in the programme's call for proposals, a copy of which is enclosed at **Annex 11**. In particular, we draw your attention to pages 9-10 of this document. You will note that this demonstrates that the approach described in the programme's thesis was embedded into the funding process for the Exploring Climate Cooling programme. Specifically, it said that *“[a]pplicants proposing outdoor experiments are strongly advised to refer to this decision tree in their proposals, and to state explicitly how the experiments that they are proposing comply with the considerations listed”*.

2(b) Any quantitative thresholds or modelling used to decide whether a proposed experiment meets those criteria.

As above, details of the criteria can be found in the programme's thesis and call for proposals documents (**Annex 10** and **Annex 11**). As noted, the call for proposals at

Annex 11 asked applicants proposing outdoor experiments to refer to the criteria and provide explanations of how their proposed experiments comply with them. At **Annex 12**, we have included copies of the initial proposals submitted by the funded applicants to the Exploring Climate Cooling programme. You will note that the proposals corresponding to the projects conducting controlled, small-scale outdoor experiments included such information for the programme team to review. However, please note that the selection of these projects does not constitute the approval of any outdoor experiments. Any outdoor experiments are subject to further approval through the process described in **3(b)** below. For ease of reference, you can find the proposal for: (i) *Natural Materials for Stratospheric Aerosol Injection* on page 80; (ii) *BrightSpark – Cloud brightening with electric charge* on page 91; (iii) *Re-Thickening Arctic Sea Ice (RASI)* on page 118; (iv) *A REsponsible innovation Framework for assessing novel spray tEchnology research To examine local albedo changes from marine brightening and its multi-scale impacts (REFLECT)* on page 171; and (v) *Marine Cloud Brightening in a Complex World* on page 181.

ARIA does not hold any further information on quantitative models or modelling used to assess proposed outdoor experiments, other than that information provided in **Annex 10** (please see **2(a)** above).

3(a) Community engagement or consultation plans, including any communication strategies for local communities at or near proposed sites (e.g. in Canada, the UK, and the Great Barrier Reef region).

When finalised, community engagement summaries and other governance documents relating to each project will be placed on ARIA's website: [ARIA | Exploring Climate Cooling](#).

At present, community engagement summaries have been finalised for one outdoor experiment: RASI. Further details about this project can be found on ARIA's website: [Exploring Climate Cooling | Re-thickening Arctic Sea Ice](#). Relevant extracts of ARIA's website can be found at Annex 3 of our letter dated 20 January 2026. The community engagement summaries for the RASI project are enclosed at **Annex 1** and **Annex 5**.

A service provider engaged by ARIA to provide advice and assistance to project teams to ensure a high quality of public engagement also holds 7 draft Engagement Plans relating to other projects being funded by the Exploring Climate Cooling programme. As these documents are working drafts, ARIA will not provide them, pursuant to Regulation 12(4)(d) of the EIR. In considering the public interest test, we are mindful that disclosure would promote transparency; however, in this instance, whilst the documents are not yet finalised, to disclose in their current format would risk confusion and misinformation. As the documents will be published once finalised, we consider that transparency will be achieved in due course but for now, the public interest favours non-disclosure.

3(b) Any records of public meetings, workshops, focus groups or correspondence with local communities relating to these experiments (minutes, summaries, slide decks, briefing notes).

Before ARIA will consider approving any outdoor experiment, project teams must carry out steps including: (i) developing a plan of how they will engage with any affected stakeholders, and (ii) conducting pre-experiment public engagement. Once project teams have carried out these steps, ARIA and its Oversight Committee will assess these plans. The Oversight Committee will then make a recommendation to ARIA, before the final decision on whether to proceed with the experiment is made by ARIA's CEO.

Details of the public engagement which took place in relation to the RASI project can be found on ARIA's website: [Exploring Climate Cooling | Re-thickening Arctic Sea Ice](#). Relevant extracts of ARIA's website can be found at Annex 3 of our letter dated 20 January 2026. At **Annex 13**, we have enclosed a copy of a tracker that the team used to record engagement and communication with local communities which took place prior to the commencement of the outdoor experiments in relation to the RASI project. In addition, please find enclosed at **Annex 14** a copy of the presentation which was presented to local community leaders as part of this engagement process.

Records of public engagement in relation to the other projects being funded by the Exploring Climate Cooling programme will be published on ARIA's website when finalised.

3(c) Any internal guidance or policy ARIA uses for determining what level of public engagement or consent is required before an outdoor experiment can proceed.

ARIA does not hold any additional documents in relation to this element of your request. As described above, the responsibility for determining the necessary levels of public engagement and consent lies with ARIA's CEO, subject to the recommendations of the Oversight Committee.

We have enclosed a copy of the Oversight Committee's recommendation, along with the formal decision letter of ARIA's CEO in relation to RASI at **Annex 15** and **Annex 16** respectively. This is illustrative of the process that takes place when determining whether sufficient public engagement and consent has taken place before an outdoor experiment is approved.

4(a) The current terms of reference for the oversight committee(s) responsible for governance of the Exploring Climate Cooling programme, including membership and decision-making powers in relation to outdoor experiments.

Details of the Exploring Climate Cooling programme's Oversight Committee can be found in the document attached at Annex C of our letter dated 6 February 2026.

Further information about the role of the Oversight Committee can be found in the document attached at **Annex 17**. **Annex 18** includes a detailed overview of the operation of the committee and its relationship with the Exploring Climate Cooling programme.

4(b) Any committee papers or minutes where the above outdoor experiments were considered, approved, paused or rejected, including any discussion of legal, ethical or ecological concerns.

Copies of the minutes of meetings of the Exploring Climate Cooling programme's Oversight Committee, during which the programme's outdoor experiments have been considered, have been provided at **Annex 19** to **Annex 23**. In addition, we have included the 'pre-reads', which were provided by the programme team to the Oversight Committee in advance of each of these meetings, at **Annex 24** to **Annex 27**.

As outlined above, copies of Oversight Committee's recommendation, along with the formal decision letter of ARIA's CEO, in relation to RASl are enclosed at **Annex 15** and **Annex 16** respectively.

5(a) The current full text of the "Future Proofing our Climate and Weather Intellectual Property Pledge", including any Submission Guidelines and descriptions of the "Pledge Repository" referred to in the grant agreements.

A copy of the current full text of the Future Proofing our Climate and Weather Intellectual Property Pledge is attached at **Annex 28**.

The details of the submission guidelines and the pledge repository have not yet been finalised. We have attached a first draft of the submission guidelines at **Annex 29**. However, please note that this document is not yet in final form, and is subject to change. When finalised, a copy of the submission guidelines will be published on ARIA's website.

5(b) Any ARIA-level policy or guidance explaining how this pledge is intended to operate in practice, particularly in relation to access for UK public bodies and the wider public.

In response to your request at **5(b)**, ARIA can confirm that we hold a draft guidance document which is currently in draft form. Therefore, under Regulation 12(4)(d) we withhold this document as it is still in the course of completion. We do intend to publish the guidance once finalised on the ARIA website and so this document will eventually be available for your review. The public interest test as set out at answer **3(a)** applies here equally.

ARIA does not hold any further documents which are responsive to this element of your request.

Yours sincerely,

ARIA

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.

Enc.

- *Annex 1: Real Ice - Community engagement summary*
- *Annex 2: Real Ice - Nunavut Impact Review Board's screening report*
- *Annex 3: Real Ice - Scientific research licence for experiments from the Nunavut Research Institute*
- *Annex 4: Real Ice - Letter to ECC programme team confirming completion of CEO conditions*
- *Annex 5: Arctic Reflections - Community engagement summary*
- *Annex 6: Arctic Reflections - Nunavut Impact Review Board's screening report*
- *Annex 7: Arctic Reflections - Scientific research licence for experiments from Nunavut Research Institute*
- *Annex 8: Arctic Reflections - Letter to ECC programme team confirming completion of CEO conditions*
- *Annex 9: Environmental Impact Assessment - Arctic Ice Thickening Field Test*
- *Annex 10: Exploring Options for Actively Cooling the Earth - Programme thesis*

- *Annex 11: Exploring Climate Cooling - Call for proposals*
- *Annex 12: Exploring Climate Cooling - Initial Proposals*
- *Annex 13: Exploring Climate Cooling - Outreach log*
- *Annex 14: Exploring Climate Cooling and RASI presentation (February 2026)*
- *Annex 15: Oversight Committee Recommendation Letter (RASI)*
- *Annex 16: ARIA CEO approval (RASI)*
- *Annex 17: Oversight Committee, ARIA's Exploring Climate Cooling programme*
- *Annex 18: Oversight Committee overview*
- *Annex 19: ECC Oversight Committee Minutes (2025.04.11)*
- *Annex 20: ECC Oversight Committee Minutes (2025.06.11)*
- *Annex 21: ECC Oversight Committee Minutes (2025.08.06)*
- *Annex 22: ECC Oversight Committee Minutes (2025.10.08)*
- *Annex 23: ECC Oversight Committee Minutes (2025.12.03)*
- *Annex 24: Oversight committee pre-read October 2025*
- *Annex 25: Oversight committee pre-read December 2025*
- *Annex 26: Oversight committee pre-read January 2026*
- *Annex 27: Oversight committee pre-read March 2026*
- *Annex 28: Future Proofing our Climate and Weather Intellectual Property Pledge*
- *Annex 29: Intellectual Property Pledge Submission Guidelines (DRAFT)*

Organisation	Person	Email	Date	Type of outreach	Content	Response?	Follow-on action and dates?	Content of follow-up / Questions, feedback received	Follow-up actions
█	█	█	28th March 2025	Email	Offered introduction to programme and RASI project, especially in context of Greenland	No			
█	█	█	28th March 2025	Email	Offered introduction to programme and RASI project, especially in context of Greenland	No			
Office of Lori Idlout MP	█	█	1st December 2025	Email	Offered briefing on RASI and the programme, and opportunity for feedback	Yes	30 min briefing of █ on 11th December. Mark presented this slide deck and then there was time for Q+A.	█ flagged that the experiments will be size ~1km² and that this seems small - asked how will you be able to know if the method works at this scale? - MARK REPLIED THAT THE EXPERIMENTS WERE DELIBERATELY SMALL SO AS TO ASSESS IMPACTS AND FEASIBILITY. WE DON'T WANT TO START LARGER THAN THIS IN CASE THERE ARE SIDE EFFECTS WE DON'T KNOW ABOUT. █ asked how were the two sites selected - MARK REPLIED THAT THIS IS BECAUSE BOTH SITES HAVE WORKSHOPS WHERE SNOWMOBILES AND PUMPS CAN BE REPAIRED. █ did not have a question, but stated that this is super cool, and was really excited and thankful for the work ARIA are doing - MARK REITERATED THAT THE EXPERIMENTS WERE JUST A START AND VERY SMALL. THICKENING AT SCALE WAS MANY YEARS AWAY, IF IT EVER HAPPENED AT ALL, AND ONLY 1 KM² MAXIMUM IN THIS PROGRAMME. █ asked around the lack of regulation in this space, and what we need from lawmakers to be able to do further our work - MARK REPLIED THAT THE PERMITTING SYSTEM IN NUNAVUT WAS VERY JOINED UP, BUT THAT THAT WAS NOT THE CASE EVERYWHERE. THERE IS A NEED TO PERFORM OUTDOOR EXPERIMENTS TO OBTAIN REAL WORLD DATA TO ALLOW GOVERNANCE AT THE INTERNATIONAL LEVEL. █ requested a copy of the presentation? - MARK REPLIED YES AND SENT HER A PDF A FEW MINUTES AFTER THE CALL █ asked how can they can continue to support the work ARIA are doing - and do we require a letter of support from them, or what else we needed from them - WE SAID WE DID NOT NEED A LETTER OF SUPPORT AT THE MOMENT THANKS, BUT WOULD VERY MUCH LIKE TO HEAR IF THERE WERE OTHERS THAT THEY THOUGHT WE SHOULD TALK TO. █ asked if we had met with the nunavut research institute? Offered to put us in touch with them and also █ the █ - MARK REPLIED THAT HE WOULD VERY MUCH LIKE TO BE PUT IN TOUCH WITH THOSE PEOPLE AND ASKED THAT █ DO SO. - The call then ended with █ saying she was "very impressed" with the work and thanking us for the briefing. We in turn thanked █ and █ for their time and their questions.	Mark emailed a copy of the presentation to █ as requested a few minutes after the call
█	█	In person	ArcticNET Dec 25	In person	█ and █ to speak with █ at ArcticNET about their project and to mention that we are keen to speak with him	Meeting did not happen	█ was ill and did not attend the conference. █ linked us up by email on 29th December		
█	█	█	9th December 2025	Email	Offered briefing on RASI and the programme, and opportunity for feedback	Yes	Followed up by email on 12th December to offer all and any times between 2nd Jan and 9th Jan. Followed up by email again to repeat offer on 5th Jan 2026		
█	█	█	10th December	Online presentation	1 h online meeting. Presented on the programme and RASI. █ and █ presented on █'s work and their climate intervention scoping exercise. There was general Q+A. We asked for an intro to folks at █ and they replied that █ and the Secretariat were the best people to talk to. We told them we were in contact. They said that █ 'know of your	Yes			
█	█	█	12th December	Email	Offered briefing on RASI and the programme, and opportunity for feedback and how the programme could support NISR		Followed up by email to repeat offer on 5th Jan 2026 (joint with █)		
Parliament of Nunavut	█	█	13th December	Email	Offered briefing on RASI and the programme, and opportunity for feedback	No	Followed up by email to repeat offer on 5th Jan 2026	█ booked in for a briefing on 3rd Feb, but then was delayed. We chatted to his assistant, █ for a few minutes, which was pleasant. █ then re-arranged the call to 20th Feb. - Mark gave introduction on ARIA. Context for programme, introduction to climate cooling, programme approach. - Mark explained how this programme will run responsibly, including introduction to the independent oversight committee and governance decision trees. - Mark Introduced Rethickening Arctic Sea Ice project. Explained experiment procedure, scale of experiment, permitting process, and some of the critical research questions. Explained RASI team structure. Highlighted the engagement to date. - Questions & Reflections from █ █ said he was "supportive of your project" and that it was "interesting" and "feasible where currents are not strong". He noted that he used to work with █ and suggested the teams connect with them (which we told him they had already). He previously did some work examining snow thickness and relating this to the melt of underlying ice. █ noted that areas by river outlets tend to thin earliest in the melt season and that the new breakwater in █ (for which he is the MLA) has caused the sea ice there to be more susceptible to early melting. We replied that we were aware that Arctic Reflections had visited █ in 2025. █ seemed satisfied with experimental plans, noting that Real Ice and Arctic Reflections had engaged with local HTOs and obtained the required NRI licences. He also said that satellite imaging of ice thickness was being undertaken by ESA, to which we replied that the team in Cambridge Bay were aware of this and were in contact with the ground team for this ESA project. We wished each other well, and the conversation ended with us thanking █ for his time and asking him not to hesitate to reach out if he had any further questions.	
Parliament of Nunavut	█	█	13th December	Email	Offered briefing on RASI and the programme, and opportunity for feedback	No	Followed up by email to repeat offer on 5th Jan 2026		
Parliament of Nunavut	█	█	13th December	Email	Offered briefing on RASI and the programme, and opportunity for feedback	No	Followed up by email to repeat offer on 5th Jan 2026		
█	█	█	29th December	Email	Offered briefing on RASI and the programme, and opportunity for feedback and how the programme could support NISR		Followed up by email to repeat offer on 5th Jan 2026 (including █)		
█	█	N/A	15th January 2026	In person	Attended █ roundtable in Abu Dhabi, where █ was chair of the panel. I contributed thoughts on responsible climate intervention research in the Arctic and █ gave details of RASI	█ made notes	Invitation to █ meeting in Rome		
█	█	█	17th February 2026	Email	Suggested that we meet and chat at the █ meeting in Rome in March				
█	█	█	17th February 2026	Email	Suggested that we meet and chat at the █ meeting in Rome in March				



Exploring Climate Cooling and RASI

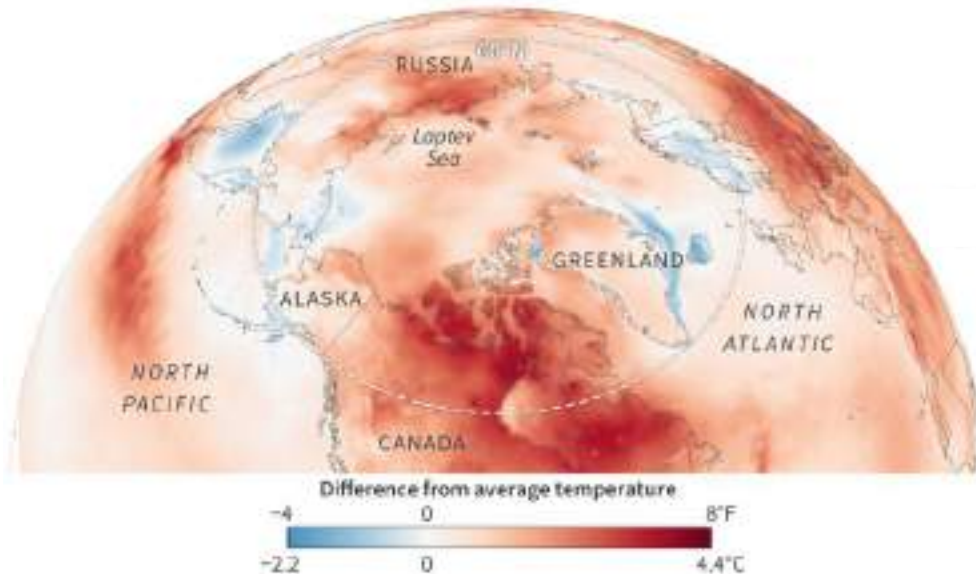
February 2026

About ARIA

- ARIA is a public sector R&D funding agency. All our funding comes from the UK Government.
- We fund teams to pursue multidisciplinary research at the cutting edge of science in areas that are often complex.
- We fund programmes of research that consist of multiple individual research projects.
- ARIA was established by the UK Government in January 2023 with high levels of autonomy and flexibility via the [ARIA Act](#).
- Programmes are developed by Programme Directors. They are not necessarily reflections of UK government policies.

The context for the Exploring Climate Cooling programme

- + Anthropogenic greenhouse gas emissions are driving rising global temperatures
- + The Arctic is warming faster than the world as a whole



According to the US National Oceanic and Atmospheric Administration, 2024 was the second warmest year on record in the Arctic

The context for the Exploring Climate Cooling programme

- + Decarbonisation is the only sustainable way to lower global temperatures, and **solar radiation modification** is **in no way a substitute** for decarbonisation
- + But, whether we like it or not, rising global temperatures are driving an intensifying debate around solar radiation modification (reflection of sunlight) to “buy time” or “shave the peak” of heating
- + Whether we like it or not, there are now for-profit companies operating in this space, whose business models rely on deployment of solar radiation modification in the near term



The context for the Exploring Climate Cooling programme

- + **Adequate governance** in this space (especially at the international level) **is lacking**, largely due to a lack of knowledge of what would be governed. Governance discussions are still hypothetical, but technology readiness is increasing in private hands.
- + **Effective decisions and effective governance require real-world data** that is transparent and widely shared (c.f. the Montreal Protocol)
 - There are examples of where such data has been collected responsibly that we can build on
 - Research $\neq$ deployment



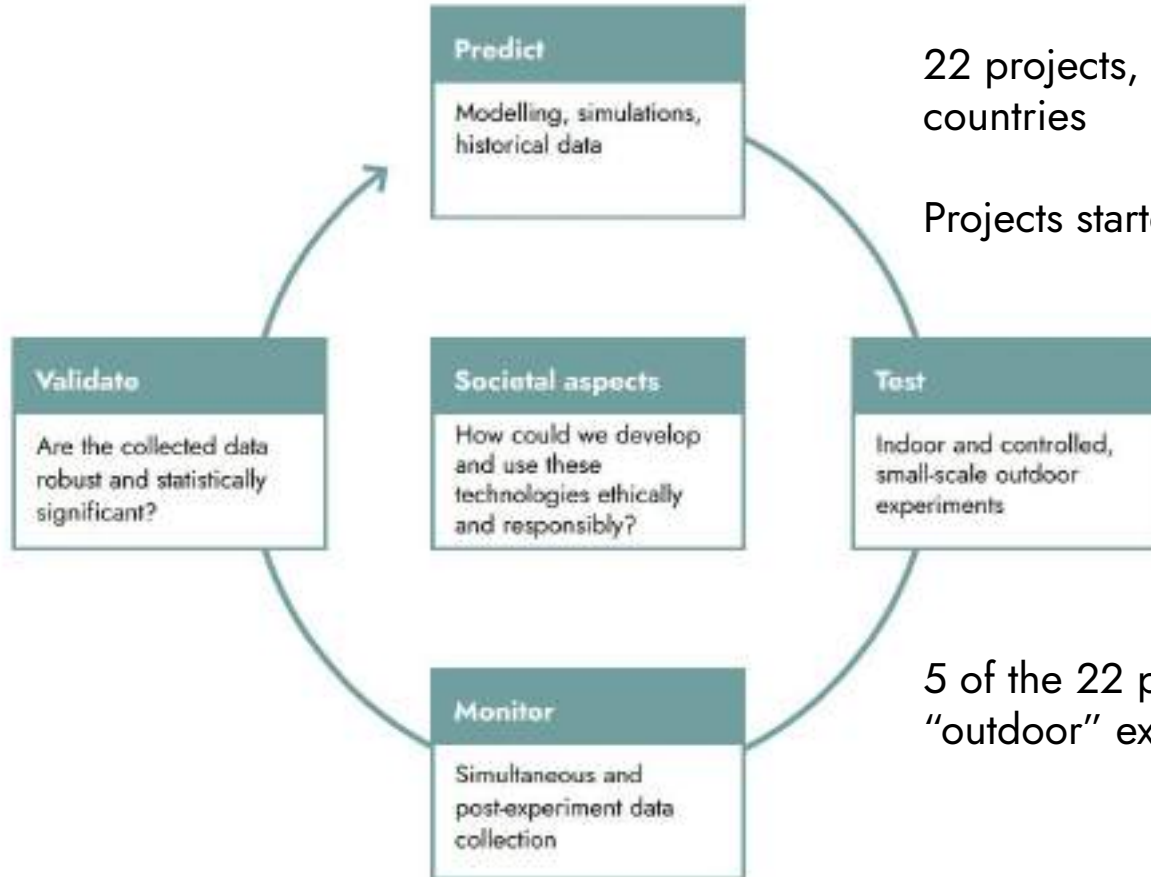
Opportunity space: Future Pondering Our Climate and Weather

Programme: Exploring Climate Cooling

Exploring Climate Cooling

This £56.8m programme aims to build a robust evidence base to explore – with independent oversight – if climate cooling approaches could ever be feasible, scalable, safe, and governable.

Programme approach



22 projects, with team leads in 12 countries

Projects started in June/July 2025

5 of the 22 projects count as “outdoor” experiments

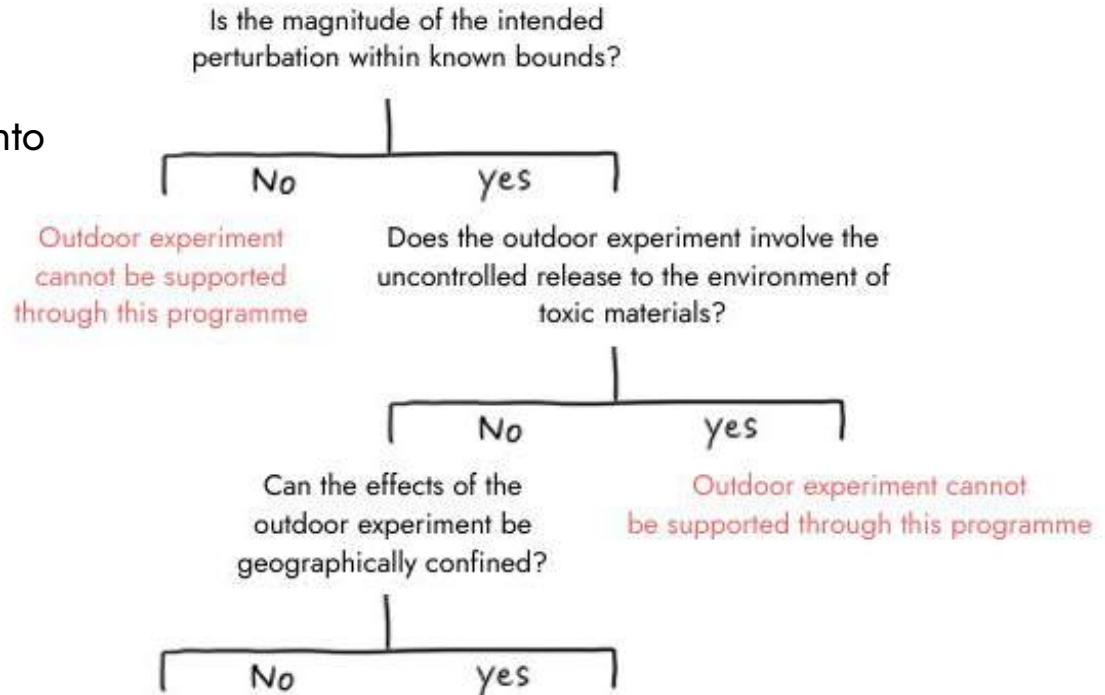
How will ARIA run this programme responsibly?

ARIA has the following high-level “governance principles” that guide how we run the programme, supported by the **independent oversight committee**:

- Fund research that will address the **most pressing critical scientific questions** in SRM.
- All experiments will be designed to **reduce direct risk** as far as possible.
- The teams we fund will have to **engage with, and respect**, key communities.
- We will **communicate proactively** and be **transparent** on how the research is conducted, outputs, and impacts.
- We will acknowledge the **broader implications** of the research that we fund.
- We will **adapt** to lessons learned during the programme and to changing circumstances.

Programme governance in practice - 1

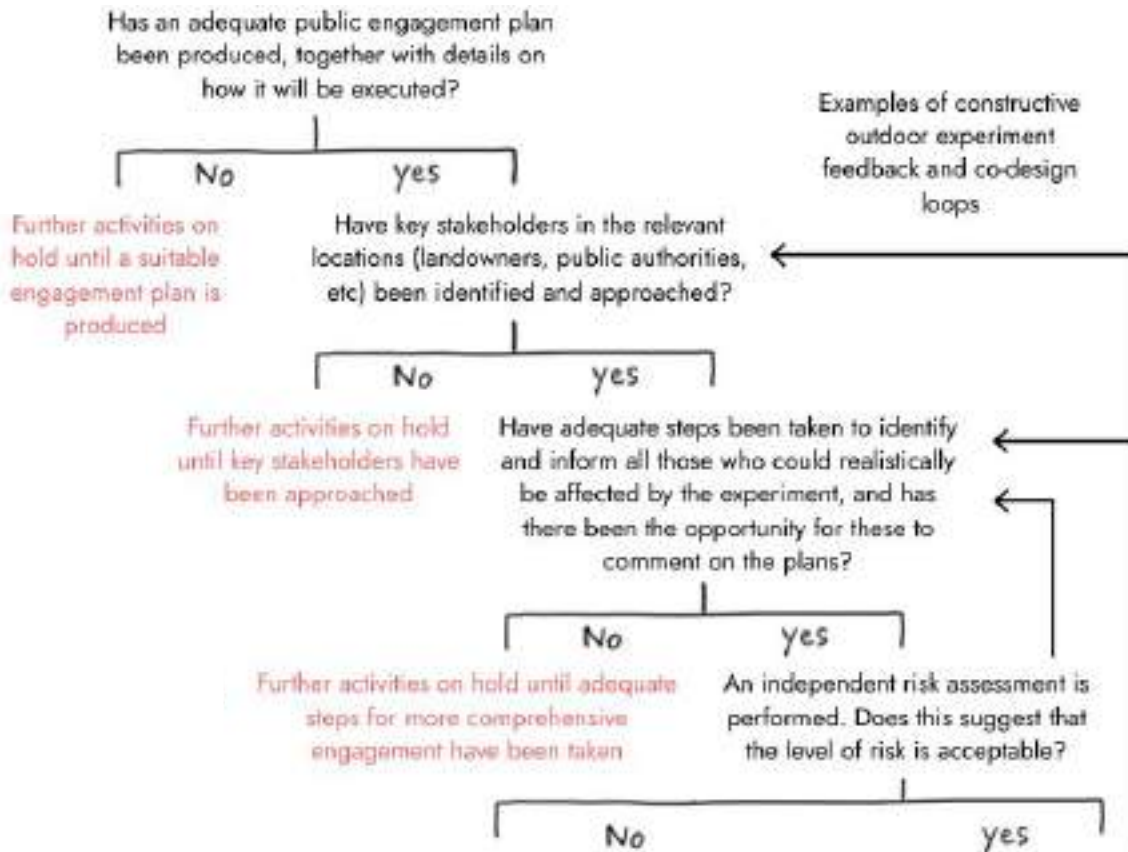
The [thesis](#) and the programme [oversight and governance document](#) describe how we are building governance, independent oversight and public engagement into the programme



Programme governance in practice - 2

The [thesis](#) and the programme [oversight and governance document](#) describe how we are building governance, independent oversight and public engagement into the programme

Oversight &
governance
document



The programme oversight committee

The programme oversight committee is a panel of experts (including international members) that is independent of the project teams and ARIA, and that makes recommendations directly to ARIA's leadership. The oversight committee helps to hold the programme team to account.

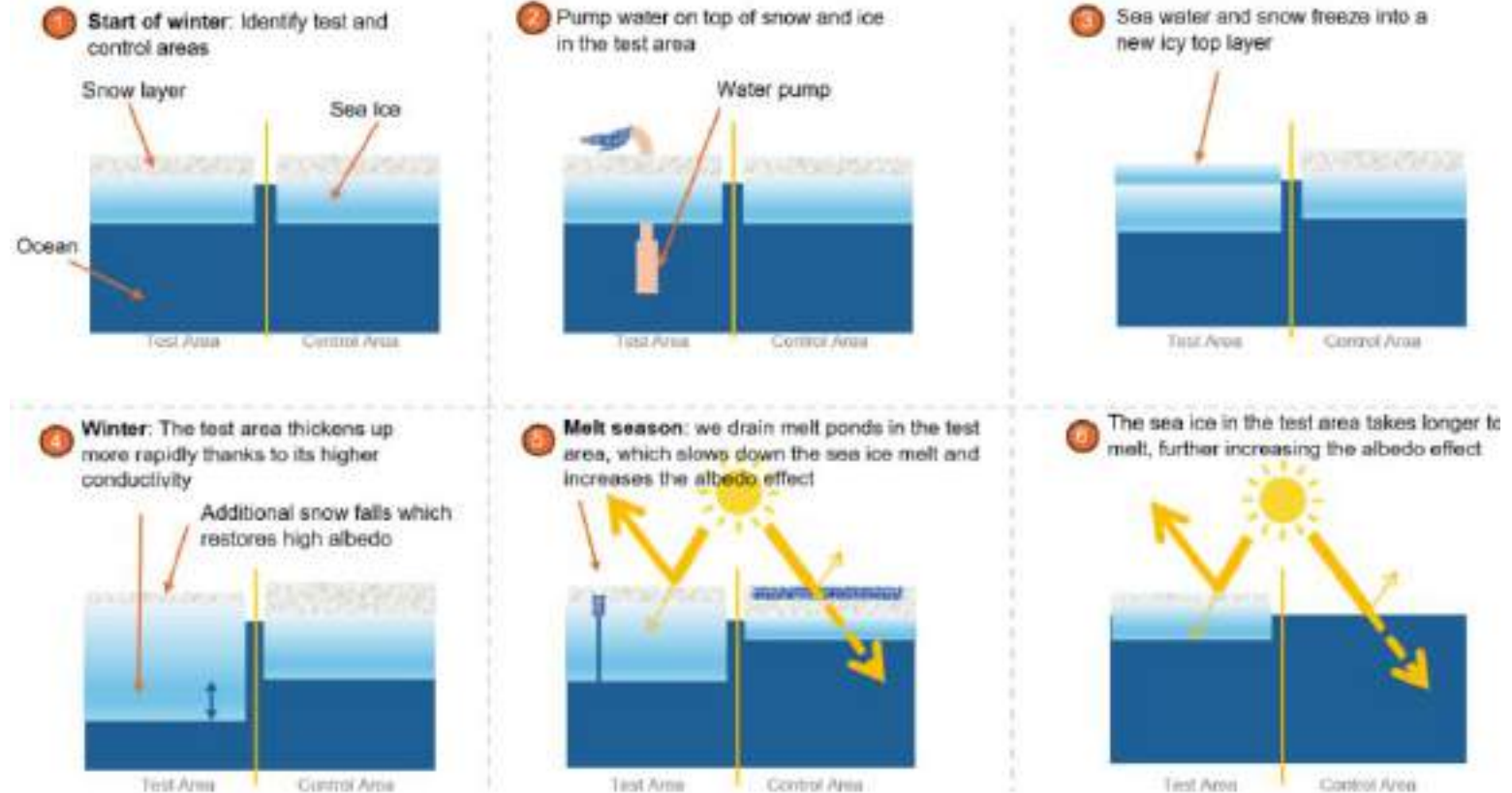


- Piers Forster (chair)
- Jessica Seddon
- Arunabha Ghosh
- Elena Kavanagh
- Jack Stilgoe
- Shuchi Talati
- Jan McDonald

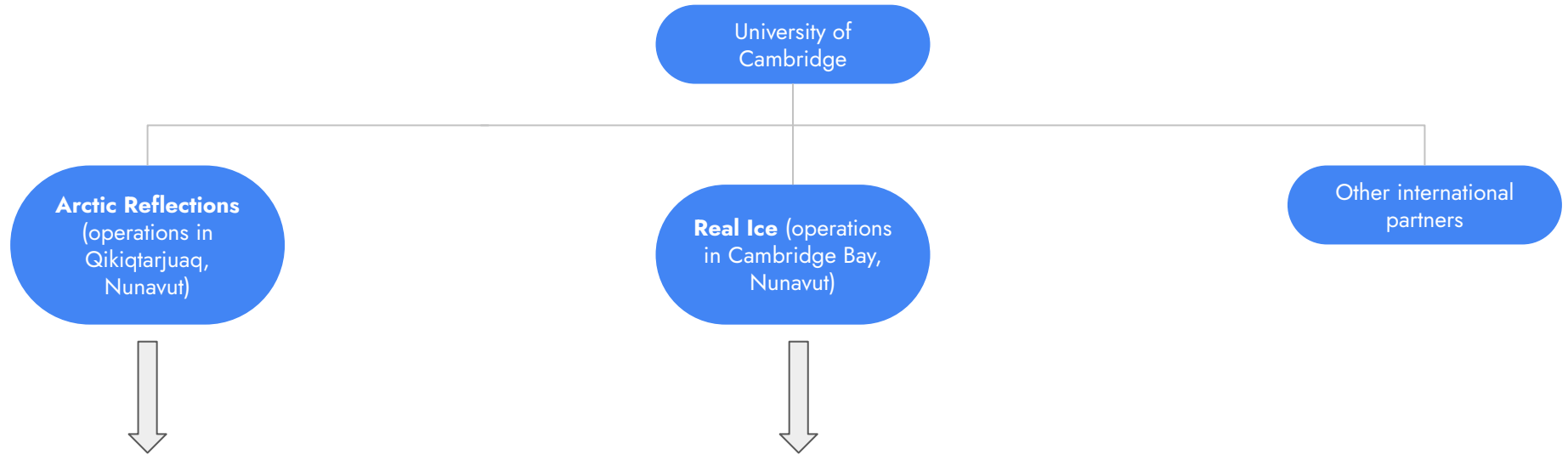
Programme Creators

- 
- + Our Creators were **announced on 7th May 2025**.
 - + We are funding **22 projects** with PIs based in **12 countries**.
 - + We are funding **7 projects in the Global South** that will conduct modelling efforts, research capacity building and governance studies, empowering these marginalized communities to contribute meaningfully to the debate. ***No outdoor experiments will be conducted in the Global South.***
 - + The portfolio contains **4 passive monitoring outdoor projects**: these include drone development for monitoring volcanic plumes, and balloon and aircraft flights to investigate cirrus cloud microphysics relevant for cloud thinning and climate monitoring.
 - + The portfolio also contains **5 small-scale outdoor experiments**.

Re-thickening Arctic Sea Ice (RASI) - 1st outdoor experiment



The RASI team's structure



Outdoor experiments on sea ice thickening over a maximum of three winters (2025/26, 2026/27 and 2027/28).

Initial scale will be $< 1 \text{ km}^2$

All experiments will be conducted under permits from the relevant local authorities

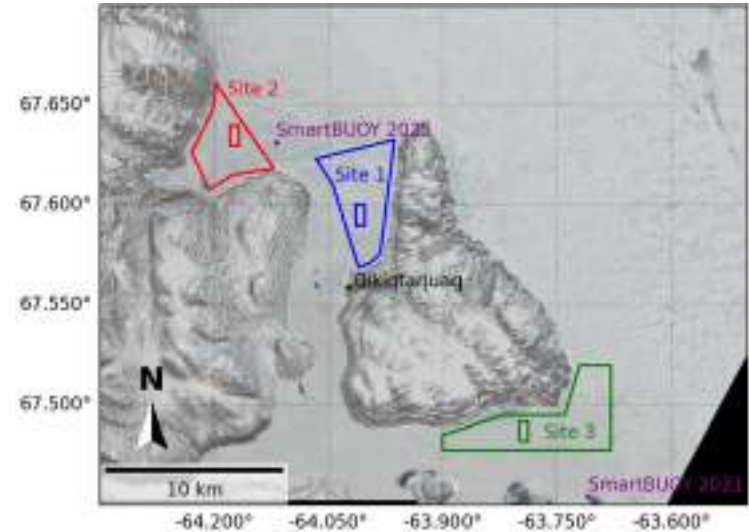
Real Ice (Cambridge Bay)

- The team have previously worked in Cambridge Bay on sea ice thickening in two previous winters
- There is a history of in-person engagement across the community going back to November 2023
- Work takes place under permit from NRI, operating with the cooperation of CHARS
- Members of the Real Ice team live in Cambridge Bay for months at a time and employ members of the local community to take part in the research and operations



Arctic Reflections (Qikiqtarjuaq)

- The team have thickened ice in Newfoundland and Svalbard in previous years
- The team visited the community in September 2025
- They met with the mayor, Elders and the local HTO
- They presented on their plans for this coming winter
- A new site was suggested, based on local ecology and the team's requirements
- A letter of support was obtained from the Senior Administrative Officer
- Work takes place under permit from NRI, operating with the cooperation of Laval's Qikiqtarjuaq Research Centre



Examples and reporting



Arctic Reflections pumping seawater onto a frozen lake in Svalbard in 2024.

Arctic Reflections were endorsed by the UN [Ocean Decade Programme](#) for their Sea Ice Restoration research.

<https://www.realice.eco/mission>

<https://arcticreflections.earth/>

<https://www.climaterepair.cam.ac.uk/>

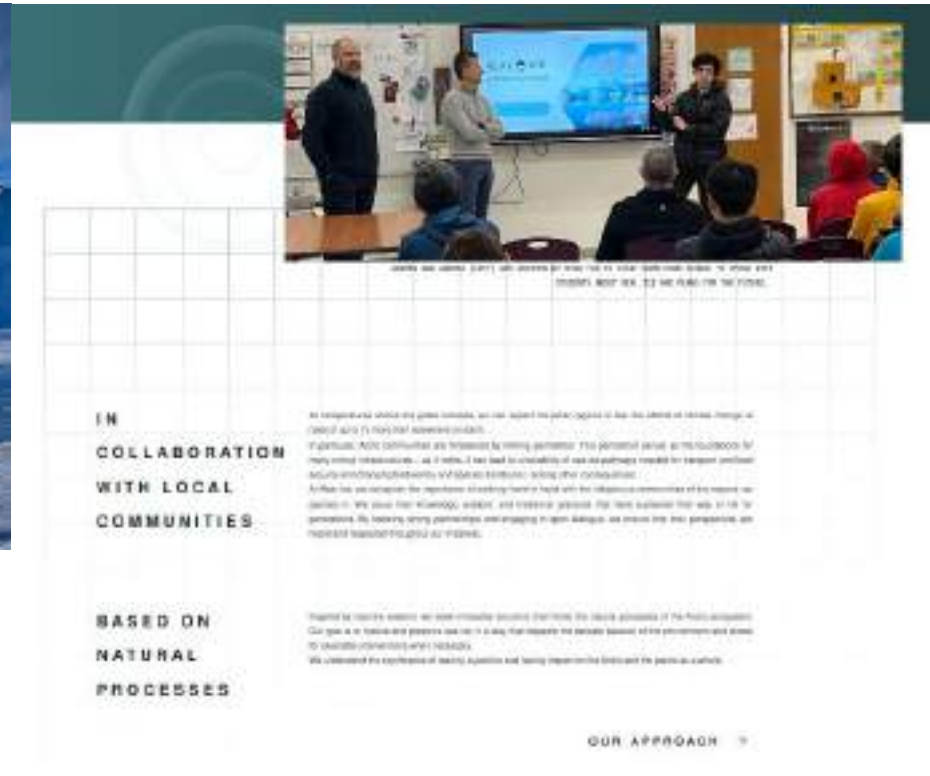
Examples and reporting



<https://www.realice.eco/mission>

<https://arcticreflections.earth/>

<https://www.climaterepair.cam.ac.uk/>



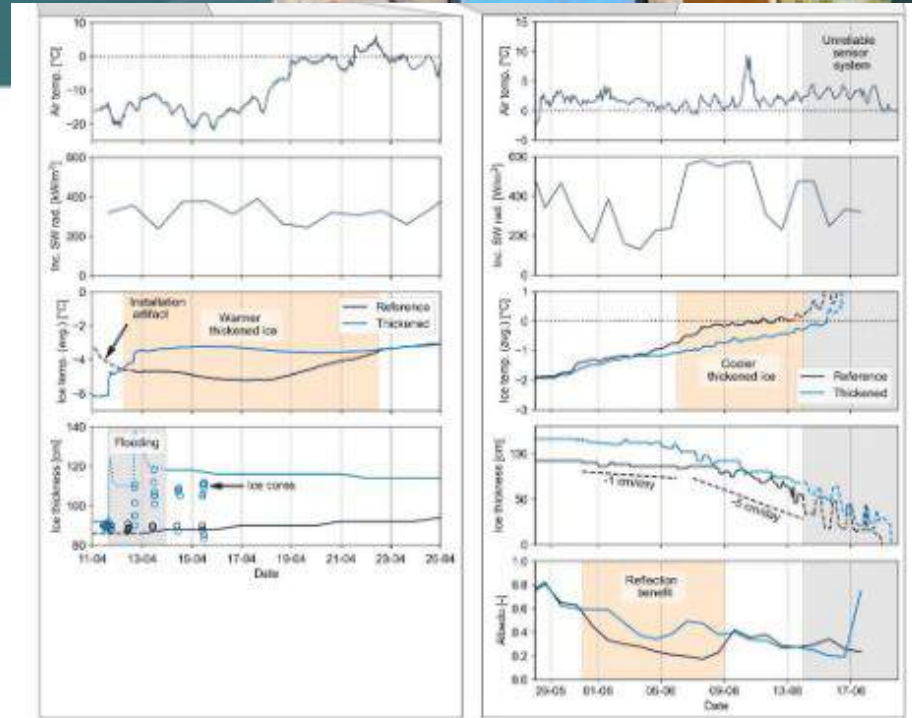
Examples and reporting



<https://www.realice.eco/mission>

<https://arcticreflections.earth/>

<https://www.climatepair.cam.ac.uk/>



Thank you

We would be very grateful to hear your questions and feedback

For updates about
ARIA's work:

[X/Twitter](#), [LinkedIn](#) +
[Substack](#) (QR)

A screenshot of the ARIA website. The header includes the ARIA logo, navigation links (Home, About us, What we do, Funding, Insights, Accessibility), a search icon, and buttons for 'Opportunity spaces' and 'Sign up for updates'. The main content area features a breadcrumb trail: Home / Opportunity spaces / Future Proofing Our Climate and Weather / Exploring Climate Cooling / Oversight and Governance. Below this, there are two buttons: 'Opportunity space: Future Proofing Our Climate and Weather' and 'Programme: Exploring Climate Cooling'. The main heading is 'Exploring Climate Cooling'. The text below the heading states: 'This £56.8m programme aims to build a robust evidence base to explore – with independent oversight – if climate cooling approaches could ever be feasible, scalable, safe, and governable.' A partial image of the Earth is visible on the left side of the main content area.

<https://www.aria.org.uk/opportunity-spaces/future-proofing-our-climate-and-weather/exploring-climate-cooling/>

Oversight Committee
Exploring Climate Cooling Programme

December 9, 2025

Dear Ilan,

Thank you for the opportunity to review the documents prepared by Real Ice, Arctic Reflections, the Cambridge Center for Climate Repair, and the Exploring Climate Cooling Programme regarding the proposed experiment by the “Rethickening Arctic Sea Ice (RASi)” project.

Our recommendation is to approve the funding for the outdoor experiment subject to:

- a) ARIA’s confirmation that all relevant laws, regulations, and permitting requirements, including Indigenous rights as set out in the UN Declaration of the Rights of Indigenous Peoples, have been followed.
- b) Continuation of meaningful, respectful engagement with local communities. On this point we have some recommendations below.

We note that (a) is in fulfillment with ARIA’s statement commitment in the November 2025 Revision of Exploring Climate Cooling Programme Oversight and Government that

“ARIA will not fund experiments where the activities proposed are prohibited by domestic or international law or that violate Indigenous rights, including those outlined in the UN Declaration on the Rights of Indigenous People. Project teams will be required to show how their tests comply with all applicable laws.”

We appreciate the extensive documentation of information on prior and ongoing engagement with communities around the experiment sites, as well as the thoughtfulness and care that it demonstrates.

While the primary engagement between Real Ice and Arctic Reflections has been with local Indigenous right-holders, it is our understanding that the Programme Director, Exploring Climate Cooling, ARIA and the Principle Investigators have, in the past, also reached out by email and informally in conversations to individuals associated with of the Inuit Circumpolar Council (ICC), Inuit Tapiriit Kanatami (ITK), and the Member of Parliament from Nunavut.

We have several additional recommendations for ARIA and for the Creator teams. These recommendations stem from the recognition that the Exploring Climate Cooling portfolio of projects has a special importance as the largest disclosed public funding for climate cooling to date, with a stated ambition to demonstrate responsible research practices. These particular experiments would also be the first to be approved under this portfolio. Their conduct, as well as perceptions of conduct, will have a bearing on the subsequent program activities. The demonstration of responsibility in research should reflect this wider context.

First, we recommend that ARIA as a whole, and particularly the Exploring Climate Cooling team, document and, most importantly, extend their “best effort” to obtain and maintain Free, Prior, and Informed consent (FPIC) from higher level Inuit bodies such as the ICC and ITK. This is in addition to the Creator teams’ continuing engagement with local bodies.

Why engage with higher level Inuit bodies.

We understand that the proposed experiments are controlled, small-scale, research efforts similar to work that has, in the past, been reviewed and approved by local bodies and non-government community representatives such as Hunters and Trappers Organizations. We also recognize that they are funded by a program that is focused on *exploring* climate cooling and has explicitly distinguished small-scale research from wider use or deployment.

The experiment, however, has the potential to set a precedent for responsible research. It is also potentially a first step in a larger evolution of scaling climate intervention. One of the participants (Real Ice)’s mission is to “prove and scale new methods of restoring and preserving Arctic sea ice using renewable energy.” (<https://www.realice.eco/mission>) Another participant, Arctic Reflections, is “committed to halting the rapid disappearance of Arctic sea ice.” (<https://arcticreflections.earth/>). The Cambridge Center for Climate Repair is “a mission-driven organisation advancing research on high impact climate repair projects that can be rolled out at scale within the next 5-10 years.” (<https://www.climaterepair.cam.ac.uk/mission>) This larger context cannot be ignored, particularly in the present moment for science, narrative, and discourse on climate change and climate intervention.

Given the larger context of the particular experiment, ICC and ITK, as organizations representing Inuit rights holders, could be considered relevant to engage with at this point, prior to scale, due to the potential transboundary impacts implied by participants’ stated intentions.

Why ARIA should lead

In the normal course of events, it is the implementing entity, rather than the funder’s responsibility to obtain FPIC. This is also noted in Item 4.1.2 of the contract between ARIA and the University of Cambridge.

Real Ice, Arctic Reflections, the Centre for Climate Repair do have a duty to be honest and transparent about their intentions and potential future trajectories for both research and possible use of ice sheet thickening.

In this case, however, we see ARIA as best positioned to lead engagement with ICC and ITK, given:

- ARIA’s role as the overarching programme coordinator and the entity best positioned to represent the collective activities of a set of projects that are exploring climate cooling approaches in which there may be a broader Inuit interest;

- the organization's overall position as an "executive non-departmental public body" of the UK government;
- ARIA's larger orientation toward catalyzing new technologies and industries (noting that the ECC program's emphasis on exploration is an exception).

Specific guidance

As a rule of thumb, engagement with ICC and relevant Indigenous rights holders should be at least as structured and formal as the ways in which ARIA has reached out to national authorities in countries where research is planned.

"Best effort" in this context obliges ARIA to undertake persistent communication, multiple attempts to engage across different channels, and being generally proactive.

To aid transparency and to establish a best practice model for transparency, we recommend keeping documentation of the dates when ARIA or partners first contacted ICC/ITK; dates of follow-up communications; notes on meetings requested, held, cancelled, or ignored; and what/when project information or materials were shared.

Finally, ARIA should reflect on the impact of going ahead without ICC and ITK consent or acknowledgement of the overall ARIA programme of work and its commitment to act responsibly. It could consider postponing if consent is not forthcoming by the time the sea-ice experiments are due to start.

Second, we recommend that Real Ice and Arctic Reflections should document and share the following processes and share an initial draft with communities around the experiment site before the start of the experiment.

- their process for achieving consent, confirming continued consent, and discerning/accepting withdrawal of consent. This documentation should include how dissent within the community and from Elders in particular is documented and handled.
- practices for community benefit, including:
 - a. Their approach to co-authorship
 - b. Their approach to other forms of recognition of contributions (including, for example: instruments, guidance on experiments, and insights from Elders and others.)

Our suggestion is for Real Ice and Arctic Reflections to keep a journal of engagement with local communities and rights holders. This is for several reasons: a) to have a clear record in case of questions about FPIC, ongoing consent, and permissions; b) to have material to be able to share on ways of working that might help future researchers and communities.

These are important to be clear about community benefit and roles and compliance with ICEE protocols. They are also an important part of making the responsible research practices visible, capable of being adopted by future projects.

Third, we recommend that both the Exploring Climate Cooling team and the RASi Creators work with Liminal Space to find practical ways to acknowledge the wider context of these experiments both in work with media at multiple scales and in how the creator teams communicate about the work themselves (e.g. on their websites).

This is in keeping with two of the programmes' governance principles:

- Communicate proactively and be transparent, open, and honest at both the programme and project level, including around levels and sources of funding, intentions, how the research is conducted, outputs, and impacts.
- Be cognisant of the broader implications of research + integrate systems thinking into research on approaches for actively cooling the climate.

Again, we would like to draw attention to the fact that while these particular experiments are relatively small-scale experiments designed to learn about the feasibility and efficacy of certain approaches to a sheet thickening, they sit within a larger geopolitical, ethical, environmental, and technological context that cannot be ignored. Avoiding this context can create distrust or misunderstanding about intent. These activities have a meaning beyond the particular place and time, and that meaning is contested and controversial. We expect that it will continue to be debated and questioned in the media discourse, as well as in potentially legal and governance settings. Throughout this contestation and debate, it is extremely important for ARIA and the creator teams to maintain openness, transparency, and full documentation of efforts and honest reflection and disclosure of intentions.

Best regards,

Piers Forster, Chair
Jessica Seddon, Secretary
Arunabha Ghosh, Member
Elena Kavanagh, Member
Jan McDonald, Member
Jack Stilgoe, Member
Shuchi Talati, Member

ADDENDUM: Explanation of the Role of the Oversight Committee

The Oversight Committee role is to assess compliance with the governance principles set out by the Exploring Climate Cooling programme. It is not to ascertain compliance with all applicable laws and regulations.

This review is based upon the information that was provided by the creator teams, as well as a subsequent conversation with the creator teams to clarify certain aspects of the ongoing engagement and the rationale and practices for working with communities. We trust that this information is complete and true with no substantive omissions.

List of Documents Reviewed

ARIA

FPCW-PR01-P015 - Re-thickening Arctic Sea Ice– Standard Grant Funding Letter
2025-11-14 ECC - Outdoor Experiment Funding Approval Submission - RASI Real Ice
ECC -Outdoor Experiment Funding Approval Submission Arctic Reflections 2025

Supplemental Documents

Real Ice

Presentation to EHTO winter 2023.pdf
Summary of Field Experiments in Cambridge Bay 2024-2025.pdf
2025-08-15 NRI License Renewal.pdf
2025-08-15-NPC File # 150891 Real Ice - January 26 Field Test in Cambridge Bay Canada_DH
(002) (1)
2025-11-20 Real Ice 2025_26 Progress with Community Engagement and Permitting
2231031-23YN044-Screening Decision Report-NIRB.pdf
EHTO-Support-Letter_Real Ice Nov 2025.pdf

Arctic Reflections

Arctic Reflections timeline.docx
250829-25YN067-NIRB Application-IR1E.pdf
Community consultation and permitting proces update for ARIA Nov 2025 v3.pdf
EIA_Qikiqtarjuaq_2026 DEF.pdf
Participant information sheet Qikiqtarjuaq.pdf

To: Exploring Climate Cooling Oversight Committee

CC: Mark Symes, Exploring Climate Cooling Programme Director

December 18 2025

Re: Re-thickening Arctic Sea Ice (RASi) outdoor experiment series, January - Summer 2026

Dear Oversight Committee members,

Thank you for your letter of 9 December 2025, in which you shared your recommendations regarding the proposed outdoor experiments by the “Rethickening Arctic Sea Ice” (RASi) project team.

The Exploring Climate Cooling Oversight Committee was established in late 2024 to provide me with independent advice and recommendations, and with the following remit:

1. To support effective oversight of the programme’s outdoor experiments and to guide transparent communication of findings;
2. To help shape international norms and standards for the responsible governance of such experiments; and
3. To contribute constructively to the wider international discussion on potential governance mechanisms for climate cooling approaches.

While the ultimate decision on whether to release funding to support any given outdoor experiment rests with me as ARIA’s CEO, your independent advice and recommendations on the RASi team’s plans have been invaluable in helping me to reach a decision.

Any decision on the release or withholding of funding for an outdoor experiment requires very careful consideration across a number of axes (technical, regulatory, respect for the rights of indigenous groups, and public and local community engagement). In light of your recommendations, those of the programme team, and my own examination of the materials related to the experiments, I am reassured that this proposed set of outdoor experiments will meet ARIA’s requirements around robust governance and responsible and ethical research as summarised in our [Programme oversight and governance document](#).

My decision is therefore to approve the release of funding for this set of experiments, subject to the following conditions:

1. That (as per your recommendation (a)) the Exploring Climate Cooling programme team commissions an independent assessment that confirms that all relevant laws, regulations, and permitting requirements, including those relevant to Indigenous rights as set out in the UN Declaration of the Rights of Indigenous Peoples, have been followed. Should this assessment indicate that the project plans fall below an acceptable threshold in any of the above named areas, then I have instructed the programme team to conduct a review of the experiments.
2. That meaningful and respectful engagement with key communities continues and is strengthened (speaking to recommendation (b) in your letter), through the following specific pathways:
 - a. That the programme team (with assistance where practical from the RASi team) increases engagement with ICC and ITK through a range of channels, making sure that key stakeholders at these organisations are offered the opportunity to receive a briefing and share their views on the RASi project and the programme in general. I have reviewed the extensive evidence provided by the RASi team and I am satisfied that the required Free, Prior and Informed Consent (FPIC) for their experiments has been secured from the communities where this research will take place — Cambridge Bay and Qikiqtarjuaq. The aim of engaging with ITK and ICC should be to work towards building consent over time with these national and international-level bodies. I have instructed the programme team to keep a log of such activity and to use their very best efforts to consult with stakeholders at ITK and ICC before the experiments start.
 - b. That the RASi team documents and shares with local communities the following before the experiments start, in a manner that is accessible for those communities:
 - i. Information on their process(es) for achieving consent, for confirming continued consent, and for discerning/accepting withdrawal of consent. This information should include in particular how any dissent within the community and from Elders will be documented and handled.

- ii. Information on practices related to community benefit, including the approach to co-authorship that will be followed and the approach that they will take to other forms of recognition of contributions (including, for example: instruments, guidance on experiments, and insights from Elders and others).

To ensure the project continues to set best-precedent for outdoor experiments in this field, the RASi team should continue to work on the following during and beyond the duration of the experiments:

1. The keeping of journals/logs by Real Ice and Arctic Reflections of their engagement with local communities and rights holders, so as to have clear and robust records to support FPIC and ongoing consent and permissions.
2. Supporting good practice in the field by sharing information in the public domain on ways of working that might help future researchers and communities. This could, for example, take the form of peer-reviewed publications on their approach and learnings related to consent and permissions (maybe also in collaboration with local stakeholders).
3. Leveraging support from The Liminal Space and the programme team to develop and implement measures to communicate with diverse audiences about the project and its wider context. Communication could be through the various websites associated with the project, in the wider media, etc.

Coupled with the activities that members of the RASi team have undertaken to date, it is my view that the conditions and suggestions above constitute a reasonable basis on which to approve funding for this set of outdoor experiments, in keeping with our commitments to this research being conducted responsibly, respectfully, transparently and for the public good.

I am very appreciative of the advice you have provided to help me reach this decision. As always, the committee is free to comment publicly (collectively or individually) on this decision, or any other matter related to the programme or the wider field.

With very best wishes,



Ilan Gur

Oversight Committee, ARIA's Exploring Climate Cooling programme

A note on the announcement of Exploring Climate Cooling R&D Creators

Congratulations to the teams selected for funding under the Exploring Climate Cooling programme.

Your work exploring the science, impacts, governance, and ethics of solar radiation modification and ice sheet thickening has the potential to set a significant precedent for responsible research on an important topic. "Geoengineering," as these approaches are sometimes referred to, is controversial. It should be debated. But any decision, whether to develop, use or ban them, should be made with as much information, and with as many perspectives and questions included, as possible.

Last year was the hottest year on record and the world and its oceans are warming at an unprecedented rate of over 0.2C per decade. Rainfall intensity and wildfire risks are increasing, along with the mounting health impacts of extreme heat.

Decarbonisation towards net zero and broader reduction of methane and other greenhouse gases must accelerate in order to limit warming and other environmental damages such as ocean acidification stemming from excess carbon dioxide. Stopping further warming, however, does not mean immediate cooling as carbon dioxide is a long-lived greenhouse gas.

Societies and ecosystems will need to adapt to living in this hotter world under more extreme conditions. Even with stable temperatures, ice will continue to melt and the deep ocean continue to warm, leading to centuries of sea-level rise. In some cases, there will likely be limits on how much it will be possible to adapt and more drastic actions such as abandoning low lying islands or changing staple food crops may be necessary.

There are possible ways to cool the planet. Achieving rapid reductions in short-lived greenhouse gases, especially methane or actively removing carbon dioxide from the atmosphere are expected to have a cooling effect. There are also various methods that

could cool the earth's surface by reflecting sunlight. These have been known, in principle, for decades. There are natural analogues: volcanic eruptions, for example, have a measurable (temporary) effect on surface temperatures. In practice, however, there are many unknowns about the efficacy, safety, and controllability of different approaches to cooling the earth's surface. There is much to learn - and many perspectives and disciplines to involve in that learning.

We want to commend ARIA for being deliberate in its choices about structuring this programme, including inviting us to constitute the beginnings of an oversight committee. The programme has taken care to solicit proposals from a range of research perspectives and geographies, including beyond the UK. It has a structured approach to reviewing and approving experiments, including specific requirements for respectful engagement with key communities. It commits to considering the wider context for how this research might be used. It has demonstrably done so in developing an IP policy unique from other ARIA programmes. Implementation of climate intervention governance, especially for small-scale outdoor experiments, is still in its early stages. There are important learnings of how to do oversight in ways that reinforce transparency, legitimate engagement, and scientific integrity that we hope this committee can guide.

To be clear: we do not exist to legitimise this programme. We advise ARIA on the risks and benefits of supporting proposed creator projects and how best to work with and across creator teams to support learning and to help ensure that findings are contextualised and communicated appropriately alongside mitigation and adaptation options. During project selection, we weighed in at various stages to advise the programme team on feedback to creators to strengthen research governance, and the ARIA leadership on prioritisation of proposals. We are pleased that ARIA has been receptive to our suggestions, including additional investment, supporting the creator teams in public and stakeholder engagement.

We are advisory: we do not have the power to prevent or withdraw funding. However, we are constituted to have an unconstrained voice that is independent of the programme, and, when needed, independent of ARIA as an organisation. We have started as a disciplinarily and geographically diverse set of actors. Membership of the committee will expand and change over the coming months. We will seek additional geographic, legal, ethical, governance scientific, and other expertise to adapt as the programme evolves. Our intention is to build the committee and wider set of collaborators to ensure that we have the expertise to ensure that key governance principles such as learning, transparency, collaboration, risk minimisation and community engagement become real and visible practice.

Looking ahead, we will advise ARIA on appropriate governance frameworks in handling different risks and opportunities around the programmes, especially for projects learning from real-world investigations. This is an opportunity to create space for a more constructive conversation on how to govern research, ensure greater inclusivity of research questions from diverse geographies, promote collaboration, and put theoretical principles into practice in ways that can serve as a governance model for research to come. We hope the work of our committee will contribute to resolving critical uncertainties about governability of approaches for climate cooling while at the same time keeping open the possibility that they will never be used.

Signed,

[Oversight Committee, Exploring Climate Cooling](#)

Exploring Climate Cooling

Programme oversight and governance

Updated January 2026

What are ARIA's core principles for governance of this programme?

ARIA will not fund experiments where the activities proposed are prohibited by domestic or international law or that violate indigenous rights, including those outlined in the UN Declaration on the Rights of Indigenous People. Project teams will be required to show how their tests comply with all applicable laws.

The governance measures that ARIA has put in place for this programme have been designed with the following principles in mind:

- **Deliver Valuable & Transformational Knowledge.** We aim to select and design for research that will address the most pressing critical scientific questions surrounding approaches for actively cooling the climate.
- **Minimise Risk.** All experiments should be designed to reduce direct risk as far as possible.
- **Engage With, and Respect Key Communities.**
- **Communicate Proactively and be Transparent, Open, and Honest** at both the programme and project level, including around levels and sources of funding, intentions, how the research is conducted, outputs, and impacts.
- **Be Cognisant of the Broader Implications of Research + Integrate Systems Thinking** into research on approaches for actively cooling the climate.
- **Learn, Adapt and be Responsive.** Success will require a willingness to adapt to lessons learned during the programme and to changing circumstances.

Measures to try and uphold these principles are discussed in the programme [thesis](#). In particular, we are:

- Working with and refining a detailed framework for approving funding for outdoor experiments in order to be transparent about our decision-making, ways of minimising risk and engagement with communities (see Figures 1-3 below).
- Opening the funding opportunity to a global pool of researchers in order to support a wider set of perspectives on critical questions.
- Maintaining a policy of transparent reporting of findings and open IP (when applied to climate intervention) in order to ensure that the knowledge gained is available for public benefit.

The programme's independent oversight committee (see below) is a mechanism intended to strengthen governance of the programme.

However, ARIA acknowledges that this is a complex and ethically-challenging research field and that circumstances unforeseen by the proposed governance measures may arise. By applying the principles above, ARIA will continue to iterate and update the programme's governance mechanisms in order to adhere to the principles above.

The role of the oversight committee and its relationship to the project teams

The programme oversight committee will have three main roles prioritised in this order:

1. Supporting ARIA's leadership in the effective oversight and governance of the outdoor experiments conducted as part of this programme, including producing guidance to ensure transparent and objective communication of findings.
2. Shaping the development of internationally-accepted and responsible norms and standards for oversight and governance of outdoor experiments of approaches for actively cooling the Earth.
3. Identifying constructive ways to contribute to the wider international discussion on possible governance mechanisms for these approaches.

The programme oversight committee is a panel of experts (including international members) that is independent of the project teams and the programme director and that makes recommendations directly to ARIA's leadership. Roughly half of the members of the

oversight committee were in place in time to contribute during the selection of projects by ARIA's leadership and the programme team. Additional members will continue to be appointed to the committee at the recommendation of the existing oversight committee members (and with the approval of ARIA's leadership) as the need arises. This flexible intake approach allowed for independent oversight during project selection, whilst also allowing the precise expertise of the committee to be tuned to best suit the projects that have been selected.

The initial members of the committee (see biographies below) were identified by ARIA on the basis of their expertise and international standing across a wide range of areas relevant to climate science and climate engineering. Potential members were then invited to join the committee by ARIA's leadership after meeting with the programme director and ARIA's CEO. These initial members have been appointed for the duration of the programme (5 years). Members appointed subsequently will be appointed for the remaining duration of the programme by invitation from ARIA's leadership, at the recommendation of the existing members of the committee and after consulting with the programme director. At the outset, the committee will have the opportunity to deliberate on and refine its terms of reference, for approval by ARIA's leadership.

Members of the committee will be paid at a fixed rate by ARIA in order to ensure that they can dedicate sufficient time to programme oversight. Remuneration will not be dependent on the progress of the project teams or on the delivery of particular recommendations regarding these teams, supporting the committee's independence. Budget will be available to allow the committee members to join in-person ARIA meetings and workshops.

The names, affiliations and biographies of the current members of the committee, together with information on their specific roles on the committee and any potential conflicts of interest are supplied below.

It is expected that the oversight committee will discuss the development of plans for outdoor experiments with the project teams and programme director, but it will be the responsibility of the project teams to develop suitable technical and non-technical plans. The oversight committee will not be involved in any direct management or day-to-day decision making for any of the projects. This approach is designed to give project teams access to the expertise of the oversight committee members (promoting the development of plans and pre-experiment activities in line with best practice), whilst allowing the oversight committee members to maintain a high level of objectivity regarding individual projects.

Budget and additional expert support services contracted by ARIA will be available to project teams to allow them to design and undertake the necessary pre-experiment public engagement and co-design activities. At the point at which project teams require additional budget in order to actually perform the outdoor tests, they will go through a formal “outdoor experiment funding approval” process, whereby their technical and non-technical plans and pre-experiment activities will be assessed, and approval for release of funds for the outdoor experiment (or series of linked experiments) will be either granted or refused by ARIA’s leadership on the basis of the materials that the project teams submit for consideration.

Outdoor experiments will only be funded if they meet the criteria outlined in the [programme thesis](#) in the section “A Suggested Framework for Outdoor Experiments”. Two key figures from the thesis are reproduced below for ease of access (Figures 1 and 2, which are called Figures 2 and 3 in the programme thesis). Further context on these figures is given in the programme thesis.

All ARIA projects must adhere to all relevant applicable domestic and international laws, and must respect the rights of indigenous peoples. For projects that propose to conduct activities that may require particular permissions, or compliance with particular regulatory or project management practices (e.g. outdoor experiments), ARIA will exercise its adaptive funding mechanism to review specific plans before funding is released for that component of the project.

An overview of the outdoor experiment funding approval process (and the role of the oversight committee in that process) is summarised in Figure 3. The decision trees in Figures 1 and 2 feed directly into this process, by informing which experiment proposals progress as far as seeking funding through the mechanism summarised in Figure 3. This figure also shows the relationship of the oversight committee to ARIA’s leadership, the ARIA board committee for ethics and social responsibility (which has visibility across all of ARIA’s programmes), the programme director, and to individual project teams. It is important to note that while ARIA’s leadership makes the final decision on any given outdoor experiment, no project that violates applicable domestic or international laws or the recognized rights of indigenous peoples would be funded.

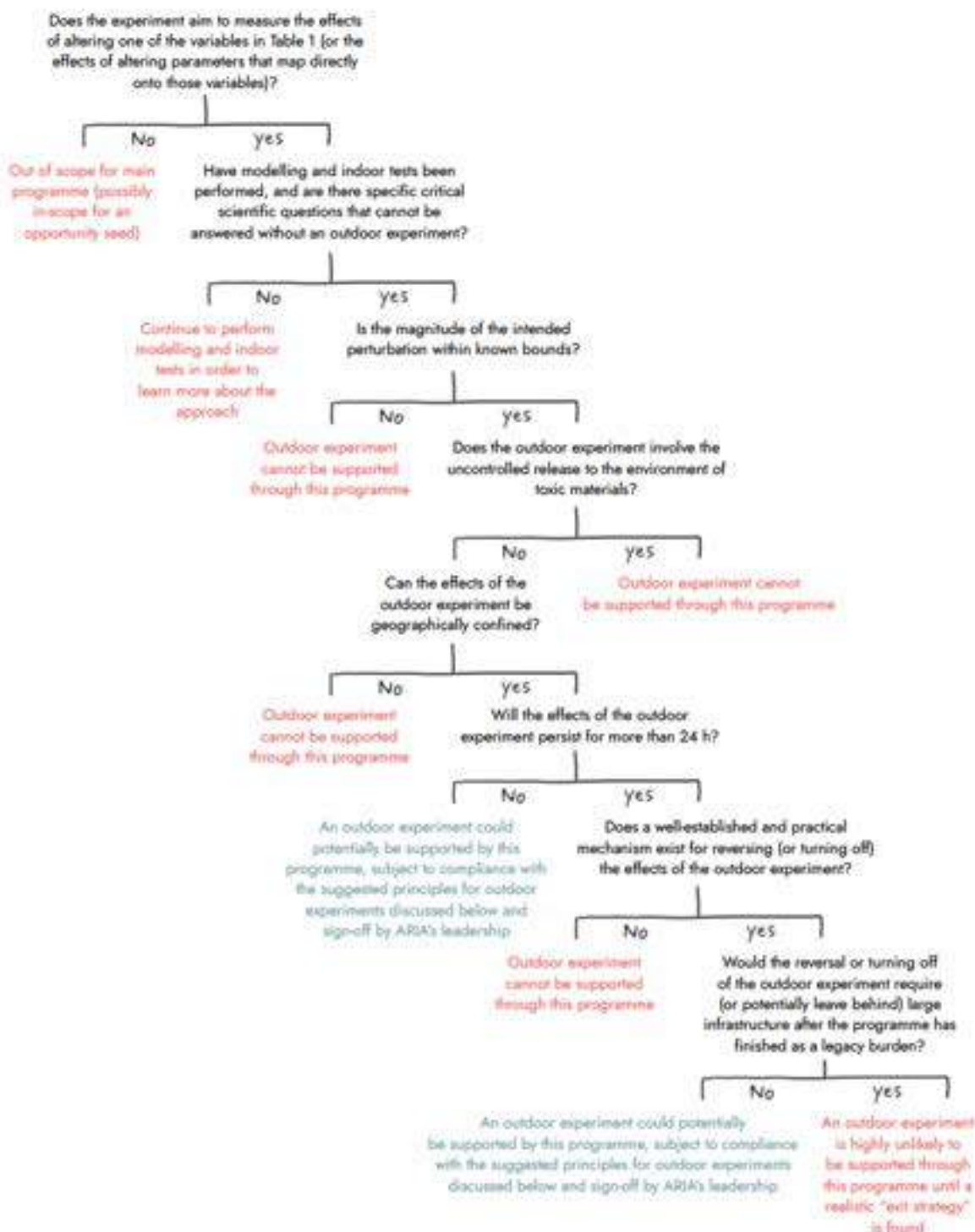


Figure 1: The suggested outdoor experiment technical consideration decision tree (called "Figure 2" in the programme thesis). Table 1 refers to Table 1 in the Programme Thesis.

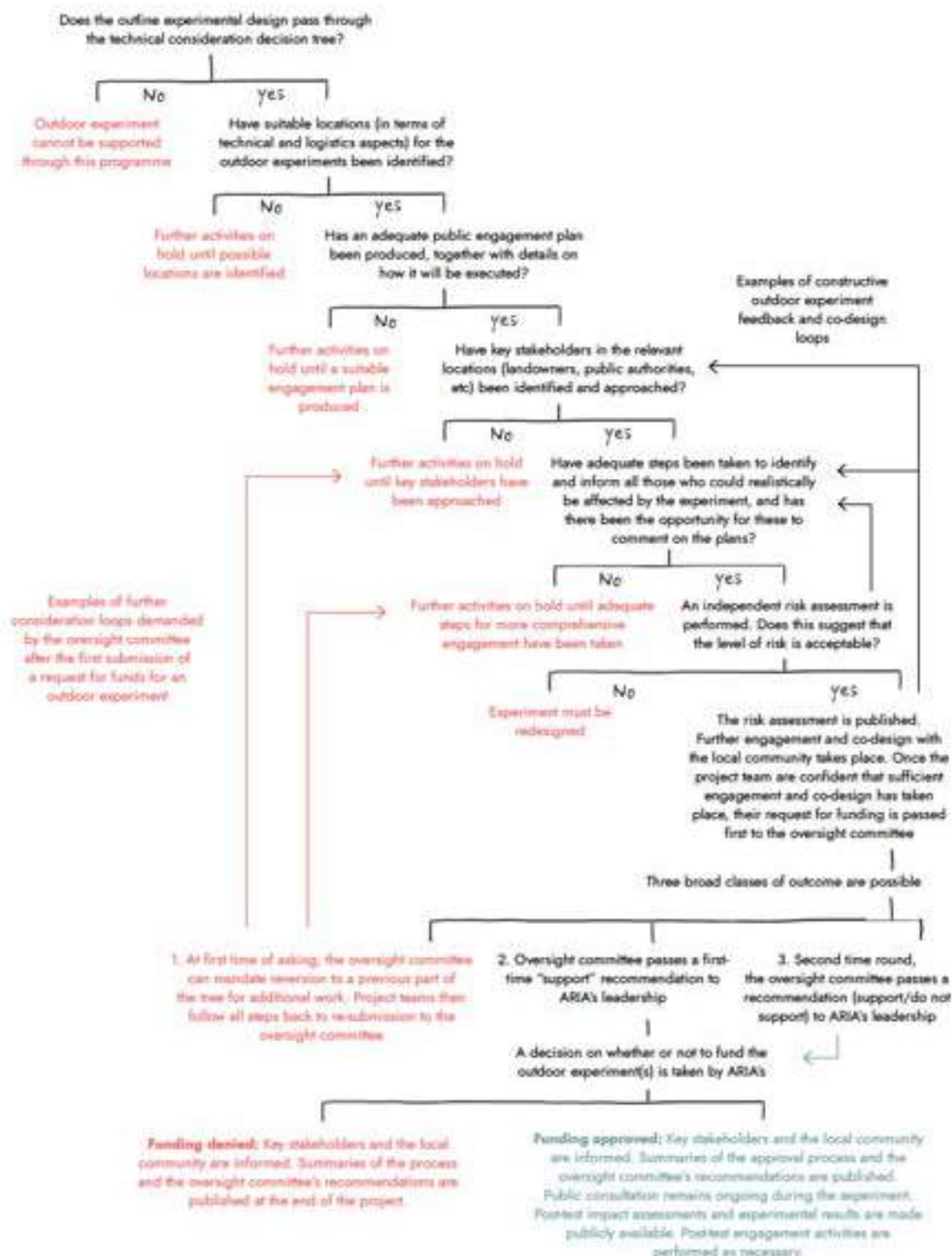


Figure 2: The suggested outdoor experiment funding approval decision tree (called "Figure 3" in the programme thesis). This figure is to be used in conjunction with Figure 1 above.

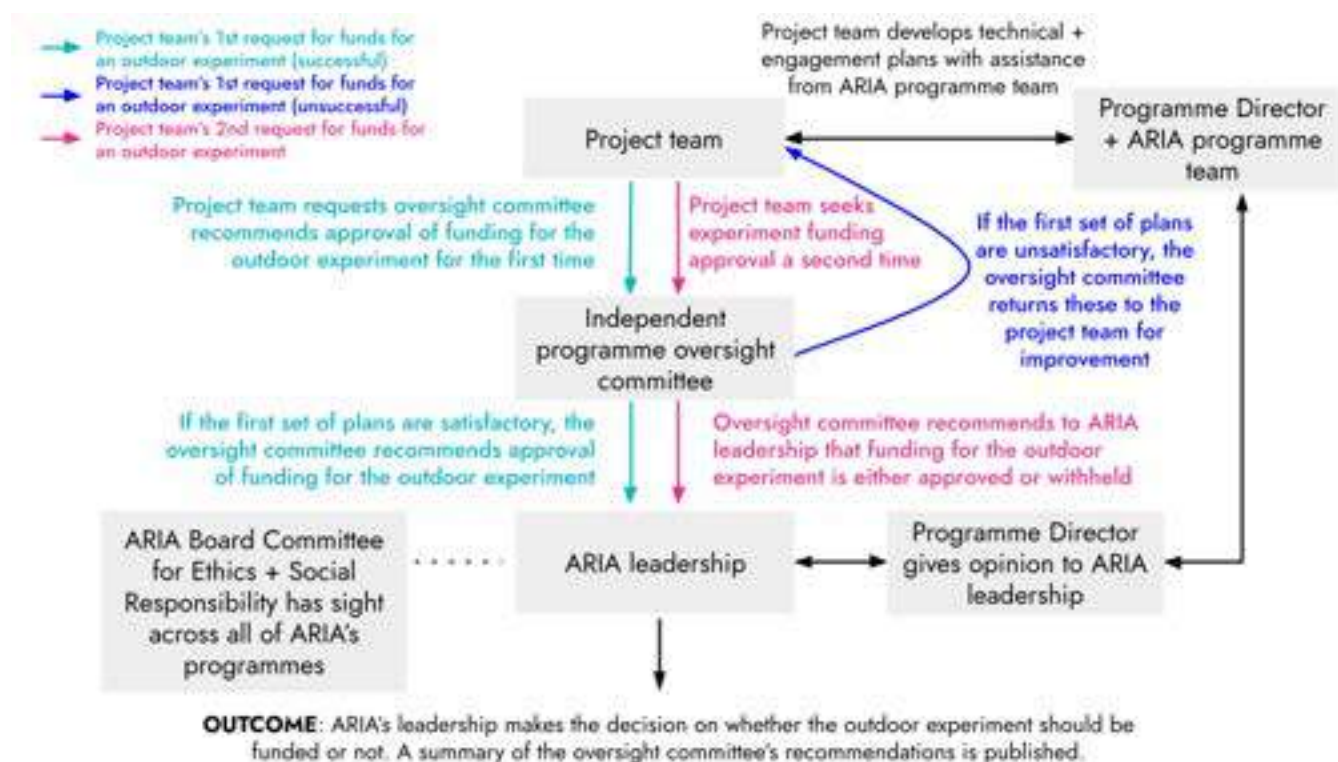


Figure 3: The relationship of the oversight committee to ARIA's leadership, the ARIA board committee for ethics and social responsibility, the programme director, and to individual project teams, together with an overview of the process by which the oversight committee can insist on alterations to project teams' plans for outdoor experiments, and how subsequent decisions will be taken.

At the outset of the outdoor experiment funding approval process, project teams will submit materials describing their plans and activities-to-date related to the outdoor experiment to the oversight committee, who will be able to scrutinise both the technical and non-technical aspects of these materials. The programme oversight committee will then make one of three recommendations to ARIA's leadership:

1. If the committee is thoroughly satisfied with the project team's plans and pre-experiment activities, then a recommendation will be made to ARIA's leadership that funding for the outdoor experiment (or series of linked experiments) should be approved (teal arrows in Figure 3).

2. If the committee is mostly satisfied with the project team's plans and pre-experiment activities, then a recommendation can be made to ARIA's leadership that funding for the outdoor experiment should be approved contingent on certain minor clarifications or amendments being made (teal arrows in Figure 3).
3. If the oversight committee is dissatisfied with the project team's plans and pre-experiment activities, then the oversight committee will have the power to refuse funding approval for any outdoor experiment (or series of linked experiments) on its own initiative at the first time of asking. Should this occur, the committee will be able to request alterations to a project team's plans and/or request that additional activities are performed prior to the start of an outdoor experiment (blue arrow in Figure 3). The project team will then be obliged to address these concerns and re-submit their updated materials to the oversight committee, with three outcomes then possible (pink arrows in Figure 3):
 - a. The committee is now thoroughly satisfied, and recommends to ARIA's leadership that funding for the outdoor experiment is approved.
 - b. The committee is now mostly satisfied, and recommends to ARIA's leadership that funding for the outdoor experiment can be approved contingent on certain minor clarifications or amendments being made.
 - c. The committee remains dissatisfied, and recommends to ARIA's leadership that funding approval for the outdoor experiment is not granted.

The ultimate decision as to whether any individual outdoor experiment (or linked series of experiments) can be funded by ARIA therefore rests with ARIA's leadership. A summary of the committee's recommendations on any particular outdoor experiment (or linked series of experiments) will be made public on the ARIA website before the experiment takes place (in the cases where funding approval is ultimately granted), or at the end of the project in cases where funding approval is not granted. This summary will be prepared by the committee members, in consultation with the programme director.

When making recommendations as to whether any individual outdoor experiment (or linked series of experiments) can be funded by ARIA, the oversight committee will consider the following criteria:

- Is there sufficient scientific value in the proposed experiment and in the knowledge that could be gained by performing it to merit an outdoor experiment?
- Does the design of the experiment minimise risk sufficiently (e.g. to experimenters, the local environment and ecosystem, to property, etc)?

- Has sufficient meaningful engagement with the local community and key stakeholders taken place, and is there sufficient evidence of experimental co-design with these groups?
- Has there been sufficient consideration of the potential broader societal ramifications of the experiment?

Current membership of the oversight committee

The following international experts are the current members of the oversight committee. The committee is chaired by Piers Forster. While the current makeup of the committee provides expertise across a range of climate fields and geographies, ARIA and the oversight committee intend to add to the membership of this committee as the programme progresses and additional perspectives are needed.

As of September 2024, committee members are paid for their participation at a rate of £575/day. ARIA expects that participation will be ~1 day/month.

Committee Membership (April 2025)

Piers Forster (Chair)

Piers Forster is a highly cited atmospheric scientist with over 30 years of experience researching the causes and impacts of climate change, as well as mitigation and adaptation approaches and their connection to national and international climate policy. He was principal investigator for some of the first publicly funded research on geoengineering, the UK's Integrated Assessment of Geoengineering Proposals over 2010-2015.

Piers is a fellow of the American Geophysical Union and has played leading roles authoring Intergovernmental Panel on Climate Change (IPCC) reports, including its Special Report on 1.5°C and its latest



IPCC 6th Assessment Report. He has sat on the UK Government's Climate Change Committee since 2018 and has served as the Committee's Interim Chair since 2023.

He is founding Director of the Priestley Centre for Climate Futures and Professor of Physical Climate Change at the University of Leeds. The Priestley Centre was founded in 2016 to support interdisciplinary research, innovation and teaching on climate and foster strong working relationships with policy makers, businesses and the third sector to support climate actions that deliver wide societal and ecosystem benefits.

Declared conflicts of interest: The University of Leeds are recipients of funding from the ARIA call. Piers Forster was not involved in the proposals or funding decisions. A contract of work between Stardust Solutions and the Priestley Centre was agreed in late 2025, which funds some of Piers Forster's time. This contract funds a postdoc that will work with Professors Dan Marsh and Piers Forster. The work is designed to test the effectiveness of sunlight reflection technology and the impact of any physical and chemistry side effects. The plan is to publish both positive and negative results as the work progresses. The work is not under a non-disclosure agreement.

Jessica Seddon (Secretary)

Dr. Jessica Seddon's work on environmental governance focuses on how new sources of data can be leveraged to enable new (and more sustainable) ways of interacting with the environment around us. Her career spans academic, programme leadership, and strategic advisory roles in the U.S., India, and internationally, focused on institutional design for integrating science into policy and social initiatives. Dr. Seddon is currently Senior Fellow and Director of the Deitz Family Initiative on Environment and Global Affairs at the Yale Jackson School of Global Affairs and a co-founder of The Institutional Architecture Lab.



Jessica worked with the ARIA programme team on the initial design of the governance approach including formation of the Oversight Committee, on which she served as Interim

Chair. As Secretary, Jessica works as a bridge between the ARIA programme team and the Oversight Committee to facilitate some of the operational aspects of the Committee's relationship with ARIA. This includes, inter-alia: conveying questions and agenda requests from the programme team to the Oversight Committee, consolidating and conveying advice from Oversight Committee to the programme team, and supporting the programme team on governance-related questions as they arise.

Declared conflicts of interest: none

Arunabha Ghosh (ordinary member)

Dr Arunabha Ghosh is an internationally recognised public policy expert, author, columnist, and institution builder. He is the founder-CEO of the Council on Energy, Environment and Water, and has led CEEW to the top ranks as one of Asia's leading policy research institutions and among the world's 20 best climate think-tanks. He played a formative role in creating the International Solar Alliance, and was a founding board member of the Clean Energy Access Network. Co-author/editor of four books and with experience in 54 countries, he previously worked at Princeton, Oxford, UNDP (New York), and WTO (Geneva). The Asia Society honoured him with the 2022 Asia Game Changer Award, for his and CEEW's "incredible work, which is making a real difference for India and for the planet".



Arunabha advises governments, industry, civil society, and international organisations around the world. In October 2024, the Government of India appointed him to the Commission for Air Quality Management. He currently co-chairs the World Economic Forum's Global Future Council on the Energy Nexus (and previously co-chaired the GFC on Clean Air). He served on the Government of India's G20 Finance Track Advisory Group and advised the Sherpa Track for India's G20 Presidency in 2022-23. In 2022, the UN Secretary-General appointed him to the High-level Expert Group on the Credibility and Accountability of Net-Zero Announcements by Non-State Actors. In 2020, the Government of India appointed him

Co-Chair of the energy, environment and climate change track for India's Science, Technology and Innovation Policy (STIP2020).

Dr Ghosh has been a member of the UN Committee for Development Policy since 2019 (nominated by the UN Secretary-General; Vice-Chair 2023-25). He co-convened the Our Common Air Commission. He is a member of several international expert advisory groups: Global Commission on the Economics of Water; High-Level Group of Economists, constituted by the French president for the One Planet Lab; and the Senior Consultative Group for the Energy Transition Accelerator.

He writes monthly columns across various platforms. A frequent speaker, he has hosted or featured in several documentaries, and his 2019 TED Talk on air quality (Mission 80-80-80) has crossed 280,000 views. He was a World Economic Forum Young Global Leader. He holds a D.Phil. from Oxford.

Declared conflicts of interest: none

Jack Stilgoe (ordinary member)

Dr Jack Stilgoe is a professor in science and technology studies at University College London, where he researches the governance of emerging technologies. He is part of the UKRI Responsible AI leadership team (www.rai.ac.uk). He worked with EPSRC and ESRC to develop a framework for responsible innovation that is now being used by the Research Councils. Among other publications, he is the author of 'Who's Driving Innovation?' (2020, Palgrave) and 'Experiment Earth: Responsible innovation in geoengineering' (2015, Routledge). He is currently chairing an oversight committee for public dialogue on geoengineering research for the Natural Environment Research Council (NERC). He previously worked in science and technology policy at the Royal Society and the think tank Demos. He is a trustee of the Royal Institution.



Declared conflicts of interest: Jack is an employee of University College London, where one of his colleagues, Cian O'Donovan, is part of The Liminal Space, the consultancy that ARIA has contracted with to support teams funded by the Exploring Climate Cooling programme in developing their public engagement plans. He recused himself from advising ARIA on The Liminal Space's proposal.

Shuchi Talati (ordinary member)

Dr. Shuchi Talati is a climate technology governance expert and founder of The Alliance for Just Deliberation on Solar Geoengineering (DSG). DSG is a nonprofit organisation working towards just and inclusive deliberation about research and potential use of solar geoengineering. She is a contributing author to the American Geophysical Union's Ethical Framework for Climate Intervention Research, Experimentation, and Deployment. Dr. Talati was the co-chair of the Independent Advisory Committee to



oversee SCoPEX, an effort to provide oversight for the proposed solar geoengineering experiment by Harvard University. She most recently served as a Presidential Appointee in the Biden-Harris Administration at the U.S. Department of Energy where she focused on creating just and sustainable frameworks for carbon dioxide removal. Dr. Talati has previously held roles in academia and civil society advising on policy and governance for emerging climate technologies, including as a Visiting Scholar at the Kleinman Center for Energy Policy at the University of Pennsylvania, an AAAS/AIP Congressional Science Fellow in the U.S. Senate and the Fellow on geoengineering research governance and public engagement at the Union of Concerned Scientists. Dr. Talati has a BS in environmental engineering from Northwestern University, an MA in climate and society from Columbia University, and PhD from Carnegie Mellon in engineering and public policy.

Declared conflicts of interest: A member of The Alliance for Just Deliberation on Solar Geoengineering is part of the team for the project entitled "Evidence-based Assessments to

Guide Perceptions, Governance, and Ethical Frameworks for South Asia," providing support on policy analysis, ethical framing and stakeholder engagement. Shuchi Talati was not involved in the review of the project proposal and will not be involved in oversight of this component of the project.

Jan McDonald (ordinary member)

Jan McDonald is Professor of Environmental and Climate Law at the University of Tasmania, Australia. Jan's research explores the legal frameworks required to responsibly govern the research, development and deployment of both solar radiation management and marine carbon dioxide removal technologies. Jan has previously worked for the United Nations Development Program in the Pacific and consulted on a range of projects to local, state and national governments in Australia, Vanuatu and the Solomon Islands. She is a Fellow of the Australian Academy of Law and co-founder of the Australian Forum for Climate Intervention Governance.



Declared conflicts of interest: none

Elena Kavanagh (ordinary member)

Dr Elena Kavanagh is an Indigenous Rights Scholar at University College Cork, Ireland, and a Research Affiliate at the Centre for the Study of Existential Risk (CSER) at the University of



Cambridge. Her broader areas of expertise include international law, Indigenous rights, human rights, and international relations, with a strong emphasis on ethical research approaches with a geographical focus on the Arctic. Elena's current research also engages with emerging global governance challenges. She examines how Indigenous knowledge and rights frameworks can inform debates on climate interventions, artificial intelligence, and the governance of outer space, particularly in relation to Free Prior and Informed Consent (FPIC), ethics, and participatory rights.

Elena completed her PhD in Law at University College Cork, where her doctoral research explored Indigenous language rights in the Arctic. During her academic work, she also engaged in field-informed research and training at the University of Lapland (Finland) and Nord University (Norway), specialising in Arctic governance, Sámi rights, and the operation of international human rights regimes in circumpolar and global contexts.

In addition to her academic work, Elena holds several international leadership roles. She currently sits on the Advisory Board of Directors of the Arctic Youth Network (Canada), serves as Chair of the Humanities and Social Sciences Working Group within the Network for Arctic Researchers in Ireland (NARI), and is the President of APECS–Ireland, where she supports early-career researchers engaging in polar and Indigenous scholarship.

Declared conflicts of interest: Elena sits on the Advisory Board of Directors of the Arctic Youth Network, a coalition-building grantee of the Climate Emergencies Forum (CEF), an initiative led by Renaissance Philanthropy, an ARIA Activation Partner.

Emeritus Members

Nana Klutse

Prof. Nana Ama Browne Klutse is a distinguished Ghanaian known for her expertise in climate modelling, climate change impacts, adaptation, and mitigation strategies, particularly in Africa. She has been involved in various high-profile research projects and has contributed significantly to global climate assessments, including her work with the Intergovernmental Panel on Climate Change (IPCC) as the Vice Chair of the Working Group I. She is a full professor, researcher and the Head of the Department of Physics at the University of Ghana. She focuses on climate variability, climate



change modelling, Solar Radiation Management, and the impacts of climate change on society for her research and often addresses how climate change affects sectors such as agriculture, water resources, and health in Africa. Prof. Klutse has also been an advocate for integrating indigenous knowledge systems with scientific research to develop more comprehensive and context-specific climate adaptation and mitigation strategies. Her work aims to inform policy decisions and promote sustainable development in the face of climate change challenges. She has received various awards and recognitions for her contributions to climate science and her efforts to improve understanding and action on climate change in Africa.

Nana Klutse was an oversight committee member from August 2024 until August 2025

ARIA EACC Oversight Committee - 2025/04/11

Approved 11.06.2025 unanimously

Attendees

Oversight Committee:

Jack Stilgoe, Jessica Seddon (Secretary), Piers Forster (Chair), Shuchi Talati

Regrets: Arunabha Ghosh, Nana Klutse

ARIA Programme Team

Mark Symes, George Horner (first 45 minutes)

[OC Note to Programme Team](#)

Summary of Decisions/Action Items

1. Jessica handed off to Piers to chair the Committee. She will continue as Secretary and liaison between the programme team and the Committee.
2. Minutes from the January 2025 meeting and decisions by email were not circulated. Will be circulated for approval in the week of April 14.
3. The announcement of teams that will receive awards under the “Exploring Active Climate Cooling” opportunity space will be in the week of May 1.
 - a. Oversight committee recommendations for ARIA
 - i. Model transparency: provide information on project-level budgets, describe the composition of the teams beyond leads - e.g the partners, whether they are academic, private, non-profit.
 - ii. Contextualize spending relative to broader climate, environment, science expenditures. Highlight the value of the observations for general understanding of the climate.
 - iii. Recognize that project Novel Materials for SAI will attract attention, even if no substances are released - prepare to contextualize.
 - iv. More generally: recognize that the internal categories (experiment vs observation) may not resonate externally - “outdoor” might be the key consideration.
 - v. Consider very proactive communication: a newsletter, blog, running set of updates about the projects in addition to reporting on milestones

- b. The Oversight Committee will provide a public comment as part of the announcement.
4. No objections to the updated statement of principles (below).
 - a. Proposed addition to point on “communicate proactively”: include “levels and sources of funding”
 - b. Additional advice for ARIA as it engages with other funders: make sure to call for transparency on the funding of projects - by a funder that adopts the principles, by the project on all of its sources of funding.
- **Deliver Valuable & Transformational Knowledge.** We aim to select and design for research that will address the most pressing critical scientific questions surrounding approaches for actively cooling the climate.
 - **Minimise Risk.** All experiments should be designed to reduce direct risk as far as possible.
 - **Engage With, and Respect Key Communities**
 - **Communicate Proactively and be Transparent, Open, and Honest** at both the programme and project level, including around levels and sources of funding, intentions, how the research is conducted, outputs, and impacts.
 - **Be Cognisant of the Broader Implications of Research & Integrate Systems Thinking** into research on approaches for actively cooling the climate.
 - **Learn, Adapt and be Responsive.** Success will require a willingness to adapt to lessons learned during the programme and to changing circumstances.
5. Oversight Committee finalized the outline for the paper on IP, with a focus on IP around SRM only since this is a particularly thorny area for balancing different goals of intellectual property.
6. Oversight Committee added some suggestions for the OC membership and agreed to
 - a. Prioritize additions with expertise in Australia and Arctic settings
 - b. Have Piers and Jessica do initial outreach to these members by OC, followed by a recommendation to the OC on additions.
 - c. Program team to meet potential members as needed to familiarize with the program.
 - d. OC to recommend additional members to ARIA CEO to invite.
7. Miscellaneous: OC requested clarity on the creator meeting in end June - what is it, when, where?

Minutes

1. Jessica described roles of Chair and Secretary.

- Chair: finalize the agenda, chair meetings.
- Secretary: propose meeting agendas; liaise with programme team for materials, inputs; prepare and circulate minutes; follow up on action items and any coordination needed with ARIA team; support chair as needed.
- Secretary considered a full voting member of the Committee for now; potential to revisit over time.

2. Programme team provided an overview of the teams likely to receive awards.

- Announcement: ~May 1, 2025
- Due diligence will be done on all creators before the announcement, but some contracts may not yet be signed so milestones, workplans may change.
- The majority of the program budget is being awarded at this point. About 10-15% has been reserved for contingencies. It is also expected that there will be a seeds call in the broader opportunity space in the coming months (up to £5m for grants of up to £500k each).
- The group discussed the alternatives to the categorization of small-scale experiments, passive monitoring, and other, noting: it's not clear what the public will care about: outdoor, perturbative, history of the researchers, something else? The programme team noted that these categories were used more for internal than communications purposes.
- The group discussed some transparency points: the project-level budgets, disclosure on the full teams (20 countries participating vs 12 countries with lead partners), including any private organizations.
- The group discussed how to address differences in local organizations/institutions for review of the projects - e.g. that the Great Barrier Reef Authority required more engagement than the local council in Canada. Reiterated the need to be proactive in creating high standards for local engagement.
- Comments on specific projects:
 - MCB (Australia + UK): Discussed importance of and prospects for future funding by Australian government, partners; optics of UK government funding work in Australia and potentially additional outdoor experiment there (Coe project partnership). Also, the importance of acknowledging prior efforts to engage without claiming that these amount to "informed

public consent” - there are always questions about who was asked, what information was provided, etc.

- Thickening Sea Ice: confirming that all sites outside of the UK will go through local ethics, permitting, legal review to the extent that it exists.
- BrightSpark: small experiment, but also limited experience with engagement.
- Novel Materials: recognize that this is not releasing anything, but will attract attention.
- Cirrus clouds (2): note that experiments with aircraft are later in the cycle; that the monitoring one may have a dependency on NOAA/exposure to political risk of working with the US government.
- Drones (Voloitude, MACE): emphasize the value of learning too.

Program Team left

3. Discuss key points for the OC note.

- a. What is the committee, from the perspective of the committee
 - i. Not here to legitimize ARIA's choices
 - ii. Advisory role with a public voice - and appreciation for the constructive relationship thus far
 - iii. Who we are- and that the group will grow.
- b. Reflections on the projects
- c. Looking ahead - what to expect and OC role. Potential commitments by the OC to use its public voice?

4. Discuss updates to principles based on conversations with other funders and potential adopters.

- a. Group discussed the benefits of replacing “local” with “key” to cover relevant non-geographic communities; also of them being shorter.
- b. Addition on transparency: insert clause about the importance of transparency about funding and all sources; convey to ARIA that this is an important principle for funders to adopt and encourage for those that they fund - and for their own funding choices.

5. Discuss IP paper outline including programme team requests.

- a. Agreed to focus on SRM only given unique issues around these ideas and research

- b. Added consideration of how IP shapes different uses of the technology - e.g. by military, private, other users
- c. Next steps:
 - i. Outline to be made into an RFP by ARIA procurement
 - ii. OC chair to sign off on RFP.
 - iii. Mark to issue RFP or provide written explanation to OC on why not.
 - iv. RFP to go out, OC to help promote.
 - v. OC to review and suggest a selection to the programme team.
 - vi. Programme team to implement OC suggestion or provide written explanation on why not
 - vii. Consultant to write.

6. OC additional members

- Jessica to check in with Nana to confirm continued ability to participate in the committee.
- Discussed a number of names in the additions document. Decided to:
- Grow organically - a few at a time.
- Prioritize additional geographic context around outdoor experiments: Arctic, Australia
- Consider replacements for Nana's geographic expertise as needed after speaking with her on availability - recognizing that some of the list have additional expertise and perspectives (around technology policy, youth)
- Next steps:
 - Jessica and Piers to reach out and interview (April)
 - Program team to meet as needed to familiarize with the program
 - P&J recommendations to OC (early May)
 - OC to recommend to ARIA CEO (early May)
 - ARIA CEO to invite (mid May)

7. Request to the programme team to finalize the dates of the creator meeting as soon as possible.

8. Agree: standing meeting every 2 months

Jessica to schedule

ARIA EACC Oversight Committee - 11.06.2025

Final - Approved 06 August 2025

Attendees

Oversight Committee:

Jack Stilgoe, Jessica Seddon (Secretary), Piers Forster (Chair), Shuchi Talati

Regrets: Arunabha Ghosh, Nana Klutse

ARIA Programme Team

Mark Symes, George Horner (first 45 minutes)

Guest

Jan McDonald (Prospective Oversight Committee Member)

Summary of Decisions/Action Items

1. Minutes from 11 April 2025 approved unanimously.
2. Programme team to facilitate breakfast meeting between OC and Liminal Space at the creator meeting in June.
3. All OC members to review the ARIA Conflict of Interest policy and send any changes to Mike Farrar. Jessica to check with ARIA about maintaining a register.
4. Programme team to develop and share a proposed workflow for programme team and OC review and feedback on outdoor experiments and other sensitive projects.
5. OC agreed to update policy to publish approved minutes online (with redactions as needed for privacy/confidentiality).
6. OC confirmed that transparency should be the next white paper topic.
7. OC recommends inviting Jan McDonald to join the Committee.
8. OC agreed that existing members should be required to participate in at least 4 (of 6) meetings in a year and fulfill their role of advising the programme team on the funded projects.

Minutes

1. Updates from the Programme team

- Liminal Space has been selected as the engagement partner. OC members were interested in meeting Liminal space. One question that arose: what would the workflow between OC and Liminal Space and funded teams be?
 - Programme team noted that Liminal Space role would be to work with the Creators to help them prepare engagement plans that would then be reviewed by the programme team and the OC as part of the adaptive management.
- The timeline for outdoor experiments was reviewed. Some observations from the OC:
 - Workflow and roles for Liminal Space, programme team, and OC need to be clarified and operationalized.
 - Will need to have a working document with up to date timelines in order to manage reviews and feedback.
 - Ideally the OC review of projects will include time for a conversation with the programme team and interaction after the review.
- Programme team reported back on conversations with Arctic researcher [REDACTED] and Inuit Circumpolar Council Climate Lead [REDACTED]. These were not formal engagements. Feedback was incorporated into updates to the governance overview.

Program Team left

2. Discussion on OC transparency.
 - Secretary reminded OC members to keep their statements on any conflict of interest up to date on the website.
 - Jan suggested that OC consider a conflict of interest register for internal use to ensure full transparency about relationships that may be considered a conflict of interest. OC agreed.
 - Minutes to be posted online (with redactions as needed for confidentiality and privacy).
3. Discussion on OC Outreach
 - *Contributions through ARIA Channels.* ARIA will be creating a quarterly newsletter on projects starting later in 2025. OC agreed to contribute to these. Programme team to provide the timelines and Secretary to organize OC contributions.
 - *White Paper:*

- Secretary updated the OC on current thinking about the process for commissioning the white paper on IP. Finding the balance between ease of procurement, compliance with procurement rules, and OC editorial independence is still a work in progress. OC members were asked to suggest authors who might be interested in applying to write the paper.
- The value of a paper on transparency was confirmed. No additional topics were added to the queue.

4. Discussion on additional OC members

- OC decided to recommend to programme team that Jan McDonald be invited to join the OC. (unanimous).
- OC confirmed that priorities were to have a member with Arctic expertise.
- The possibility of recruiting an OC member with expertise in European policy developments was discussed. OC did not see the need for this expertise at this point given the range of funded projects.
- OC agreed that sitting members should be asked for a commitment of at least 4 meetings a year and participation in project reviews.

ARIA EACC Oversight Committee - 06.08.2025

Draft for review/confirmation 08.10.2025

Attendees

Oversight Committee:

Piers Forster (Chair), Jessica Seddon (Secretary), Arunabha Ghosh, Jan McDonald, Shuchi Talati

Regrets: Nana Klutse

ARIA Programme Team

Mark Symes, George Horner, Mike Farrar (first 45 minutes)

Guest

██████████ (Prospective Oversight Committee Member)

Summary of Decisions/Action Items

1. Minutes from 11 June 2025 approved unanimously.
2. No conflicts of interest other than those currently disclosed in the governance overview were declared.
3. OC supports the addition of staff focused on communications to the programme team. It recommends considering adding a person who can serve as a knowledge broker in addition to scientific communication.
 - a. **Action:** ECC Programme team will develop a job description for the additional staff member and share it with the OC for any comments.
4. OC supports the addition of secretarial support to the OC, to be selected by the OC and paid by ARIA.
 - a. **Action:** The OC Chair and Secretary will draw up a job description and recommendations for recruitment.
5. OC supports the use of the Governance and Responsible Innovation budget for the Capetown Engagement Initiative as a pilot for broader engagement of communities early in the research process.
6. **Action:** The programme team will alert the OC and provide them with overview and procurement documents if and when a call for Opportunity Seeds in the Future Proofing Climate & Weather opportunity space is scheduled.

7. OC noted the ongoing NERC dialogue on SRM and was supportive of ARIA and OC members contributing to it.
8. OC to consider commenting on the Royal Society report when it is published.
9. OC confirmed that its role is to provide advice on governance; verifying project legal compliance with applicable rules and regulations is the responsibility of ARIA's lawyers or their designated experts.
10. OC notes the project milestone and timelines gantt chart shared by the programme team as the comprehensive "single source of truth" on review and milestones.
 - a. **Action:** Programme team and Secretary to work together to ensure that key items are brought before the OC with sufficient warning.
11. The OC had a number of suggestions for the programme team if the team decided to create or support an entity designed to support responsible research on SRM, including:
 - a. The "who" of the entity matters for credibility, legitimacy, and effectiveness.
 - b. The entity should consider support services for stakeholders beyond researchers, with particular emphasis on enabling a level playing field between researchers and other stakeholders.
 - c. Supporting engagement and learning across projects on practical implications of general principles of engagement is important.
12. The OC would like to continue to commission the white paper on IP, recognizing its value for the broader community and potential to inform future refinement of the programme approach to IP.
 - a. **Action:** Programme team to consider procuring the IP white paper based on the scope provided by the OC and with the input of the OC as reviewers.
13. The OC would like to commission a white paper on implementation of transparency.
 - a. **Action:** OC to develop a scope and share that with the programme team for comments. Scope will be finalized in the 1.10.2025 meeting and shared with a programme team to procure.
14. The OC requests the programme team to share written updates in advance of the meeting rather than an outline with verbal update.
 - a. **Action:** Programme team to consider this approach for the October 1, 2025 meeting.
15. Shuchi Talati has agreed to be the liaison from the OC to Liminal Space. Liminal Space to be invited to the next OC meeting.
16. OC recommends that ARIA formally invite [REDACTED] to join the OC, pending confirmation of no conflict of interest.

- a. **Action:** ARIA to consider inviting [REDACTED]; new members (including Jan) to be announced as soon as [REDACTED] replies.
 - b. **Revision (September 17):** After review of potential conflicts of interest with the [REDACTED], it was decided that [REDACTED] would not be able to serve on the OC. The OC and programme team deeply appreciate [REDACTED]'s expertise.
17. OC recommended that Nana Klutse be removed from the Oversight Committee. Her expertise and perspective is highly valued but due to lack of time she has not been able to participate fully.
- a. **Action:** OC Chair and Secretary to ask Nana for recommendations on a replacement member. ARIA to revise Nana's status to former member of the Oversight Committee, with term August 2024 - August 2025.

Minutes

1. Introductions

- [REDACTED] introduced herself as a PhD student [REDACTED]
[REDACTED]
[REDACTED]
[REDACTED].

2. Review of Minutes and Conflicts of Interest

- Piers Forster asked for approval of the previous meeting's minutes and inquired about any conflicts of interest. The minutes were approved, and no conflicts of interest were declared.

3. Updates from the Programme team

- **Program Team Resource Allocation**
 - Mark Symes proposed adding resources to the program team, specifically a role for program-related communications and engagement, to alleviate the disproportionate workload on the existing comms team.
 - PF, JS, and ST strongly supported the communications resource, with ST citing past failures in communication from advisory committees on governance work.

- JM suggested a "knowledge broker" function to act as an intermediary with policymakers or other end-users, beyond just communicating science outputs.
- PF asked if the communications person would directly interact with program teams to support their communications and also handle governance-related communications. Mark Symes confirmed that the comms hire would be part of the program teams, liaising directly with funded projects to help them manage their communication strategies, particularly around engagement.
- **Secretarial Support for Oversight Committee**
 - Mark Symes also floated the idea of obtaining secretarial support for the Oversight Committee (OC). The OC supported the idea.
- **Governance and Responsible Innovation Budget (GRIB)**
 - Mark Symes described a new initiative under the GRIB: the Cape Town Engagement Initiative, a pilot for a broader approach to engaging new groups early in the research process.
 - This initiative is co-developed with The Alliance for Just Deliberation on Solar Geoengineering and the University of Capetown. DSG will run a workshop where delegates, including scientists, the public, and other interested parties, would identify research questions. It will cover its own costs. ARIA would fund collaborative projects between South African and UK researchers to answer these questions.
 - ST noted that this model aims to create a research ecosystem responsive to people's needs and shape questions into researchable ones, facilitating collaboration between social scientists, physical scientists, and civil society.
 - MT noted that the team is interested in whether this model, potentially with other partners, could be relevant for other regions where ARIA has work.
 - Liminal Space Workshop Mark Symes announced that the Liminal Space workshop will take place from September 29-30 in London, inviting all Oversight Committee members to attend. This workshop will provide

initial training to creators on engagement approaches, with most attendees being creators from ARIA programs and other initiatives.

- Mark Symes noted that the Oversight Committee can request specific spending from this £5 million budget. The requests should be made through meeting minutes. ARIA will then process these requests through normal procurement processes, with the OC having a chance to comment on the tenders or hires.

- **Seeds Program Update**

- Mark Symes provided an update on "Seeds," which are small, speculative projects of no more than £500,000, that explore broader opportunity spaces not funded by the main program, ranging from weather to off-earth terraforming. He indicated that the timing for when the Seeds call will open is still unknown, but the Oversight Committee will be informed and given the solicitation documents for comment once a date is set.

- **Renaissance Philanthropy Activation Partnership**

- Mark Symes updated the committee on discussions with Renaissance Philanthropy, one of the ARIA Activation Partners. Renaissance has a separate program, ARC, that funds research and partnerships to predict, prevent, and prepare for catastrophic climate risks. ARIA does not fund this program.
- ARC has adopted ARIA's high-level governance principles. ARIA has requested more frequent meetings and better information sharing with Renaissance Philanthropy, to consider how to implement the high-level principles for their program in practice and align with ARIA's values of transparency, active communication, and value for knowledge.

- **Engagement with other UK Programs**

- Mark Symes informed the committee about NERC, a separate UK funder, running a public dialogue on SRM modeling, which involves engaging 56 individuals in regional workshops across the UK to gather their ideas on SRM research. Mark Symes mentioned that ARIA could potentially provide materials for this dialogue and noted that Jack Stilgoe, a member of this committee, chairs the NERC committee.
- JS, ST, and PF inquired about the release date and public comment period for the Royal Society report on SRM.

- PF suggested that the Oversight Committee could comment on the report as a collective.
- AG noted the potential for conflicting reports and processes from different UK based publicly funded institutions to contribute to a sense of powerlessness, lack of control, and accountability among those without a say in these processes, despite the institutions being separate. JS agreed and noted that OC should consider this in public outreach.

- **Project Compliance and Oversight**

- OC confirmed that its role is to provide advice on governance; verifying project legal compliance with applicable rules and regulations is the responsibility of ARIA's lawyers or their designated experts.
- Mark Symes and Mike Farrar presented a project timeline document to the Oversight Committee, which details contractual milestones for each project, including "go no-go" milestones and public engagement milestones related to outdoor experiments or activities.
- JS noted that this document can be a single source of truth for the Secretary to use to highlight areas for OC consideration and provide forewarning for review needs. PF agreed that this would be necessary to focus the OC attention.

- **Enabling Responsible Outdoor Experiments**

- Mark Symes presented a suggestion from Renaissance Philanthropy to establish an ARIA-supported entity that would create space for responsible outdoor experiments, potentially offering support services for engagement, regulatory compliance, setting experiment boundaries, or other activities.
- JS emphasized the importance of "who" this entity would be, stressing that it needs to be seen as a credible and legitimate "honest broker" to successfully create space for responsible outdoor experiments.
- OC members ST expressed concern about framing such an entity as providing "support services" to researchers, arguing that this framing is problematic in the context of governance, especially given existing public skepticism around SRM. AG highlighted the need for support services for the communities around and affected by research to balance the support for researchers - suggesting the creation of an equally positioned space

for communities to carry on dialogue with researchers when they might lack resources. He noted the relevance of entities such as the Advisory Ctr for WTO Law, to support lower-resourced countries to participate in WTO negotiations as well as similar efforts in climate negotiations.

- All noted the value of support services on engagement, particularly for involving relevant communities in defining research questions. This is particularly the case when high-level guidelines are being translated in a variety of specific forms of implementation. Learning across and from this variety could be an important part of the role of such an enabling entity.

Program Team left

4. OC Outreach

- **White Paper on Intellectual Property (IP)** The committee agreed that the IP paper is still very relevant and important, as IP issues have historically caused project cancellations and affect how communities benefit from research. The committee decided to proceed with commissioning the IP white paper.
- **White Paper on Transparency** The committee decided to proceed with scoping a white paper on transparency to be recommended for procurement by ARIA.

5. Oversight Committee Operational Aspects

- **Improving Information Flow and Secretariat Support:**
 - OC strongly reiterated the need for secretariat support to summarize information, highlight controversial aspects, and ensure a sustainable operational rhythm.
 - OC requested that programme team provide written updates in advance of the meeting rather than an outline with verbal updates. This will save time in the meetings, enable more discussion, and also ensure a record.
 - JM requested a briefing from the programme team and access to more complete descriptions of projects.

- **Liaison with Liminal Space**

- JS presented a suggestion from Liminal Space for a designated oversight committee member to maintain regular contact regarding engagement sufficiency and emerging issues. ST expressed interest in being the liaison, noting that it aligns with their other work, and suggested the secretariat could assist in communicating information back to the broader committee to manage the liaison's workload. OC agreed it was a worthwhile idea to enhance engagement and understanding.
- OC agreed to invite Liminal Space to the October 1 meeting to discuss their approach and reflections on the projects and portfolio.

6. Discussion on additional OC members

- OC decided to recommend to programme team that [REDACTED] be invited to join the OC. (unanimous).
- OC agreed that NK should be asked to step down if she cannot commit to joining at least 4 meetings in a year and contributing advice to the programme team.
- OC agreed that if NK steps down she should be asked to suggest suitable replacements with similar regional, policy, and science insights.
- OC agreed that new members should be announced as soon as [REDACTED] responds to the invitation.

ARIA EACC Oversight Committee - 08.10.2025

Attendees

Oversight Committee:

Piers Forster (Chair), Jessica Seddon (Secretary), Arunabha Ghosh, Jan McDonald, Shuchi Talati, Jack Stilgoe

ARIA Programme Team

Mark Symes, George Horner, Mike Farrar (first 70 minutes)

Guests:

[REDACTED], [REDACTED] (Liminal Space) (first 24 minutes)

Summary of Decisions/Action Items

1. Minutes from 06 August 2025 approved unanimously.
2. No conflicts of interest other than those currently disclosed in the governance overview were declared.
3. Engagement workshop was discussed, considered overall successful in building creator interest and capacity to engage with relevant communities in diverse and meaningful ways around their research.
 - a. **Action:** Liminal Space to document workshop and recommendations for next steps.
 - b. **Action:** Liminal Space and Programme team to consider ways of sharing training materials with a wider group of researchers/funders.
 - c. **Action:** Programme team and OC to consider how best to respond to general creator demand for support in designing and implementing engagement - beyond the original focus on 7 projects.
4. Programme team reviewed timeline and process for OC input on draft engagement plans and review of funding milestone for the RASI project review in November.
 - a. **Action:** Programme team to develop graphic of process.
 - b. **Action:** Programme team to include a requirement for creator teams to self-certify full disclosure in its request for funding approval.
 - c. **Action:** Programme team to consider ways to build in ongoing review/adjustment of approach to experiments after funding milestones.

- d. Action:** OC to include an explicit discussion of what the OC review is based on and what its limitations are in its statement.
5. Programme team discussed planned and potential investments in communications about the research.
 - a. The OC appreciated the intention to hire additional communications personnel
 - b. The OC recommended not pursuing a partnership with SRM360 on science communications around tipping points and climate cooling.
 - c. OC noted the importance of clear communication about ARIA programmes and their rationale but questioned additional investments in knowledge brokering.
6. Oversight Committee approved job description for the Secretary
 - a. Action:** Programme team to work with ARIA procurement to prepare the job description
 - b. Action:** OC members to circulate, Chair and Secretary to review applicants and select a shortlist, OC members to interview and recommend selection to the Chair. Chair chooses Secretary.

Minutes

1. Debrief with Liminal Space & Programme team
 - 83 attendees for the engagement workshop
 - Overall positive feedback from the creator teams, including from some teams who had been skeptical about the need for building engagement capacity.
 - End result: creator teams showing more visible commitment to engagement with relevant communities, interest in learning about different ways to build conversations.
 - ST, JSt were present, both confirmed level of enthusiasm and interest.
 - OC recommended continued emphasis on skills, approaches, practical guidance that teams could use, including on misinformation/disinformation.
 - OC recommended extensive documentation and potentially sharing of the documentation currently being shared with creator teams with other funders and researchers who might benefit.
 - Program team confirmed that ARIA has the flexibility to financially support and/or update contract timelines to allow teams to increase engagement, change their projects in response to feedback, or otherwise deepen interaction around their work.
 - Liminal Space noted mismatch between level of wider interest in support on engagement training and advice and current terms of reference that emphasize support to 7 teams in particular.

Liminal Space team left.

2. Discussion with Programme Team on upcoming Rethickening Arctic Sea Ice (RASI) review.

- Programme team reviewed the history of the project and outline process and timeline for OC advice.
- Noted that draft engagement plans would be shared with the OC for feedback to the programme team before the formal review around the funding milestone.
- Secretary and Chair reviewed OC's formal role in review for funding milestone.
 - OC can unilaterally reject engagement plan and return it to the Creator with directions on what needs to be revised.
 - Creator then has to resubmit to Programme Team for a second review before returning it to the OC.
 - If not rejected: OC writes an advisory letter to the ARIA CEO.
 - ARIA CEO considers the OC letter, any inputs from the Programme Team, any other information and makes a decision. The CEO is the decisionmaker.
 - OC can comment publicly on the CEO decision, including sharing its recommendations.
- OC discussed other additional aspects of review.
 - Independent review of legal compliance, including with applicable indigenous rules, is the responsibility of ARIA and/or a contractor chosen by ARIA
 - Noted that the information that the OC receives is self-reported by the team. The team should include a certification that they are not withholding information as well as provide sufficient detail on consultations to enable an independent review of the stated engagement in the future.
 - Noted that an OC recommendation to approve funding is a statement that the work thus far has been acceptable and that the plans are comprehensive. It is not a guarantee that the project will not have to be reviewed or stopped later based on future events.

3. Discussion with Programme Team on research communications

- Programme team discussed intention to hire additional coms and engagement support. The OC appreciated the need for doing so.
- Programme team shared a proposal from SRM360 to develop an explainer around tipping points and climate intervention.
 - OC recommended that ARIA not accept the proposal.
- OC members questioned whether ARIA should extend beyond communication and explanations of its work and the reasons for the programmes into more general knowledge brokering. OC noted that explanations are not neutral.
- Programme team described upcoming workshop on tipping points and climate interventions. OC noted that this should focus on developing the ARIA programme theses, focus areas, and priorities for collaboration across programmes rather than the broader ongoing, wider discussions on the implications of tipping points.

Programme Team left

4. OC structure

OC discussed secretary role and finalized job description.

OC discussed need to identify additional members with Arctic expertise in particular.

5. OC agreed to review white paper scopes via email.

ARIA EACC Oversight Committee - 03.12.2025

Attendees

Oversight Committee:

Piers Forster (Chair), Jessica Seddon (Secretary), Arunabha Ghosh, Jan McDonald, Shuchi Talati, Jack Stilgoe, Elena Kavanagh

ARIA Programme Team

Mark Symes, George Horner, Mike Farrar (0:50-0:90)

Guests:

[REDACTED] (Author, IP White Paper) (0:15 - 0:30)

Summary of Decisions/Action Items

1. The OC welcomed new member Elena Kavanagh
2. Minutes from 08 October 2025 approved unanimously.
3. Piers Forster declared a new conflict of interest regarding research in his lab at Leeds funded by Stardust and committed to transparency about the research and all findings.
 - a. **Action:** Piers to provide an updated Col statement for the ARIA website.
4. OC members met [REDACTED] and discussed approach to IP white paper.
 - a. **Action:** [REDACTED] to provide an outline and a proposed schedule for drafts/OC inputs before the January meeting.
5. OC members discussed and agreed on recommendations for the ARIA CEO regarding funding for outdoor experiments in the Rethickening Arctic Sea Ice (RASI) project.
 - a. **Decision:** OC recommended that ARIA approve the funding for the experiment, subject to independent confirmation of legal compliance and other conditions. OC also provided recommendations to the program team on ARIA engagement with Inuit leadership.
 - b. **Action:** Secretary to draft and OC members to finalize and approve joint OC note to ARIA CEO based on the comments and discussion.
6. Program Team provided updates on their engagement with key public sector stakeholders and on the schedule for creator engagement plans and funding milestones where an OC recommendation would be sought.

- a. **Action:** OC requested program team to provide documentation on funding milestones further in advance of the CEO decision in order to enable more ability to ask questions and receive answers.
 - b. **Action:** OC invited new ARIA CEO to join a future meeting (January 28 or March 25, 2026).
7. OC and Program Team discussed Liminal Space Engagement Workshop Feedback
 - a. **Action:** Program team to consider expanding Liminal Space' scope of work to include creating guidance for creators, program team, and ARIA to engage with the larger geopolitical and technological development contexts around climate cooling.

Minutes

1. OC welcomed Elena Kavanagh
 - Notes on Elena's selection are available as "Interim Report Jan 2026: OC Member Addition"
2. Minutes from 8 October approved unanimously.
3. Discussion on Conflict of Interest
 - Piers Forster disclosed that his research group at Leeds received £600,000 from Stardust to conduct studies of aerosol circulation in the stratosphere, leveraging their expertise in stratospheric circulation and chemistry. He committed to keep all results in the public domain and confirmed that he had not signed an NDA with Stardust, ensuring the lab could publish all results regardless of outcome.
 - OC members asked for a received confirmation that negative results and non-results could and would be published.
 - OC members noted that Stardust's general website and communication was not transparent.

██████████ *joined the call.*

4. Discussion on IP White Paper
 - OC and ██████████ discussed the context for the paper as part of fulfilling roles 2 and 3 as outlined in the governance document by providing practical, actionable menus of options for research funders and researchers to implement responsible government.

- Group discussed some of the ways in which IP rules do and could shape SRM research and future evolution, noting that new forms of IP law and policy may need to be developed.
- Group discussed modes of working to allow the OC to provide substantive and editorial guidance without slowing down the production of the paper.

5. Decision on Recommendation to ARIA CEO regarding RASI funding.

- OC shared comments and reflections on the materials provided by the Creator teams for review as well as the question and answer session between the OC, Creators, and Programme team.
- Piers Forster and Jessica Seddon reviewed the timeline for an OC decision as well as the context for OC review within ARIA's research governance.
- Jessica reminded the OC of the protocol agreed to earlier: OC writes a unified statement, with notes of dissent if needed. She also clarified that the committee's role is to certify consistency with ARIA principles (transparency, respect, engagement, context cognizance), not legal compliance since ARIA contracts with a local law firm for permitting review and legal compliance.
- OC members discussed various aspects of the experiments as it had been presented in the documents as well as in the OC interaction with the Creator teams.
- The key points from this discussion are recorded in the OC Note to ARIA CEO.

6. Updates from the Program Team

- Program team shared information on ongoing engagement with key public sector stakeholders.
- Program team shared updates on ARIA staff, including the selection and future appointment of a new CEO
- OC requested new CEO to join an OC meeting when she joins.
- Program team provided a schedule of upcoming engagement plans and outdoor experiment funding approval, noting that advice on engagement plans was optional but welcome, while recommendations to ARIA CEO on funding milestones for outdoor experiments was the core OC duty.
- OC requested program team to provide as much advance notice as possible for documents related to engagement plans and especially outdoor experiment funding approvals. For recommendations on funding for outdoor experiments, OC requested that the process allow more time to ask and receive answers to questions on the documents that creators provide.

7. Discussion Liminal Space Engagement Workshop Feedback

- OC affirmed value of the work that Liminal Space was doing with creators.
- OC encouraged program team to expand Liminal Space's scope of work to include guidance for creators, program team, and ARIA to engage with the larger geopolitical and technological development context around climate cooling, including training on how to both communicate specific current work and acknowledge potential future implications.
- OC and program team agreed that it would be beneficial for the new communications hire that the program team is planning to work closely with Liminal space.

Exploring Climate Cooling

Oversight committee meeting pre-read

Updated October 2025

Contents

1. Rethickening Arctic Sea Ice (RASI) project outdoor experiment approval timelines and template documents
2. Notable updates on other projects
3. Liminal Space engagement workshop (29th and 30th September 2025)
4. Update on dedicated comms lead and other comms support
5. Other matters
 - a. Seeds
 - b. Tipping points workshop
 - c. Proposal for explainers on tipping points and climate cooling

1. RASI project

The RASI team has a stagegate around producing a draft engagement plan for review by the programme team and oversight committee due by 12th October. When the engagement plan is received, the programme team and Liminal Space will conduct a preliminary review, and we will refer this on to the oversight committee for comments.

The RASI team plans to conduct two outdoor experimental campaigns in Northern Canada this winter under permits from the Nunavut Impact Review Board (each one performed by one of two sub-teams, see below). Both sub-teams plan to start experimental work in late January or February, pending receiving their permits and approval of their plans by ARIA. **There is a separate [outdoor experiment approval form](#)** that we will use to capture information on experiment details, engagement, etc, specific to the experimental campaign

in question. We welcome comments on this draft. RASI will be the first team to use this template.

The RASI team's two sub-teams are:

1. **Real Ice.** The Real Ice sub-team plans to operate in Cambridge Bay, Nunavut. They have worked in this location in previous years and they intend to leverage existing networks and to build on previous engagement activities. Local stakeholders apparently view the fact that Real Ice has secured multi-year funding positively (as this implies some longer-term commitment to the community than is usual for research activities in the area). Real Ice have applied for a two-year permit for ice thickening activity from the Nunavut Impact Review Board and they are cautiously optimistic that this will be granted in December/January. This would then allow thickening to start (pending ARIA approval) in late January or February.
2. **Arctic Reflections.** [REDACTED] ([REDACTED]) recently returned from a visit to a number of potential host communities in Nunavut (elsewhere to Cambridge Bay). He was apparently well-received everywhere, with one community expressing a wish to host a campaign this winter. He is now exploring options for permitting with this community.

Given the expected experiment start dates, we will ask RASI to submit their completed outdoor experiment approval form by **14th November**, to allow a decision by 12th December 2025. In the event that alterations are required, this will then give at least a month before the window in which the teams would prefer to start work opens.

The suggested timeline for this outdoor experiment review is provided below for feedback. Activities involving the OC are highlighted in yellow. The "proceed track" assumes that the plan is acceptable and the team is on track to proceed to an outdoor experiment starting in January 2026. The "reconsider track" gives an indication of what a "reject" signal means at each stage of the process.

Date	Action	Proceed track	Reconsider track
14th November	Submission of outdoor experiment approval form	-	-

14th - 18th November	Programme team internal review	Review passed; documents passed to oversight committee	Documents returned to creators. A new timeline for review is issued to all parties
19th November	Oversight Committee receive outdoor experiment approval form	-	-
19th November - 3rd December	Oversight committee review period	-	-
3rd December	Recommendation produced (can be approved / should not be approved)	Oversight committee escalates approval documents with comments to CEO in a letter (copy to programme team)	Oversight committee requests that the programme team returns the documents to creators with OC comments. Programme team informs the CEO of the OC's recommendation. A new timeline for review is issued to all parties
3rd - 10th December	CEO deliberation	CEO approves experiment	CEO rejects experiment
11th - 12th December	Programme team collate feedback (from OC, CEO and their own), highlighting changes required to experimental plan	[Assumption here is that the CEO and OC's requested amendments are sufficiently minor that they are content for the programme team to judge whether or not the resulting changes are sufficient]	-
12th December	RASI team informed of approval process outcome	Team have until 9th January to make any required amendments and supply suitable evidence and/or updated plans to programme team	ARIA will only consider a substantially revised experimental plan that fully addresses the concerns raised.
Jan 9th - Jan 16th	Programme team consider revised experimental plan	Creator team is informed that their minor amendments are satisfactory, and the outdoor	Creator team is informed that their minor amendments are not satisfactory, and plans are

		experiment can begin (pending permits, etc). OC and CEO are informed.	returned to creators for amendment. This cycle continues until the programme team are satisfied

2. Notable updates on other projects

Other than RASI (see above), the following projects have milestones to submit outline engagement plans and other key documents for review by the programme team and oversight committee within the next year:

Team	Document type	Expected submission date
Natural Materials for Stratospheric Aerosol Injection	Draft communication and engagement plan agreed with ARIA and oversight committee	Early Jan 2026 (this was originally scheduled for October 2025, but balloon launches are now delayed until Spring 2026 at the earliest)
Brightspark	Draft engagement plan	Early Jan 2026
Brightspark	Initial technical feasibility study and possible site identification	Early Jan 2026
MACE	Draft engagement plan	Early Jan 2026
De-risking cirrus modification	Draft engagement plan	Early Jan 2026
Natural Materials for Stratospheric Aerosol	Updated communication and engagement plan	Early Jan 2026

Injection	agreed with ARIA and oversight committee	
REFLECT	Draft engagement plan	Early March 2026
REFLECT	Suitable field sites identified and initial technical feasibility study	Early March 2026
Natural Materials for Stratospheric Aerosol Injection	Summary of comms and engagement undertaken to date supplied to ARIA and oversight committee	July 2026
Marine Cloud Brightening in a Complex World	Update on ongoing community engagement and future plans	July 2026

3. Liminal Space workshop

The Liminal Space and UCL hosted a two day workshop (29th and 30th September) in London for the creator teams on the programme to discuss the importance of engagement, to get teams thinking about which types of engagement activities might be useful for their projects and to encourage the creators to support each other with engagement. This was especially useful for the teams who plan to conduct outdoor experiments but it was pleasing also to see how teams whose projects are based around monitoring, modelling and governance were also inspired regarding engagement that they could do. The team from Liminal did a fantastic job with the various activities and some teams came a very long way in their attitudes to engagement and their willingness to take this aspect of their projects seriously. Some of the Liminal team will join the committee meeting on 8th October.

4. Update on dedicated comms lead and other comms support

Comms lead: The job advert for the permanent Future Proofing our Climate and Weather comms lead closed on 30th September with 127 applications. We are currently screening

these. There are some very promising candidates. The role will involve producing and implementing a comms strategy for the programme and assisting creators with their own comms plans.

We expect interviews of the shortlisted candidates to take place throughout October.

We welcome suggestions from the OC as to whether/how the committee would like to have input into this process. I don't think it will be possible for OC members to serve on the interview panel, but it would, for example, be possible for the OC to suggest questions that might be asked at interview.

Interim comms support: We expect that the permanent comms lead will be able to start by the end of February 2026. However, it was felt within ARIA that some support may be needed in the shorter term, especially as the RASI outdoor experiments could start before this and with COP and UNEA coming up in the next few months. There was a mood at Climate Week that the programme should try to more effectively own the conversation around responsible research within the portfolio.

With this in mind, we are looking to appoint a consultant to support the programme team with comms in the near term (to start ASAP) for 5-6 months. Again, we welcome OC comments on this and in particular things we should be asking the shortlisted candidates about during interviews.

5. Other matters

a. Seeds

There is still no date for when a seeds call might be issued in the Future Proofing our Climate and Weather opportunity space. One concern on this subject was that more comms support was required before a date could be set for opening the call. Therefore, it could be that a call can be opened before Christmas if a suitable consultant can be found. Otherwise, it looks as if the seeds call will be postponed to Spring/Summer 2026.

b. Tipping points workshop

██████████ is in the process of planning a small workshop to explore the intersection of the Exploring Climate Cooling programme with the [Forecasting Tipping Points](#) programme, with invitees from the SRM and tipping points modelling communities. The goal of the workshop is to bridge the gap between these communities, and surface key research questions regarding the feasibility of SRM as a tool to prevent the onset of various temperature induced tipping points. Key outputs may include formulating long term research aims for the Earth System Modelling community, and creating new collaborations across both communities. This is being co-organised with ██████████ (██████████). The workshop will be invitation-only and will take place in London in January 2026.

c. Proposal for explainers on tipping points and climate cooling

The programme team received [a proposal from SRM360](#) to produce two explainer articles and accompanying infographics. One would be on the possible application of SRM for protection of coral reefs, and the other would be on tipping points more generally. SRM360 would also organise a panel discussion and other promotional activities to publicise these works. The programme team have sought feedback from ██████████ on this proposal and would also welcome any OC comments on this proposal.

Exploring Climate Cooling

Oversight committee meeting pre-read

Updated December 2025

Contents

- 1. Timelines for Oversight Committee input into projects in 2026
 - a. Summary of projects with an outdoor component
 - b. Engagement plans
- 2. Update on new CEO
- 3. Update on dedicated comms lead and other comms support
- 4. Other matters
 - a. Seeds
 - b. Proposal for explainers on tipping points and climate cooling - outcome
 - c. Responsible research activities

1. Timelines for Oversight Committee input into projects in 2026

- a. **Summary of projects with an outdoor component:** The following table lists all nine projects that have some outdoor component (either perturbative experiments or monitoring) and the activities that are planned for 2026.

Project name	Ultimate intention of project	Planned activities of note for the Oversight Committee occurring in 2026
Re-Thickening Arctic Sea Ice	Outdoor perturbative experiment to assess	1. Outdoor experiment series Jan-March 2026 2. Observations of ice during melt over spring and

(RASi)	thickening of sea ice	summer 2026 (including melt pond drainage) 3. Preparations and engagement for outdoor experiments in winter 2026/27 (including reporting of results from winter 2025/26)
Marine Cloud Brightening in a Complex World	Outdoor perturbative experiment to assess marine cloud brightening	Continuing engagement with key stakeholders and local communities
REFLECT	Outdoor perturbative experiment to assess marine cloud brightening	Site selection and initial engagement expected in second half of 2026
BrightSpark	Outdoor perturbative experiment to assess marine cloud brightening	1. Engagement for outdoor experiments scheduled to begin by April 2026 2. Test flight of drones expected July 2026 3. Test flight of drones with sensors working expected October 2026 4. [Perturbative experiments are not due to commence until winter 2027/28]
Novel Materials for Stratospheric Aerosol Injection	Analysis of samples deliberately placed in (and then removed from) the stratosphere	Short duration (up to 24 h) balloon launches scheduled currently for mid 2026 onwards, subject to agreement and operationalisation of a suitable engagement plan. These launches are likely to occur in the UK.
De-risking cirrus modification	Prediction of how cirrus clouds might be modified by soot emitted by a standard jet, including a series of flights of such a jet.	Development and implementation of engagement plan, starting in early 2026, supporting monitoring campaign in winter 2027/28
INPUT:ACCESS	Collection and analysis of ice nucleating particles from high-level cloud	First balloon flights expected from December 2025 to evaluate the performance of the balloon-borne ice spectrometer for monitoring cirrus clouds
Stratoguard	Development of a high altitude balloon that other teams could use	First balloon test flights are expected from March 2026 (no payload, just to evaluate the performance of the balloon power system and steerable parachute for balloon

	for experiments	recovery). First flights with payload will be for Harvard as part of <i>Novel Materials for Stratospheric Aerosol Injection</i> from mid 2026 (pending suitable engagement by the Novel Materials for Stratospheric Aerosol Injection team).
MACE	Monitoring and analysis of volcanic plumes	1. Test flight of drones in the UK due in Spring 2026 2. First flights of drones in volcanic locations (subject to engagement process) were originally expected in summer 2027. If engagement goes well and the drones function as anticipated, first flights in the field could be brought forward.

- b. **Engagement plans:** The following projects have milestones to submit outline engagement plans and other key documents for review by the programme team and oversight committee within the next year:

Team	Document type	Previously communicated date on which OC will receive	Status update of document
Natural Materials for Stratospheric Aerosol Injection	Draft communication and engagement plan agreed with ARIA and oversight committee	Early Jan 2026 (this was originally scheduled for October 2025, but balloon launches are now delayed until mid 2026 at the earliest)	Still on course for Jan 2026
Brightspark	Draft engagement plan	Early Jan 2026	See row below
Brightspark	Initial technical feasibility study and possible site identification	Early Jan 2026	Due to some miscommunication, we now expect that this will be delayed into Spring 2026. We expect that this will in turn delay the

			engagement plan
MACE	Draft engagement plan	Early Jan 2026	Still on course for Jan 2026
De-risking cirrus modification	Draft engagement plan	Early Jan 2026	Still on course for Jan 2026
Novel Materials for Stratospheric Aerosol Injection	Updated communication and engagement plan agreed with ARIA and oversight committee	Early Jan 2026	Still on course for Jan 2026
Novel Materials for Stratospheric Aerosol Injection	Summary of comms and engagement undertaken to date supplied to ARIA and oversight committee	July 2026	Likely to be delivered significantly earlier than this as we have specified that engagement should begin before balloon launches start
Marine Cloud Brightening in a Complex World	Update on ongoing community engagement and future plans	July 2026	Still on course for July 2026
REFLECT	Draft engagement plan	October 2026	Still on course for October 2026
REFLECT	Suitable field sites identified and initial technical feasibility study	October 2026	Still on course for October 2026

2. Update on new CEO

On November 19th, ARIA announced that its new CEO will be [Kathleen Fisher](#). Kathleen will formally take over from Ilan at the beginning of February 2026. It could be useful for the Oversight Committee to meet with Kathleen shortly after she joins. Ilan Gur will continue to receive and act on Oversight Committee recommendations until Kathleen starts.

3. Update on dedicated comms lead and other comms support

Comms lead: Panel interviews of the shortlisted candidates for the permanent Future Proofing our Climate and Weather comms lead will commence w/c 1st December. Four candidates have progressed to this stage. We hope to make an offer before the end of the year.

Interim comms support: Plans to appoint a consultant to support the team until the comms lead starts will not be taken forward, and ARIA's existing comms functions will support the team in the interim.

4. Other matters

- a. **Seeds:** Given the likely timeline for hiring the comms lead, we do not at the moment anticipate that the Opportunity seeds funding call will open before May 2026 at the earliest.
- b. **Proposal for explainers on tipping points and climate cooling:** As per the discussion in our last meeting, we declined the offer from SRM360 to produce explainer articles and accompanying infographics on SRM and coral reefs.
- c. **Responsible research activities:** We will update the OC on plans to hold conversations with stakeholders on responsible research in the field. The programme team is also giving consideration to what could or should be done to promote responsible research with other public funders, both in the UK and internationally. For example, should ARIA consider trying to convene other national and international public funding agencies to share learnings and discuss what responsible research in this space might look like? If so, who might it be useful to include and who might be able to facilitate such discussions?

Exploring Climate Cooling

Oversight committee meeting pre-read

Updated January 2026

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1. Invoicing

When invoicing ARIA for time spent on Oversight Committee business, please send invoices to [REDACTED] and also add the generic [REDACTED] email address in cc as well. This will ensure more timely payment should [REDACTED] be away.

2. Update on RASI

The programme team thanks the Oversight Committee for their detailed and immensely useful recommendations. Taking these recommendations into account, Ilan approved funding for the RASI outdoor experiments for winter 2026 in late December.

The programme team provided this [update](#) to the Oversight Committee on 5th January.

Since then, a dedicated [RASI webpage](#) has been built out on the ARIA website. This gives information mostly related to Real Ice (including their permits and engagement plan), as well as the Oversight Committee's recommendation letter and Ilan's response to that.

Real Ice arrived in Cambridge Bay on 9th January and have begun operations.

Arctic Reflections received their screening report from Nunavut Impact Review Board on 12th January, with a recommendation that the responsible minister permit the work to proceed. We anticipate that the project will be deemed as approved on 27th January and that a permit to conduct the work will be issued then. A draft legal compliance review has been completed by Wills and Shrier, which indicated that the work seemed compliant with all relevant regulations and the prevailing interpretation of UNDRIP in Canada. A final compliance review will be completed once the permits are in hand. Documents and descriptions for Arctic Reflections will then be added to the RASI webpage, to match those for Real Ice.

Arctic Reflections have shown the programme team a draft of their policy on consent and community contributions. This is now being reviewed by members of the local community in Qikiqtarjuaq. This will be uploaded to the webpage before work starts.

Meanwhile, stakeholder engagement at the programme level continues.

3. Update on Engagement Plans

Some of the engagement plans that were due to be received in January have been delayed due to the relevant teams needing to re-appraise technical aspects of their experiments, which will have a bearing on the engagement that is required. The intimate connection that exists between initial experiment design and initial engagement design is a key learning from the first months of the programme.

As of now, two of the engagement plans due in January have been received, for [Derisking Cirrus Modification](#) and [MACE](#). It should be noted that both of these are classed as monitoring projects (rather than “outdoor perturbative experiments”) and so we do not have plans for either project to go through any subsequent outdoor experiment approval process. However, we did ask both teams to produce engagement plans and for these to be shared with ARIA and the Oversight Committee for feedback before the plans were put into execution.

Feedback on these plans for improvement would be appreciated by February 17.

We hope to then share the two delayed remaining engagement plans in March.

4. Update on Activation Partners

On 3rd December, ARIA communicated to Renaissance Philanthropy that ARIA would not be funding the next phase of the Climate Emergencies Forum (CEF). ARIA support for CEF has now ended, although ARIA has committed to funding the recipients of CEF’s [Coalition-Building Grantees](#) in full.

Therefore, as of now, the only ARIA Activation Partners directly contributing or associated with the Exploring Climate Cooling programme are Amodo and Pillar VC, the latter through their Encode for AI Fellowship. Amodo, based in Sheffield, provides design and fabrication expertise to a number of project teams within Exploring Climate Cooling to build scientific apparatus. The Encode for AI Fellowship embeds AI talent inside academic labs across ARIA’s opportunity spaces. One of the fellows is using AI to improve climate intervention modelling capability. The programme team is not directly involved in the work, but we are closely following the fellowship to ensure consistency with the programme in values and language.

The programme team did not appoint Activation Partners directly and instead these were selected at the organisation level. Therefore, we sometimes hear of Activation Partner activities that are a surprise to us. We will endeavour to pass on to the Oversight Committee details of any new initiatives that come to light.

5. Update on programme comms

Programme comms Director: Panel interviews of the shortlisted candidates for the Future Proofing our Climate and Weather comms lead were held w/c 1st December. Following these interviews, the decision was taken to re-advertise the role as a more senior position, with the title of Strategic Director of Communications for the programme. The applications window for this role has now closed and we hope to have made an offer by the end of February. ARIA's existing comms functions will continue to support the team in the interim.

Documentaries: ARIA has been approached by a number of documentary makers interested in the programme (from profiling individual projects to programme-level thematics) and some Creators have expressed an appetite to produce their own short films or video content about their projects. Some of these proposals include requests for financial contributions (this is increasingly standard in the commissioning cycles for science documentaries). Any such assistance (if provided) would most probably be provided from the programme's Governance and Responsible Innovation Budget. *As we assess proposals and begin to make decisions on these requests, what key considerations, principles, guidelines should we bear in mind?*

Comms narrative: Liminal Space has shared feedback from Creators on the programme's comms and narrative: *There is appetite from project teams for ARIA to lead with a stronger Exploring Climate Cooling programme narrative that visibly differentiates its work through governance, ethics and community engagement, rather than leaving teams' work to be interpreted within a generic geoengineering frame. Stardust has come up a few times and there's some concern that without a more visible narrative there's a risk the Exploring Climate Cooling work gets misunderstood within the nascent public understanding of geoengineering. The Liminal Space sees an opportunity to tell this story whilst building the public's capacity to understand and consider Exploring Climate Cooling science and ethics.*

To inform the programme's comms efforts, we invite the Oversight Committee's perspectives on the Exploring Climate Cooling programme's narrative and the support provided to Creators.

6. Other matters

- a. **Seeds:** Given the likely timeline for hiring for the comms role, it seems reasonable to assume that the Opportunity seeds funding call will not open before April 2026 at the earliest.
- b. **New CEO:** The programme team have requested that Kathleen Fisher joins for part of the Oversight Committee meeting on 25th March.
- c. **Responsible research and constructive governance activities:** We will update the OC in the meeting on recent discussions with government stakeholders.

The Exploring Climate Cooling and Forecasting Tipping Points programmes held a joint workshop on 15th and 16th January to bring together scientists from the tipping points and SRM communities to co-design a shared research roadmap that tackles some of the key gaps in our understanding between tipping points and how SRM may impact them. A white paper/meeting summary authored by the scientists present that highlights future research that could be beneficial to both communities is in preparation (at this time, the intention is to publish this white paper on the ARIA website). This could inform literature submissions for the impending IPCC AR7 deadline in early 2027.

- d. **Empowering New Voices in SRM - workshop and funding call:** DSG and University of Cape Town are planning to hold a 2-day, in-person, co-creation focused convening in Cape Town in April 2026 to elicit questions on SRM that might be answered through research. ARIA plans to fund a small number (3-5) projects that aim to address these questions through a dedicated call for proposals at some point in mid 2026. Of note:
 - i. The funding for these projects (up to £250k) will be drawn from the Governance and Responsible Innovation Budget
 - ii. The intention is for a majority of the funding to go to global south researchers
 - iii. ARIA intends to trial a new expedited pitch-to-panel reviewing and selection process for these projects
 - iv. ARIA is considering working through a UK partner organisation (a university or suitable NGO) to disperse funds and coordinate the project. This partner may be selected through a separate call
 - v. The intention is for projects to last 12-18 months and to report back to the workshop delegates
 - vi. The call will be open to researchers present at the workshop, as well as those not present at the workshop.

7. Appendix: Timelines for Oversight Committee input into projects in 2026

- a. **Summary of projects requiring Oversight Committee input:** The following table lists all nine projects that have some outdoor component (either perturbative experiments or monitoring) and the activities that are planned for 2026.

Project name	Project classification	Planned activities of note for the Oversight Committee occurring in 2026
Re-Thickening Arctic Sea Ice (RASi)	Outdoor experiment	1. Outdoor experiment series Jan-March 2026 (already scrutinised by OC and ARIA, and approved) 2. Observations of ice during melt over spring and summer 2026 (including melt pond drainage) - also already approved 3. Preparations and engagement for outdoor experiments in winter 2026/27 (including reporting of results from winter 2025/26)
Marine Cloud Brightening in a Complex World	Outdoor experiment	Continuing engagement with key stakeholders and local communities
REFLECT	Outdoor experiment	Site selection and initial engagement expected in second half of 2026
BrightSpark	Outdoor experiment	1. Engagement for outdoor experiments was scheduled to begin by April 2026, but we now expect this to be delayed at least into mid 2026 2. Test flight of drones was expected Sept 2026 - again, this may be delayed 3. Test flight of drones with sensors working expected about 3 months after test flights 4. [Perturbative experiments are not due to commence until winter 2027/28]
Novel Materials	Outdoor experiment	Short duration (up to 24 h) balloon launches were scheduled

for Stratospheric Aerosol Injection		for mid 2026 onwards, subject to agreement and operationalisation of a suitable engagement plan. The team is now actively exploring whether drones would be a more effective platform for these experiments, which may delay first launches into autumn of 2026 or later. These launches will involve analysis of samples placed in (and then removed) from the stratosphere. The project teams expect these are likely to occur in the UK (site still to be selected).
De-risking cirrus modification	Passive monitoring	Development and implementation of engagement plan, starting in early 2026, supporting monitoring campaign in winter 2027/28. Oversight committee will be asked to comment on the engagement plan
INPUT:ACCESS	Passive monitoring	First balloon flights commenced in December 2025 to evaluate the performance of the balloon-borne ice spectrometer for monitoring cirrus clouds.
Stratoguard	Passive monitoring	First balloon test flights are expected from March 2026 (no payload, just to evaluate the performance of the balloon power system and steerable parachute for balloon recovery).
MACE	Passive monitoring	1. Test flight of drones in the UK due in Spring 2026 2. First flights of drones in volcanic locations (subject to engagement process) were originally expected in summer 2027. If engagement goes well and the drones function as anticipated, first flights in the field could be brought forward. 3. Oversight committee will be asked to comment on the team's engagement plan.

- b. **Summary of Engagement plans:** The following projects have milestones to submit outline engagement plans and other key documents for review by the programme team and oversight committee within the next year:

Team	Document type	Previously communicated date on which OC will receive	Status update of document
Natural Materials for Stratospheric Aerosol Injection	Draft communication and engagement plan agreed with ARIA and oversight committee	Early Jan 2026 (this was originally scheduled for October 2025). However, due to evaluation of whether to not to use drones instead, we expect the engagement plan to be delayed until March	Now expected March 2026
Brightspark	Draft engagement plan	Early Jan 2026	See row below
Brightspark	Initial technical feasibility study and possible site identification	Early Jan 2026	We expect that this will be delayed into Spring 2026. We expect that this will in turn delay the engagement plan
MACE	Draft engagement plan	Early Jan 2026	Draft engagement plan submitted
De-risking cirrus modification	Draft engagement plan	Early Jan 2026	Draft engagement plan submitted
Novel Materials for Stratospheric Aerosol Injection	Updated communication and engagement plan agreed with ARIA and oversight committee	Early Jan 2026	Not expected until summer 2026
Novel Materials for Stratospheric Aerosol Injection	Summary of comms and engagement undertaken to date supplied to ARIA and	July 2026	Not expected until summer 2026

	oversight committee		
Marine Cloud Brightening in a Complex World	Update on ongoing community engagement and future plans	July 2026	Still on course for July 2026
REFLECT	Draft engagement plan	October 2026	Still on course for October 2026
REFLECT	Suitable field sites identified and initial technical feasibility study	October 2026	Still on course for October 2026

Exploring Climate Cooling

Oversight committee meeting pre-read

Updated March 2026

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1. Kathleen Fisher

ARIA's new CEO, Kathleen Fisher, will join the OC meeting for around half an hour to meet OC members and to ask and answer questions. Kathleen has been briefed on the role of the OC in the programme.

2. Update on RASI and Arctic engagement

Both Real Ice and Arctic Reflections have now finished pumping operations and there will now be a pause in most field work until May when preparations for the melt season will begin. Both teams reported very cold temperatures causing some problems for them during thickening, but overall both teams were very pleased with how things went both technically and with their partnerships with local communities.

Mark was at [REDACTED] Forum in Rome in early March, where he engaged in constructive conversations with [REDACTED] ([REDACTED]), and took part in a panel discussion with [REDACTED] (immediate past [REDACTED]) and [REDACTED] about geoengineering.

3. Programme Review

The Exploring Climate Cooling programme's first annual review will take place on 16th June. Programme annual reviews are opportunities to take stock of a programme's progress to date and to help guide decision making on what happens next for the programme. Programme annual reviews involve the programme team, ARIA's executive team and external experts. ARIA's CEO is the decisionmaker for the review meeting, where the four possible outcomes are:

1. Terminate the programme
2. Continue with the programme without significant change
3. Pivot the programme to new objectives by re-distributing existing resources
4. Scale the programme by adding new resources

The programme team has the opportunity to suggest who the external reviewers could be and suggestions for these will be discussed with the OC in the committee meeting. These reviewers should be independent of the programme and its current structures.

Separately, the programme team thinks that it would be helpful for there to be some mechanism for the OC to be able to feed back to ARIA's executive on the programme's performance to date and what role the OC sees for the programme going forward. Suggestions for how this might happen will be discussed with the OC in the committee meeting.

4. Update on Engagement Plans

We are expecting outline engagement plans for Brightspark and SAIM to be submitted for feedback before the end of March. These plans will not be as detailed as for RASI as they are exclusively forward-looking.

Feedback on these plans would be appreciated by 17th April.

We are also planning to put some information on what these experiments might involve (e.g. diagrams to explain the experiments) on the ARIA website in the next few weeks.

5. Update on programme comms

Programme comms Director: Following interviews of a number of candidates, [REDACTED] has been appointed Strategic Director of Communications for the programme. [REDACTED] is well-qualified for this role as she has been leading the programme's comms since its inception, whilst also performing a similar role for a number of other programmes. [REDACTED] will transfer from ARIA's central comms team to the programme team on 1st April and will be working full-time on the programme from 1st May.

6. Other matters

- a. **Seeds:** Now that the Strategic Director of Communications role has been filled, the seeds call is expected to go live in early June. It would be useful to discuss in the OC meeting the stage at which the OC would like to have input into the selection process, with the programme team's tentative suggestion being that OC input occurs at interview stage after shortlisting (likely to fall over two weeks in mid September).
- b. **Nuffield Council on Bioethics:** The programme team have submitted materials to Nuffield Council on Bioethics' [call for evidence](#) on solar radiation modification, which we have stated can be published by Nuffield and attributed to the ARIA Exploring Climate Cooling programme.
- c. **NERC-Sciencewise consultation:** The report from this public dialogue is expected imminently. We may have more to update in the OC meeting if the publication has taken place by then. The OC's thoughts on whether ARIA seeks to build from this dialogue (or launch dialogue-type activities of other sorts) would be welcome.

- d. Empowering New Voices in SRM - workshop and funding call:** As an update to this item from the last meeting, University of Exeter has been selected as the UK partner organisation to assist with distribution of funds to projects aiming to answer the questions elicited at the workshop. Exeter will receive £50k to cover dispersal of funds, due diligence and provision of staff time for technical assistance with projects. The remaining £200k will be awarded to teams working on answering the questions, most of whom we expect will be global south researchers.

We expect that the request for proposals will open in mid May for around 4 weeks. We expect to put out some comms around the upcoming call in mid April to give potentially interested teams time to prepare.

7. Appendix: Timelines for Oversight Committee input into projects in 2026

- a. **Summary of projects requiring Oversight Committee input:** The following table lists all nine projects that have some outdoor component (either perturbative experiments or monitoring) and the activities that are planned for 2026.

Project name	Project classification	Planned activities of note for the Oversight Committee occurring in 2026
Re-Thickening Arctic Sea Ice (RASi)	Outdoor experiment	1. Outdoor experiment series Jan-March 2026 (now complete) 2. Observations of ice during melt over spring and summer 2026 (including melt pond drainage) 3. Preparations and engagement for outdoor experiments in winter 2026/27 - initial thoughts from the team suggest they will submit their outdoor experiment approval materials in early autumn
REFLECT	Outdoor experiment	Some outreach to key stakeholders is expected over the next month or so. Site selection and initial community engagement is expected towards the end of 2026
BrightSpark	Outdoor experiment	1. Outreach to key stakeholders is expected to start over the next month or so 2. Community engagement for outdoor experiments is expected to be underway by mid 2026 3. The creator team has suggested that some perturbative experiments may be possible in late 2026. This will have to depend on appropriate engagement, support from local communities and suitable environmental impact assessment
Novel Materials for Stratospheric Aerosol Injection (SAIM)	Outdoor experiment	Short duration (up to 24 h) balloon launches were scheduled for mid 2026 onwards, subject to agreement and operationalisation of a suitable engagement plan. The team is now actively exploring whether drones would be a more

		effective platform for these experiments, which may delay first launches into autumn of 2026 or later. These launches will involve analysis of samples placed in (and then removed) from the stratosphere. A definition of how these experiments would happen on a technical-logistics basis is still lacking.
Marine Cloud Brightening in a Complex World	Outdoor experiment	Continuing engagement with key stakeholders and local communities
De-risking cirrus modification	Passive monitoring	Development and implementation of engagement plan, starting in early 2026, supporting monitoring campaign in winter 2027/28. Oversight committee has provided comments on the engagement plan
INPUT:ACCESS	Passive monitoring	First balloon flights commenced in December 2025 to evaluate the performance of the balloon-borne ice spectrometer for monitoring cirrus clouds. Further flights are continuing
Stratoguard	Passive monitoring	First balloon test flights were expected from March 2026 (no payload, just to evaluate the performance of the balloon power system and steerable parachute for balloon recovery). These have now been delayed into summer 2026.
MACE	Passive monitoring	1. Test flight of drones in the UK due in Spring 2026 2. First flights of drones in volcanic locations (subject to engagement process) were originally expected in summer 2027. If engagement goes well and the drones function as anticipated, first flights in the field could be brought forward. 3. Oversight committee has commented on the team's engagement plan.

- b. **Summary of Engagement plans:** The following projects have milestones to submit outline engagement plans and other key documents for review by the programme team and oversight committee within the next year:

Team	Document type	Previously communicated date on which OC will receive	Status update of document
Novel Materials for Stratospheric Aerosol Injection (SAIM)	Draft engagement plan	Early Jan 2026 (this was originally scheduled for October 2025). However, due to evaluation of whether or not to use drones instead, we expect the engagement plan to be delayed until March	Expected by end of March 2026
Brightspark	Draft engagement plan	Early Jan 2026	Expected by end of March 2026
REFLECT	Draft engagement plan	October 2026	Still on course for Oct 2026
Novel Materials for Stratospheric Aerosol Injection	Updated communication and engagement plan agreed with ARIA and oversight committee	Early Jan 2026	Not expected until summer 2026
Novel Materials for Stratospheric Aerosol Injection	Summary of comms and engagement undertaken to date supplied to ARIA and oversight committee	July 2026	This will now be merged with the line above, and expected summer 2026
Marine Cloud Brightening in a Complex World	Update on ongoing community engagement and future plans	July 2026	Still on course for July 2026
Brightspark	Outdoor experiment approval submission	Feb 2027	August 2026 has been requested by the creators. ARIA has not yet agreed on whether to bring

			this forward or not
RASI	Development of community and stakeholder engagement strategy submitted to ARIA programme team and Oversight Committee. Outdoor experiment approval submission for Year 2 experiments	October 2026	Expected September 2026
Novel Materials for Stratospheric Aerosol Injection	Outdoor experiment approval submission	-	The team are still not able to define what the experiment would involve, and so an expected delivery date for this document is not possible at the moment

Future Proofing our Climate and Weather Intellectual Property Pledge

1. Submission of Pledged Patents and Experimental Data

- 1.1 The Pledgor undertakes to submit relevant details of all Pledged Patents to the operator of the Pledge Repository in accordance with the Submission Guidelines.
- 1.2 The Pledgor undertakes to:
 - (a) submit (or provide a link to a publicly available digital copy of) all Experimental Data to the operator of the Pledge Repository in accordance with the Submission Guidelines; and
 - (b) publish such Experimental Data in accordance with the Submission Guidelines.

2. Experimental Data Licence

- 2.1 Subject to Clause 6.1, the Pledgor hereby grants a royalty-free, non-exclusive licence under the Experimental Data to any party that wishes to accept it ("Experimental Data Licensee") solely for the purpose of carrying out research in the Field.
- 2.2 The licence granted under Clause 2.1:
 - (a) is non-transferable and non-sublicensable;
 - (b) permits research activities but does not permit development, manufacture, sale or other exploitation of products or services under the Experimental Data.
- 2.3 The Experimental Data Licensee may conduct relevant research activities itself or in collaboration with a third party, provided that the Experimental Data Licensee must ensure that such third party agrees to comply with the terms of Clause 2.4 as if such third party were the Experimental Data Licensee.
- 2.4 The Experimental Data Licensee must
 - (a) at all times when using the Experimental Data comply with all Laws; and
 - (b) to the extent that any data relating to the Field is generated by or on behalf of the Experimental Data Licensee in the course of carrying out research activities based on or using the Experimental Data or the Pledged Patents, make such data available on the terms of this Pledge (and such data shall be deemed to be Experimental Data pursuant to this Pledge).

3. Research Licence

- 3.1 Subject to Clause 6.1, the Pledgor grants a royalty-free, non-exclusive licence under the Pledged Patents to any party that wishes to accept it ("Research Licensee") solely for the purpose of carrying out research in the Field.
- 3.2 The licence granted under Clause 3.1:
 - (a) is non-transferable and non-sublicensable; and
 - (b) permits research activities but does not permit development, manufacture, sale or other exploitation of products or services under the Pledged Patents.
- 3.3 Subject to Clause 6.1, the licence granted in accordance with Clause 3.1 shall subsist until the expiry of the final Pledged Patent.
- 3.4 The Research Licensee may conduct relevant research activities itself or in collaboration with a third party, provided that the Research Licensee must ensure that such third party agrees to comply with the terms of Clause 3.5 as if such third party were the Research Licensee.

3.5 The Research Licensee must:

- (a) at all times when using the Pledged Patents comply with all Laws; and
- (b) to the extent that any patents relating to the Field are filed by or on behalf of the Research Licensee covering data generated in the course of carrying out research activities based on or using the Pledged Patents or Experimental Data, make such patents available on the terms of this Pledge (and such patents shall be deemed to be Pledged Patents pursuant to this Pledge).

4. **Commercial Licence**

- 4.1 The Pledgor undertakes to grant a non-exclusive licence on reasonable terms under the Pledged Patents and/or Experimental Data to any Signatory that requests it ("Commercial Licensee") for the purpose of carrying out commercial activities (including development, manufacture, sale or other exploitation of products or services) in the Field.
- 4.2 The Pledgor must grant the licence set out Clause 4.1 in good faith and in a timely fashion following such a licence being requested by the Commercial Licensee.
- 4.3 The Commercial Licensee must at all times when using the Pledged Patents and/or Experimental Data comply with all Laws.

5. **Pledgor Know-How**

At the request of a Licensee, the Pledgor undertakes to negotiate in good faith with any Licensee regarding a non-exclusive licence in the Field under any Know-how owned by such Pledgor that is necessary for a Licensee to use the technology covered by the Pledgor's Pledged Patents. Such licence may be for research or commercial purposes as agreed between the Pledgor and Licensee.

6. **Termination**

- 6.1 The Pledgor may terminate any licence it grants to an Experimental Data Licensee and/or Research Licensee under this Pledge in the event that such Licensee:
 - (a) materially breaches the terms of such licence or this Pledge; or
 - (b) breaches any Laws in its use of the Experimental Data or Pledged Patents (as applicable).

7. **Transfers of Pledged Patents and/or Experimental Data**

The Pledgor undertakes to make any future assignment of the Pledged Patents and/or Experimental Data to any other party (the "Recipient") conditional on the Recipient (and any successor in title) agreeing to be bound by the terms of this Pledge.

8. **No Warranty**

The Pledgor provides the Pledged Patents and the Experimental Data on an "as is" basis. The Pledgor makes no express or implied warranty or representation concerning the Pledged Patents or Experimental Data including but not limited to non-infringement or to the accuracy or completeness of the Pledged Patents or Experimental Data.

9. **Compliance with Laws**

For the avoidance of doubt, nothing in this Pledge operates to require a Pledgor, Licensee or Signatory to do any acts or grant any rights that do not comply with Laws.

10. **Further Publication or Licensing**

For the avoidance of doubt, nothing in this Pledge operates to restrain a Pledgor from publishing or licensing any Experimental Data or Pledged Patents more widely or on more permissive terms than those described herein.

11. **Governing law and jurisdiction**

This Pledge (including any non-contractual disputes or claims arising in connection with this Pledge) will be governed by and construed in accordance with the laws of England and Wales and the parties irrevocably submit to the exclusive jurisdiction of the courts of England and Wales.

Part 1: Definitions

1. In this Pledge, unless the context otherwise requires, the following definitions shall apply:

Experimental Data	means data generated by or on behalf of the Pledgor relating to the Field and identified by the Pledgor for inclusion in the Pledge pursuant to Clause 1.2;
Field	means approaches for intentionally altering the Earth system through solar radiation modification, modification of ocean circulations, modification of cloud properties, surface engineering works, or weather modification;
Know-how	means the information, methods, formulae, processes and/or applications which may or may not be documented and which enable the use of the technology covered by the Pledged Patents;
Law(s)	means any applicable law, statute, bye-law, regulation, order, regulatory policy, guidance or industry code having the force of law, rule of court, delegated or subordinate legislation in force from time to time;
Licensee	means any Commercial Licensee, Research Licensee or Experimental Data Licensee;
Pledge	means the commitments in relation to patents, know-how and data set out in this pledge document;
Pledge Repository	the website or other digital repository designated by the Advanced Research and Invention Agency (or any successor or nominee) from time to time as the repository for Experimental Data and Pledged Patents under the Pledge
Pledged Patents	means patents or patent applications owned by the Pledgor relating to the Field and identified by the Pledgor for inclusion in the Pledge pursuant to Clause 1.1;
Signatory	means any party who has agreed to be bound by the terms of this Pledge; and
Submission Guidelines	means the guidelines governing the submission of Experimental Data and details of the Pledged Patents to the Pledge Repository, as amended from time to time.

Research Data and IP Submission Guidelines

1. Introduction & Purpose

- **Statement of Principle:** All project teams funded through the Exploring Climate Cooling programme have committed to adhering to an IP pledge as laid out in the ARIA funding Agreement. The purpose of the pledge is to ensure that all research data and patents developed in the projects funded by the ARIA programme remain freely available for use for research purposes, supporting the commitment to transparency set out in the programme thesis principles.
- **Objective of these Guidelines:** These submission guidelines are in place to ensure that all project teams understand their responsibilities and obligation to make research data freely available, and to provide a clear process for data submission, in addition to the guidelines outlined in the Data Management Plan.

2. Data & Patent Submission Requirements

- **How to submit:**
 - All research data and details of patents will be deposited by project teams on a Zenodo, independently hosted repository with a community page managed by the ARIA team.
 - The Zenodo Community page can be accessed [here](#), where data can be uploaded.
 - For detailed guidance on how to upload data, please refer to this document
 - **Data:** ARIA will manage submissions to the Zenodo repository but all data is to be uploaded by the project teams. It is the responsibility of the project teams to suitably prepare data for submission and ensure that the data is produced in line with the agreed upon Data Management Plan.

This includes all relevant metadata and clear descriptions of the data uploaded.

- **Details of patents:** Project teams must submit the following information in relation to all patents which they submit to the pledge:
 - Title
 - Application number
 - Short description of patent
 - Publication number (if applicable)
 - Patent jurisdiction
 - Owner of the patent/registration
 - Application date
 - Publication date (if applicable)
 - Links to any relevant databases (e.g. Espacenet or Google Patents)
- **When to submit:**
 - It is the responsibility of the project teams to ensure that data is made available promptly.
 - In certain instances where there is clear justification, teams may request to temporarily withhold the release of data. For example, this may be until results are peer reviewed and/or published in scientific journals. ARIA will consider these requests on a case-by-case basis.
 - Teams are encouraged to make data sharing a priority throughout the project lifetime.
 - Details of patent applications should be shared promptly following the filing of such applications.
- **Where to submit:**
 - All data will be required to be deposited on Zenodo, a designated, independently hosted central repository.
 - Teams may also wish to make their data available elsewhere, for example on their own institutional repositories or Github page. This is encouraged by the programme team, however this must be in addition to, and not in place of, submission to the ARIA central repository.

3. Contact & Support

- For any questions or clarifications relating to the Submission Guidelines or the Data Management Plan please contact cool-creators@aria.org.uk.
- ARIA reserves the right to update the Submission Guidelines from time to time.



Real Ice

Winter 2025/26

Community Engagement and Permitting: Cambridge Bay, Nunavut

Introduction

Plans for field tests in the winter 2025/26

Real Ice has undertaken a series of small-scale sea ice thickening field studies beginning in January 2023 in Nome, Alaska (Real Ice project: T1), followed by subsequent campaigns in Cambridge Bay, Nunavut, on Canada's Victoria Island, in January 2024 (T2) and from December 2024 to July 2025 (T3). These studies have been designed to advance understanding in several key areas: the enthusiasm, interest and engagement of local communities with the research, the logistical and operational challenges of conducting research on the ice, the engineering feasibility of thickening sea ice through water pumping from beneath the ice surface, and the scientific dynamics associated with snow flooding in the winter and, more recently, melt pond drainage during the spring season.

Beginning in January 2026, Real Ice plans to resume work in Cambridge Bay, collaborating with the same local partners and within the same geographic area, while refining the study design in light of insights gained from the previous three winters of research. For this forthcoming season, the project will focus on thickening a single designated section equivalent to one quarter of the 1 km² area identified in collaboration with the local Hunters and Trappers Organisation, and employing more efficient pumping methods and improved measurement techniques. We expect to complete the core ice thickening operations by March 2026, then to monitor and measure the target area until the onset of the melt season (May to July 2026), when we will complete the observations and perform smaller-scale operations to test the effectiveness of melt pond drainage.

Research Protocol

Real Ice is dedicated to upholding the principle of Free, Prior, and Informed Consent (FPIC) in all research activities, placing particular emphasis on authentic and sustained engagement with local communities at the grassroots level. Recognising that much of the Arctic falls under the shared stewardship of Indigenous peoples, Real Ice acknowledges their central role in the governance and decision-making processes that affect their traditional lands and waters. Environmental preservation is a fundamental concern for these communities, who consistently advocate for the protection of the Arctic's fragile ecosystem.

The ability of Real Ice to conduct research in the region rests upon the willingness of local permitting authorities, civic organisations, and Indigenous hunting and trapping bodies to grant access and to collaborate in research design, implementation, and knowledge exchange. Such collaborations foster research that is respectful, inclusive, and attentive to community values while explicitly supporting the rights of Indigenous partners.

To guide these interactions, Real Ice follows the Inuit Circumpolar Council's Protocols for Equitable and Ethical Engagement ([ICC EEE Protocols](#)), hereafter referred to as "Protocols", which serve as a comprehensive framework for ethical research. These protocols require that Inuit be integrally involved in all decisions affecting them and that their knowledge systems are regarded as equally valid as Western scientific approaches. The protocols promote good governance through transparency, mutual accountability, and trust-building, and call for partnerships based on respect, shared data stewardship, and equitable distribution of any benefits arising from research activities within Inuit communities. Real Ice is committed to the thorough incorporation of these protocols in all aspects of its work.

A fundamental principle underpinning all of Real Ice's engagements and activities with local communities is the establishment of realistic expectations regarding the outcomes achievable through small-scale testing. We do not advocate for, promise, project, or discuss any potential deployment of the technology in Cambridge Bay or elsewhere; our focus remains firmly on the scientific and engineering insights derived from this limited research. Should questions arise about the ultimate aim of successful research, we may reference the longer-term aspiration of fostering an indigenous-owned industry capable of scaling up the technology. However, we emphasize that any actual deployment would be contingent upon overcoming numerous regulatory, security, economic, and technical challenges—most of which are beyond Real Ice's influence.

Summary of our technical and operational plans

Location

The winter 2026 research study location, selected with the collaboration of members of the local hunters and trappers organisation, is approximately 7km from the hamlet of Cambridge Bay on the sea ice. The water in this location is >20m deep.



Method

During the study, we will thicken a sea ice area of approximately 0.25 km² as part of the designated 1 km² target area. The ice thickening operations will start in January 2026 when the ice is safe and stable, and continue until the end of March. Ice and snow thickness, temperatures and salinity measurements will be taken actively (drilling holes and collecting ice cores) and passively (through embedded ice thickness measurement devices) throughout the winter and melt season. In the spring, we will also perform melt pond drainage by making small holes in the ice. Aerial and satellite images will also be used to assess and record the conditions of the target area.

Past Community Engagement in Cambridge Bay

Formal Nunavut and Cambridge Bay Permissioning Timeline

The organisations that manage the permissions for research in Cambridge Bay, Nunavut, are as follows:

1. Nunavut Planning Commission (**NPC**) - a multi-year license may be granted
2. Nunavut Impact Review Board (**NIRB**) - required upfront and applies as long as the multi-year NPC agreement is in place
3. Nunavut Research Institute (**NRI**) - a multi-year license may be granted
4. Local Hunters and Trappers Organisations - in the case of Cambridge Bay, this is Ekaluktutiak Hunters and Trappers Organisation (**EHTO**) - annual approval
5. Research facility support from Polar Knowledge's Canadian High Arctic Research Station (**CHARS**) (if facilities are being used) - annual approval

Descriptions of each of the above organisations can be found in Appendix A

January 2024 (T2)

August 2023: EHTO initial briefing and operating permission request
August 2023: NPC initial research license application
August 2023: CHARS research support application
September 2023 NIRB initial research license application
September 2023 NRI initial research license application
November 2023 NPC multi-year research license granted {2023 - 2026}
*November 2023 NIRB research approval granted**
November 2023 NRI multi-year research license granted {2023 - 2026}
November 2023 CHARS research support for T2 granted
November 2023 EHTO permission for T2 granted

December 2024-June 2025 (T3)

August 2024 : EHTO T2 briefing and operating permission for T3 request
October 2024 NPC 2nd year of the multi-year license confirmed
October 2024 EHTO permission for T3 granted
November 2024 NRI 2nd year of the multi-year license confirmed
November 2024 CHARS research support for T3 granted

** NIRB does not issue a new annual research license approval in the case of multi-year grants by NPC and NRI provided that the research has not changed substantially year to year.*

Community Engagement History

Real Ice's engagement in the Arctic is inspired by the principle of "Nothing About Us Without Us" (Protocol 1), ensuring that all research and operational decisions are made in close partnership with local communities and stakeholders. Initial engagement began in January 2022 with meetings in Iqaluit and subsequently in Nome, Alaska, where approval was received from Nome tribal and city authorities to conduct preliminary field tests.

Since 2023, collaboration with the Cambridge Bay Hunters and Trappers Organisation (EHTO) has been central to project planning, including the co-design of research methods, field site selection, research results briefings and annual securing of formal letters of support (Protocols 1,6 & 7). Members of EHTO have been involved in daily research activities, contributing their traditional knowledge and skills in crucial activities such as setting up and maintaining a safe camp out at sea, travelling on the sea ice in all weather conditions, performing key operations such as drilling through ice, securing, transporting and recovering equipment, measuring results, and actively making sure team members are safe from weather, environment and wildlife.

This deliberate, grassroots approach has established a foundation of mutual respect and shared interest in addressing sea ice loss (Protocol 2). The members of EHTO that contributed to the research studies over the last two winters will be named as contributors in a peer-reviewed paper from the University of Washington's Prof Edward Blanchard-Wrigglesworth, expected in pre-print in Q4 2025.

Active and ongoing dialogue with Cambridge Bay Elders is a core aspect of Real Ice's approach. Regular briefings at the Heritage Society, designed explicitly for Elders, reflect the project's commitment to recognising and integrating Indigenous knowledge (Protocol 2). Wider trust-building has been accomplished through open discussions with the Hamlet Council, Mayor, and other civic leaders. Additionally, hiring local Inuit guides and consultants and joining the Kitikmeot Chamber of Commerce have further invested in local capacity (Protocol 5).

Critical to Real Ice's effectiveness is sustained community presence in Cambridge Bay. Maintaining a multi-month base in the community each ice season enables formal and informal dialogue with hunters, trappers, guides, Elders, teachers, and other residents. Engagement activities include public Q&A sessions in community halls and CHARS, briefings at EHTO board and council meetings, and one-to-one meetings with local community members, Elders and leaders. This embedded approach facilitates EHTO team members' traditional knowledge sharing, fosters trust, ensures project transparency, and allows research operations to respond to local needs and feedback directly.

A central aspect of our work is our collaboration with the Cambridge Bay Hunters and Trappers Organisation (EHTO), who are the primary holders of traditional knowledge about the ecosystem in the region. The community as a whole and this group in particular relies on hunting and fishing for sustenance. Our collaboration with EHTO is essential to ensuring that our research adopts a holistic approach that respects and acknowledges Traditional Inuit Knowledge. EHTO members, as active hunters, trappers and fishers who frequently operate on the sea ice during the hunting & fishing seasons, possess unmatched expertise in navigating and understanding the ecology of the region and how the ice behaves under varying conditions. They are, in many ways, on the front lines of climate change adaptation within their

communities. Each time we seek permission to conduct research, we engage in detailed discussions with EHTO representatives about our plans and share results from previous research periods. Their feedback is integral, and we work collaboratively to refine ideas and methodologies. This process has been followed consistently over the past two years in Cambridge Bay, and again in the current field season. EHTO has played a significant role in shaping experiment design—including in the selection of research sites—drawing on local ecological understanding, wildlife patterns, hunting routes, ice conditions and history and local geography. During our January 2024 field test, limited consultation with EHTO led to the selection of a site that proved too shallow and near the coast, compromising the success of the trial—an outcome that reinforced the value of their involvement. Site selection encompasses layers of local and traditional knowledge, from wildlife movement patterns, safety aspects, shipping routes, snowmobile pathways, availability of nearby land trails, hunting, fishing and other economic or recreational activities in the area. In-depth discussions with EHTO during the 2024 spring about our specific research requirements led to an improved site selection for the 2024/25 winter that incorporated aspects such as travel times for optimal daylight pumping time during the key research months, distance from shore for reduced boundary effects, minimum sea depth for more realistic water temperature patterns, and ability to fly an aerial drone from shore over the selected site during the melt season.

At the beginning of the 2024/25 ice thickening tests, we discovered that we didn't have enough of a key tool used for our pumping sessions to stop the backflow of water after pumping: the "cofferdams". After discussing the issue with a local EHTO member, the secondary school carpentry lab came to support our activities by producing a number of additional wooden cofferdams that allowed us to continue our operations as planned over the following months giving us the opportunity to interact with the next generation of hunters and trappers.

Several Inuit members of the Cambridge Bay EHTO are also acknowledged as named contributors to the Real Ice and University of Washington academic paper scheduled for pre-print publication in December 2025, as they actively contributed to research aspects such as setting up test areas, taking ice and snow measurements and running aerial drone surveys.

An evolving partnership with the Canadian High Arctic Research Station (CHARS) has led to opportunities for Real Ice to present at open community evenings and participate in knowledge exchange with elder hunters and trappers, reinforcing Indigenous expertise as essential to responsible research.

Youth engagement is also a growing priority: at Kiilinik High School, engineering demonstrations, collaboration on sled building for field tests, classroom visits, and joint presentations with Real Ice scientific collaborators and local partners have built student awareness of and interest in the research (Protocol 4).

The project's collaborative approach has drawn international attention, with media and documentary crews visiting Cambridge Bay to document the science and local reactions to climate-driven sea ice changes. This exposure has amplified Inuit voices in discussions about the region's environmental challenges and underscores the broader impact of meaningful, community-led research engagement: [The Narwhal: July 2025](#)

Engagement Diary

[A montage of photos showing Real Ice meeting community members and key stakeholders, which has been redacted. The image showed a timeline of engagement and meetings from 2022 to 2025].

Community Engagement Q&A

The following are questions that we have been asked during some of the engagement events we organised.

Stakeholder Group	Examples of Stakeholder Questions	Type of Engagement	Real Ice Responses
EHTO	<i>How long before this could be rolled out to help save the hunting routes - caribou are disappearing through the thin ice</i>	<i>Board meeting</i>	<i>We are only in research mode at the moment. We hope that positive research results may lead to a larger-scale test, but it would be years before any potential rollout that would help mitigate the effects of thinner ice between Victoria Island and the mainland, so that fewer caribou are lost.</i>
Mayor & The Council	<i>Do you intend to run your research for multiple years</i>	<i>Formal update at the council chamber</i>	<i>Yes, as part of the Climate Cooling program, we have a 3-year research plan, which we intend to carry on in Cambridge Bay, in collaboration with the local community</i>
Elders	<i>How thin is the ice this year?</i>	<i>Listening meeting at Heritage Society</i>	<i>We explained that we were seeing a maximum of 1.8m. They were shocked and explained that when they were younger, the ice was 9ft thick in the bay.</i>
Wider Community Members	<i>Is the new ice that you create strong?</i>	<i>Informal open community meeting at Elders Palace</i>	<i>The new ice from flooding is on the surface of the ice stack, and it was about 30cm thick last winter. This sits on top of the existing 1.5m of ice that was created naturally, from the bottom. We don't know whether the top stack is stronger or weaker than the ice at the bottom, but in principle, we want to test the idea that thicker ice should survive longer during the summer, which would hopefully benefit communities and wildlife.</i>

CHARS	<i>How long is it taking for the ponds to turn into hard new ice.</i>	<i>Part of daily operations discussion</i>	<i>We explained that in typical cases it takes 12-48 hours for the water to freeze, and this depends on weather conditions and the depth of the pond. As an example, with temperatures in the -30C range and ponds around 10-15cm deep (very typical in our experience), we usually see a full freeze in under 24 hours.</i> <i>We also explained an edge condition where, in early December 2024, when the sea ice was only around 40cm thick, we observed some bending of the sea ice layer under the weight of the pumped water. This created deeper ponds, which took around 48 hours to freeze completely.</i> <i>This opened up a conversation about how much later the freezing of the sea was observed over the last couple of years and how this delay had created issues at the start of our testing operations. For this reason, we have changed our plans for next winter to only start ice thickening in January. {please see section at the bottom of this table for tracker}</i>

Local secondary school	<i>If there are seal breathing holes in the area you are covering, will you block them?</i>	<i>Field demo to students</i>	<i>We don't believe so, because the water we pump would flow back into the sea if there was a hole in the ice, and it would not block it, but it is something we will keep in mind in our research. We constantly monitor our pumping activities and the test area, and we will check and consult with our guides if we observe any seal breathing holes. The test area was selected with the help of HTO in a place where seal activity in the winter hasn't been observed for many years. {please see section at the bottom of this table for tracker}</i>

Local secondary school	<i>Will you drain all the water of the bay if you keep pumping sea water on top of the ice?</i>	<i>Field demo to students</i>	<i>In the specific tests we are conducting we are covering a very small area and pumping a tiny amount of water, when compared with the sea water under the sea ice. If and when this method was scaled to larger areas, a way to think about this, is that we would pump enough water to recreate the ice thickness that already existed a few decades ago - in practice we would pump perhaps 1 or 2 ft of sea water on top of ice, where we have hundreds if not thousands of ft of sea water underneath. {please see section at the bottom of this table for tracker}</i>

Community hypotheses tracker for 2026 testing

The following are questions from stakeholders that Real Ice will actively track and report on to the community for additional feedback:

1. Does the thicker ice created by pumping last longer in the summer?
2. Is the new ice that we create strong?
3. How long does it take for ponds to freeze?
4. Are there seal holes in the bay? Are seals using the newly drilled holes?

Free, Prior and Informed Consent

In Nunavut, we engage fully with the formal annual renewal process through the Nunavut Planning Commission (NPC), the Nunavut Impact Review Board (NIRB), and the Nunavut Research Institute (NRI). This process ensures that our work in Cambridge Bay aligns with the regulatory frameworks respected by both local and territorial authorities, providing the community with confidence that our activities meet the appropriate Nunavut research standards.

Within the hamlet, community-level consent and support are expressed primarily through the elected leadership—namely, the Mayor, Council, HTO, and Elders. We maintain ongoing engagement with these representatives throughout the year, particularly in winter and spring, through regular formal and informal meetings and updates. These engagements allow us to explain research objectives, share results, answer questions, and listen to guidance or concerns.

Each year, as part of the formal approval and reporting cycle, the following federal, territorial, and local organisations receive copies of our NRI annual report and associated permits:

- NIRB Environmental Administrator
- NPC Senior Planner

- Kitikmeot Inuit Association (KitIA) Lands Department
- CIRNAC Lands Department (Crown-Indigenous Relations and Northern Affairs Canada)
- Mayor and Senior Administrative Officer, Cambridge Bay
- Chairperson, Cambridge Bay Hunters and Trappers Organisation (HTO)
- Nunavut Tunngavik Incorporated (NTI) Department of Research, Monitoring & Evaluation
- Nunavut Climate Change Centre

These bodies provide the foundational permissions for research activities conducted outdoors in and around Cambridge Bay.

Process of Consent and Community Engagement

Our approach to FPIC in Cambridge Bay emphasises openness, accessibility, and continuous relationship-building rather than one-time written consent. We communicate our project plans and findings through in-person community meetings, both formal and informal. For example:

- Public forums and town hall-style discussions are held at the Elders Palace and the Canadian High Arctic Research Station (CHARS). Notices are posted in public spaces, such as at the two supermarkets and in community spaces, and shared on social media to ensure broad awareness.
- Engagement through traditional leadership—the Elders, Mayor, and HTO representatives—ensures that our activities are reviewed and discussed with those most trusted by the community to represent collective interests.
- Indicators of consent are evidenced through continued participation, verbal support during meetings, and community collaboration—for instance, sharing local knowledge, providing logistical support, attending our presentations, and inviting us to participate in community events.

Consent, in this context, functions as an ongoing relationship of trust. While formal approval is renewed annually through NRI and related bodies, community permission is reaffirmed through regular, transparent engagement and dialogue with experts in the community, particularly the hunters and trappers - who are the holders of traditional knowledge of the sea ice ecosystem and the community's adaptation to reduced/delayed/thinner sea ice. Should concerns arise, the hamlet leadership or HTO could communicate these directly to us or withdraw their endorsement through established local channels, at which point research would be paused pending further discussion and resolution.

Our approach was strongly informed by early experiences in Nome, Alaska, where community members emphasised the fatigue caused by extractive research practices. We are mindful of these lessons and strive to ensure that participation in Cambridge Bay is voluntary, respectful, and grounded in local priorities.

Sustainability and Renewal of Consent

Community consent is sustained through our commitment to returning each year, sharing results, and involving local hunters and Elders in the ongoing development of the ice-thickening research. The recurring invitation to continue our work, along with tangible support from residents—such as assistance during fieldwork and warm hospitality—indicates active, informed acceptance.

We are currently developing an internal process to formalise how withdrawn consent would be recognised and addressed, ensuring that both formal permit structures and community-derived permissions remain aligned and respected. Our goal is to ensure that research in Cambridge Bay continues to advance scientific understanding while strengthening mutual trust and

collaboration with the community.

Feedback Loops

Our sustained presence in Cambridge Bay—where we maintain a multi-month base each ice season—enables regular, often daily, formal and informal dialogue with hunters, trappers, guides, Elders, teachers, and other residents. This constant presence and the active involvement of community members in our operations help us remain responsive to the community's evolving insights and needs throughout each research season.

Community Interaction and Feedback Mechanisms

Engagement occurs through multiple channels designed to support a continuous feedback loop:

- Public forums and information sessions: We hold open Q&A sessions at community halls and the Canadian High Arctic Research Station (CHARS), where residents can discuss the research, raise concerns, or offer suggestions.
- Governance meetings: We participate in briefings with the Hunters and Trappers Organisation (EHTO) Board, the local Council, and other community leadership bodies to update them and formally collect their input on the design and execution of tests.
- Day-to-day informal exchanges: Because our researchers live within the community, we are readily available in everyday settings—at the café, shops, or local offices—which encourages casual conversations that often yield valuable feedback.
- School engagement: Our team and visiting scientists conduct demonstrations and presentations for students, creating an open space for younger community members and educators to ask questions and share perspectives.
- Active involvement of community members in our research: local guides, technical operators and a number of local companies take part in our operations, from managing the logistics (receiving, storing, fixing, transporting, lending our equipment), to actively enabling and participating in daily ice thickening and measurement operations, helping us build and deploy field equipment (e.g. cofferdams, sleds, measurement tools) and driving the safety and rescue operations within CHARS and EHTO.

This embedded, responsive structure fosters trust and ensures a transparent two-way communication flow, allowing feedback to immediately inform adjustments to our operations.

Community Collaboration in Research Design

The selection of the 2024/25 research site in Cambridge Bay was a collaborative effort between members of the EHTO and our field team. Together, they identified a location that balanced Real Ice's research objectives with community priorities by ensuring:

- No interference with hunters' regular transit routes,
- Reasonable proximity to the hamlet,
- Adequate water depth for research accuracy, and
- Maintain a distance from the coastline to minimise disruption during the spring melt.

Structured and Responsive Feedback Loops

- EHTO Daily Collaboration: Hunters and guides from the EHTO work alongside our team each day, advising on weather, ice conditions, and local best practices. Their input

repeatedly shapes our day-to-day methods and data collection.

- EHTO Formal Meetings: In February 2025, our team was invited to present at an EHTO evening board meeting—an important sign of trust and community endorsement. We shared progress updates and fielded direct questions from board members. We will return in October 2025 to present our 2024/25 results and seek guidance and approval for the 2026 research season.
- Mayor and Council Engagement: Between February and June 2025, we held three direct meetings with the Mayor and Council, including a formal presentation in the council chamber. In these sessions, we shared interim findings, discussed long-term plans, and invited feedback. We will return in October 2025 to present the full results and collect any formal feedback or recommendations.

Ongoing Feedback and Responsive Action

Feedback operates as a circular and renewable process:

- Immediate comments or concerns raised during fieldwork or public meetings are addressed directly by the research leads in Cambridge Bay.
- Formal updates are provided at fixed intervals (winter, spring, and post-season) to all key bodies, including EHTO and the Hamlet Council.
- Adjustments to our research methods or sites are discussed publicly, ensuring transparency and reaffirming local consent.
- If substantial concerns were raised, the same local channels—EHTO, Mayor, or Council—would serve as the formal routes for dialogue and potential recalibration of our activities.

This multi-layered feedback loop—daily, seasonal, and annual—ensures that our work remains community-driven, inclusive, and adaptive to local perspectives.

Contributions to the local economy in Cambridge Bay

Employment

Real Ice contracted with EHTO for four Inuit research participants. These Inuit acted as guides and as collaborators/research participants for the daily operations out on the ice. During the melt season, these Inuit research participants assisted us with monitoring and measuring the ice thickness.

Equipment & Facilities: We rented vehicles for the extended periods of the winter and spring (trucks, snowmobiles and an ATV) from local outfitters. We rented a venue (The Elders Palace in Cambridge Bay) twice to host our community consultations. We used the local hardware shop (Kitikmeot Supplies) for equipment purchases.

Travel and Food: Over the course of winter & spring 2024/25, 23 individuals travelled to Cambridge Bay to participate in the Real Ice field study, including scientists from the University of Cambridge, the University of Washington, Arizona State University and the University of Oslo. In addition, 3 film crews and 2 journalists made the journey to Cambridge Bay to spend time

with the project and with the local community. We shopped in the local supermarkets and ate at the local cafe throughout our stays.

Economics Summary

In total, the Real Ice T2 & T3 projects have resulted in spending of over C\$250,000 on services and supplies in Cambridge Bay, the majority of which was spent during the winter months when tourism and visitor numbers are at their lowest in the hamlet.

Progress with Community Engagement:

Winter 2025/26

Permissioning Status for research period Jan 2026 - Jul 2026 (T4)

Approvals required: 4

Approvals secured up to 20 November 2025: 4

15 August 2025 Nunavut Planning Commission

3rd year of the multi-year **license confirmed** {ends Dec 2026}

File # 150891, Associated NIRB File No.: 23YN044

27 August 2025 Nunavut Research Institute

3rd year of the multi-year **license confirmed** {ends Dec 2026}

License#: 04 001 26R-M

04 September 2025: Canadian High Arctic Research Station

3-year research support **agreement signed** {2026-2028}

6th November 2025: EHTO support letter **signed** covering the period (Jan-Jun 2026)

POLAR Knowledge/ CHARS research support & collaboration

In 2024 and 2025, Real Ice's research activities benefited from both in-kind and direct financial support from the Canadian High Arctic Research Station (CHARS), including accommodations, laboratory access, and fees for local guides. However, due to recent budget constraints within POLAR Knowledge Canada, CHARS will no longer be able to provide such support moving forward. Consequently, Real Ice will transition to covering costs independently, paying negotiated fees for CHARS accommodation and workshop access each winter, and engaging local guides through direct contracts with the Ekaluktutiak Hunters and Trappers Organisation (EHTO).

A three-year research support partnership, established through a negotiated agreement in September 2025 with POLAR/CHARS, now secures Real Ice access to CHARS facilities for the duration of the RASI field test program without the need to reapply annually. This agreement also promotes multi-year collaboration opportunities with other POLAR programs. It provides discounted rates for essential equipment, such as snowmobiles, further supporting the continuity and effectiveness of Real Ice's Arctic research operations.

Community Engagement Plans Winter 2025/6

Building on the trust relationships developed with local hunters and trappers, Indigenous leaders, and Elders, Real Ice will prioritise several core components of community engagement in the coming year:

Recognition of Indigenous Knowledge (Protocol 2).

Traditional knowledge is fundamental to the preservation of sea ice ecosystems. Real Ice will collaborate closely with EHTO and other community members throughout the winter and spring, drawing on their expertise to both guide operations safely across the ice and actively participate in ice thickening research design & operations. By foregrounding the contributions of Indigenous knowledge holders, the research aims to deepen understanding of local ecological dynamics and ensure that the value of traditional perspectives is made explicit within project outcomes.

Continued Elder Engagement (Protocol 2).

Regular briefings for Elders at the Heritage Centre will continue, reaffirming the project's commitment to inclusive participation and the transmission of knowledge across generations. These briefings, which have been very well received, provide an essential forum for sharing findings, gaining guidance, and honouring the perspectives of community Elders.

Communication with Intent (Protocol 4).

A series of public meetings will be held in Cambridge Bay's community spaces and with the hamlet's civil leadership to present findings from the previous year's study and to facilitate open discussion about ongoing research. These sessions will be documented to capture feedback, questions, and insights from community members and leaders, ensuring that the project remains transparent and responsive to local input. We will not collect data outside of the direct scope of the Real Ice project.

Building Meaningful Partnerships (Protocol 6).

Real Ice seeks to strengthen existing collaborations by contracting directly with EHTO as full research team members and guides for the coming winter. Through these embedded research team members from EHTO, we seek to enhance partnership both individually and collectively with those who serve as stewards of Inuit hunting traditions. Additionally, Real Ice has commissioned, from one of the members of EHTO, three custom sleds to be built for field operations this coming winter. These were co-designed with this team member. Further, the partnership with Kiilinik High School will be deepened through outreach activities such as an art competition, site visits, and presentations by visiting scientists.

Planned Activities

Real Ice has a track record of holding multiple community events in Cambridge Bay each winter & spring. **We are committed to holding a similar number of events in 2026.**

Project

Date	Individual/ Group	Real Ice contributors	Topic	Targeted Outcome	Protocol
Oct-Dec' 25	[Name redacted]	Arctic Operations	Sled design	Collaborative design for sleds for winter '26 research	1,2,6,8
Nov '25	EHTO	Simon Woods & remote support where feasible	Briefing Q&A on '24/'25 results	Provide copy of the results of last winter's testing. Respond to questions. Document Q&A {Completed}	1,2,6
Nov '25	EHTO	Simon Woods & remote support where feasible	Briefing & discussion on '26 plan	Solicit feedback on coming winter's technical and engagement plan. Document Q&A. {Completed} Discuss and agree terms for team participation of EHTO members {Completed}	1,2,3,6,8
Jan-Jun' 26	EHTO	On site team	Continuous learning	Daily collaboration out on the ice with EHTO members as fully participating team members bringing their traditional knowledge to the research, in addition to guiding the team across the ice.	1,2,3,4,5,6

Wider Community in Cambridge Bay

Date	Individual/ Group	Real Ice contributors	Topic	Targeted Outcome	Protocol
Nov '25	Mayor of Cambridge Bay	Simon Woods	Briefing on R&D and community engagement plans for '26	Solicit feedback on coming winter's engagement plans. Document Q&A {Completed}	1,2,3,4,5,6
Jan '26	Community at Large	On site teams	Community Feedback at Elders Palace	Present the project and its history in Cambridge Bay. Ask our indigenous partners to be part of those presentations. Solicit Q&A both in the meeting and in the informal gathering around tea & cake afterwards	1,2,3,4,5,7
Feb '26	School Students	On site teams	Youth understanding of the Real Ice research	Hold an art competition to portray the Real Ice research at the Secondary School with art supplies prizes for the school and the student.	1,4,6

Feb '26	Mayor, council members and community at large	On site teams	Information on the research captured as audio	Audio interviews/discussion when members of the Council and the Mayor visit the Real Ice research site. Package up in podcast format. The Mayor has agreed to broadcast these materials on the local radio.	1,2,4,6
Mar '26	Community at Large	On site teams	Community Feedback at Elders Palace	Present the project with an update on progress for winter '26. Recap the history of the project in Cambridge Bay. Ask our indigenous partners to be part of those presentations. Solicit Q&A both in the meeting and in the informal gathering around tea & cake afterwards	1,2,3,4,5,7
Jan - Jun '26	Secondary School Students	On site teams	Presentations by visiting scientists	Scientists joining the Real Ice research present their areas of expertise/interest to classes at the Secondary School and answer questions from the children.	1,4,6

Unfunded But Potentially Impactful Additional Scope

Date	Individual/ Group	Real Ice contributors	Topic	Targeted Outcome	Protocol
Jan - Jun '26	Cambridge Bay Elders and EHTO	On site teams + professional videographers	Ice history	Continue to document the history of the sea ice in Cambridge Bay as told on video by the Elders, at the Heritage Center. The documentary to be owned by the community. Take additional footage of the Real Ice work in order to produce a short documentary explaining the research, the rationale behind the research and the collaboration with the local community that makes it possible.	1,2,6

Next Steps and Gaps

While Real Ice has demonstrated positive intent and compliance with Inuit engagement protocols, gaps remain in co-development, data sharing and ownership, Inuit-led governance, and long-term capacity-building.

We place the highest priority on adhering to formal permitting requirements together with consistent alignment of our engagement activities with the principles outlined in the Protocol. Our approach has been grounded in grassroots collaboration, built through direct dialogue with local communities, fostering partnerships, and conducting work jointly.

We commit to keeping the ARIA team updated on project level engagement planning, activities, inputs and feedback.

Looking ahead, we recognise the need to deepen engagement with senior levels of Inuit and Canadian national institutions to advance the broader guiding protocols for this type of research in Canada, which will become increasingly significant as we operate within the ARIA/RASi program framework. We request that ARIA engage with organisations such as ECCC, ICC and ITK through its British Government connections.

Additional resources would strengthen our capacity to employ Inuit advisors, translators, and trainers, while also providing essential support for governance structures and monitoring mechanisms. ARIA's facilitation with both national and supra-national Inuit organisations would further enable alignment with all eight protocols, ensuring that future work is genuinely Inuit-led and co-developed.

APPENDIX A

Research Permitting Organisations for Cambridge Bay, Nunavut

- **Nunavut Planning Commission (NPC)**

The NPC is responsible for the development, implementation and monitoring of land use plans that guide and direct resource use and development in the Nunavut Settlement Area.

- **Nunavut Impact Review Board (NIRB)**

The Nunavut Impact Review Board (NIRB) is an institution of public government created by the Nunavut Agreement (NA) to assess the potential impacts of proposed development in the Nunavut Settlement Area prior to approval of the required project authorisations. Using both traditional knowledge and recognised scientific methods, the NIRB assesses the potential biophysical and socio-economic impact of proposals and will make recommendations and decisions about which projects may proceed. The Board may also establish monitoring programs for projects that have been assessed and approved to proceed.

- **Nunavut Research Institute (NRI)**

The Nunavut Research Institute is a Division of Nunavut Arctic College (NAC) and is responsible for administering the Scientists Act, which applies across the entire territory of Nunavut. The Act requires that anyone conducting research in the health, social sciences, or natural/physical sciences disciplines must first obtain a license from the NRI.

- **Ekaluktutiak Hunters and Trappers Organisation (EHTO)**

The EHTO manages sustainable harvesting, oversees wildlife management, and creates economic development opportunities. It primarily focuses on regulating hunting and trapping practices to ensure the long-term health of wildlife and benefit the local Cambridge Bay Inuit community. HTOs are non-government organisations that play a crucial role in representing Nunavut Inuit residents in these areas.

- **Polar Knowledge, Canadian High Arctic Research Station (CHARS)** A state-of-the-art research facility located in the vibrant Canadian Arctic community of Cambridge Bay, Nunavut. The Canadian High Arctic Research Station (CHARS) operated by Polar Knowledge Canada, has been designed and built to optimise innovation in Arctic science and technology, to welcome visitors, and to provide researchers with the accommodation and technical services they need. It's an innovative facility that can support a wide range of research needs – from ecosystem monitoring to DNA analysis – and where Indigenous Knowledge is recognised as fundamentally necessary to the co-creation of new knowledge.



SCREENING DECISION REPORT NIRB FILE No.: 23YN044

NPC File No.: 150112

October 31, 2023

Following the Nunavut Impact Review Board's (NIRB or Board) assessment of all materials provided, the NIRB is recommending that a review of the screen Real Ice Development Company Limited's (Real Ice) "Real Ice-November Field Test in Cambridge Bay, Canada" is not required pursuant to Article 12, Section 12.4.4(a) of the *Agreement between the Inuit of the Nunavut Settlement Area and Her Majesty the Queen in right of Canada (Nunavut Agreement)* and s. 92(1)(a) of the *Nunavut Planning and Project Assessment Act*, S.C. 2013, c. 14, s. 2 (*NuPPAA*).

Subject to the Proponent's compliance with the terms and conditions as set out in below, the NIRB is of the view that the project proposal is not likely to cause significant public concerns, and it is unlikely to result in significant adverse environmental and social impacts. The NIRB therefore recommends that the responsible Minister accepts this Screening Decision Report.

OUTLINE OF SCREENING DECISION REPORT

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The primary objectives of the NIRB are set out in Article 12, Section 12.2.5 of the *Nunavut Agreement* and are confirmed by s. 23 of the *NuPPAA*:

Nunavut Agreement, Article 12, Section 12.2.5: In carrying out its functions, the primary objectives of NIRB shall be, at all times to protect and promote the existing and future well-being of the residents and communities of the Nunavut Settlement Area, and to protect the ecosystemic integrity of the Nunavut Settlement Area. NIRB shall take into account the well-being of the residents of Canada outside the Nunavut Settlement Area.

The purpose of screening is provided for under Article 12, Section 12.4.1 of the *Nunavut Agreement* and s. 88 of the *NuPPAA* which states:

NuPPAA, s. 88: The purpose of screening a project is to determine whether the project has the potential to result in significant ecosystemic or socio-economic impacts and, accordingly, whether it requires a review by the Board...

To determine whether a review of a project is required, the NIRB is guided by the considerations as set out under Article 12, Section 12.4.2(a) and (b) of the *Nunavut Agreement* and s. 89(1) of *NuPPAA* which states:

NuPPAA, s. 89(1): The Board must be guided by the following considerations when it is called on to determine, on the completion of a screening, whether a review of the project is required:

- (a) a review is required if, in the Board's opinion,
 - i. the project may have significant adverse ecosystemic or socio-economic impacts or significant adverse impacts on wildlife habitat or Inuit harvest activities,
 - ii. the project will cause significant public concern, or
 - iii. the project involves technological innovations, the effects of which are unknown; and
- (b) a review is not required if, in the Board's opinion,
 - i. the project is unlikely to cause significant public concern, and
 - ii. its adverse ecosystemic and socioeconomic impacts are unlikely to be significant or are highly predictable and can be adequately mitigated by known technologies.

It is noted that under Article 12, Section 12.4.2(c) and s. 89(2) of the *NuPPAA* that the considerations set out in s.89(1)(a) prevail over the considerations set out in s. 89(1)(b) of the *NuPPAA*.

As set out under Article 12, Section 12.4.4 of the *Nunavut Agreement* and s. 92(1) of the *NuPPAA*, upon conclusion of the screening process, the Board must provide its written report to the Minister. The contents of the NIRB's report are specified under *NuPPAA*:

NuPPAA, s. 92(1): The Board must submit a written report to the responsible Minister containing a description of the project that specifies its scope and indicating that:

- (a) a review of the project is not required;
- (b) a review of the project is required; or
- (c) the project should be modified or abandoned.

Where the NIRB determines that a project may be carried out without a review, the NIRB has the discretion to recommend specific terms and conditions to be attached to any approval of the project proposal pursuant to paragraph 92(2)(a) of *NuPPAA* as follows:

NuPPAA, s. 92(2) In its report, the Board may also

- (a) recommend specific terms and conditions to apply in respect of a project that it determines may be carried out without a review.

PROJECT OVERVIEW & THE NIRB ASSESSMENT PROCESS

1. Project Referral

On July 5, 2023, the NIRB received a referral to screen Real Ice Development Company Limited's (Real Ice) "Real Ice-November Field Test in Cambridge Bay, Canada" project proposal from the Nunavut Planning Commission (Commission), which noted that the project proposal is outside the area of an applicable regional land use plan. Pursuant to Article 12, Sections 12.4.1 and 12.4.4 of the *Nunavut Agreement* and s. 87 of the *NuPPAA*, the NIRB commenced screening this project proposal and assigned it file number **23YN044**.

All documents received and pertaining to this project proposal can be accessed from the NIRB's online Public Registry at www.nirb.ca/project/125838.

2. Screening Process Timelines

The following key stages were completed for the screening process:

Date	Stage
July 5, 2023	Receipt of project proposal and referral from the Commission.
July 5, 2023	Request to complete public registry online and provide information pursuant to s. 144(1) of the <i>NuPPAA</i>
September 14, 2023	Receipt of online application from Proponent
September 23, 2023	Scoping pursuant to s. 86(1) of the <i>NuPPAA</i>
October 13, 2023	Public engagement and comment request
October 24, 2023	Receipt of public comments
October 31, 2023	Issuance of Screening Decision Report

3. Project Scope

Project:	Real Ice-November Field Test in Cambridge Bay, Canada				
Region:	Kitikmeot				
Location:	Cambridge Bay				
Closest Community:	Cambridge Bay	Distance (approximate)	Within 10 kilometres (km)	Direction	South
Summary of Project Description:	The Proponent intends to pump ocean water on top of forming ice to determine if this will increase ice formation.				
Project Proposed Timeline:	November 2023				

As required under s. 86(1) of the *NuPPAA*, the Board accepts the scope of the project as set out by the Real Ice in the proposal. The scope of the project proposal includes the following undertakings, works, or activities:

- Use of a hydrogen fuel cell powered pump to pump seawater on top of sea ice over an area of approximately 1 hectare;
- Monitoring of ice thickness; and
- Use of snowmobiles to access test site

4. Inclusion or Exclusion to Scoping List

The NIRB has identified no additional works or activities in relation to the project proposal. As a result, the NIRB proceeded with screening the project based on the scope as described above.

5. Public Comments and Concerns

Notice regarding the NIRB's screening of this project proposal was distributed on October 13, 2023, to community organizations in Cambridge Bay, as well as to relevant federal and territorial government agencies, Inuit organizations, and other parties. The NIRB requested that interested parties review the proposal and the NIRB's proposed project-specific terms and conditions, and provide the Board with any comments or concerns by October 23, 2023, regarding:

- Whether the project proposal is likely to arouse significant public concern; and if so, why;
- Whether the project proposal is likely to cause significant adverse eco-systemic or socio-economic effects; and if so, why;
- Whether the project proposal is likely to cause significant adverse impacts on wildlife habitat or Inuit harvest activities; and if so, why;
- Whether the project proposal is of a type where the potential adverse effects are highly predictable and mitigable with known technology, (and providing any recommended mitigation measures); and
- Any matter of importance to the Party related to the project proposal.

On or before October 24, 2023, the NIRB received comments from the following interested parties:

- **Crown-Indigenous Relations and Northern Affairs Canada**
- **Transport Canada**

a. Summary of Public Comments and Concerns Received during the Public comment period of this file.

The following provides a summary of the comments and concerns received by the NIRB:

- **Crown-Indigenous Relations and Northern Affairs Canada**
 - Recommended standard terms and conditions regarding refueling of snowmobiles.
 - Recommended standard terms and conditions regarding consultation.
 - Recommended Proponent clarify potential impacts on water quality.
 - Recommended Proponent provide further information on hydrogen fuel used by the pump.
- **Transport Canada**
 - No comments.

b. Comments and Concerns with respect to Inuit Qaujimaningit and Traditional and Community Knowledge

No concerns or comments were received with respect to Inuit Qaujimaningit and traditional and community knowledge in relation to the proposed project. However, Inuit Qaujimaningit and traditional and community knowledge is incorporated into the terms and conditions recommended below based on information collected from prior and similar projects, data collected and mapped by the Commission, and other available sources.

ASSESSMENT OF THE PROJECT PROPOSAL IN ACCORDANCE WITH PART 3 OF NUPPAA

In deciding whether a review of the project is required, the Board considered whether the project proposal may result in significant ecosystemic or social impacts. As per s. 90 of the NuPPAA, the Board completed its assessment and determined significance of impacts considering Inuit Qaujimaningit as well as traditional and community knowledge.

The following is a summary of the Board's assessment of the factors that inform the determination of significant impacts with respect of this project proposal:

Factor	Comment
The size of the geographic area, including the size of wildlife habitats, likely to be affected by the impacts.	▪ The physical footprint of the proposed project components will cover approximately 1 hectare on the sea ice within 20 kilometers of Cambridge Bay. ▪ The proposed project would take place within habitats of far-ranging wildlife species such as migratory and non-migratory birds, Arctic fox, Arctic hare and Species at Risk.

Factor	Comment
The ecosystemic sensitivity of that area.	No specific areas of ecosystemic sensitivity have been identified by the Proponent within the physical footprint of the proposed project.
The historical, cultural and archaeological significance of that area.	No specific areas of historical, cultural and archaeological significance have been identified by the Proponent within the physical footprint of the proposed project. As the project activities will be carried out on the sea ice, impacts are highly unlikely.
The size of the human and the animal populations likely to be affected by the impacts.	The proposed project is unlikely to result in impacts to local human and animal populations.
The nature, magnitude and complexity of the impacts; the probability of the impacts occurring; the frequency and duration of the impacts; and the reversibility or irreversibility of the impacts.	- A zone of influence of up to 10 km from the most potentially disruptive project activities was selected for the NIRB's assessment. - With adherence to the relevant regulatory requirements and application of the mitigation measures recommended by the NIRB, no significant residual effects are expected to occur.
The cumulative impacts that could result from the impacts of the project combined with those of any other project that has been carried out, is being carried out or is likely to be carried out.	The NIRB has not identified any past, present, and reasonably foreseeable projects at this time; however, the mitigation measures recommended by the NIRB have been designed to reduce cumulative effects should projects occur in the area in the future.
Any other factor that the Board considers relevant to the assessment of the significance of impacts.	No other relevant factors were identified.

Views of the Board

Based on the information in the previous section, the NIRB has identified several concerns and provides the following views about whether or not the proposed project may result in significant impacts. Additionally, the NIRB proposes terms and conditions that would mitigate the potential adverse impacts identified.

The NIRB has also listed specific Acts and Regulations that may be applicable to the project proposal, but these should not be considered as a complete list and the Proponent is responsible to ensure that it follows all Acts and Regulations that may be applicable to the project proposal.

Ecosystem, wildlife habitat and Inuit harvesting activities:

Valued Component	Wildlife such as caribou, muskox, migratory and non-migratory birds, Arctic fox, Arctic hare and Species at Risk.
Potential effects:	Potential adverse effects to muskox, migratory and non-migratory birds, Arctic fox, Arctic hare and Species at Risk from noise and visual disturbance generated from the daily transportation of personnel via snowmobile to the proposed research sites, research activities, and use of drones.
Nature of Impacts:	The probability of impacts occurring is considered to be low in magnitude, infrequent in occurrence, and reversible.
Mitigating Factors:	The proposed project is located on sea ice in the vicinity of Cambridge Bay with minimal physical footprint in areas regularly travelled by residents. Therefore, the proposed project is unlikely to result in impacts on local human and animal populations.
Proposed Terms and Conditions:	Water Courses/Water Bodies – 6 and 7 Waste Management – 8 and 9 Wildlife General – 18 through 20 Caribou and Muskoxen Disturbance – 21 through 23 Land Use and Restoration of Disturbed Areas – 25 through 29
Related Acts and/or Regulations:	1. The <i>Species at Risk Act</i> (http://laws-lois.justice.gc.ca/eng/acts/S-15.3/index.html). Attached in Appendix A is a list of Species at Risk in Nunavut. 2. The <i>Wildlife Act (Nunavut)</i> and its corresponding regulations (http://www.canlii.org/en/nu/laws/stat/snu-2003-c-26/latest/snu-2003-c-26.html).

Valued Component	Potential negative impacts to water quality
Potential effects:	There is potential for negative impacts to water quality due to snowmobile travel and research activities carried out on the sea ice.
Nature of Impacts:	The probability of impacts occurring is considered to be low in magnitude, infrequent in occurrence, and reversible.
Mitigating Factors:	The proposed project is located in the vicinity of Cambridge Bay with minimal activities and physical footprint in areas regularly travelled by residents. The water pumping activities are unlikely to have long-term negative effects.
Proposed Terms and Conditions:	Water Courses/Water Bodies – 6 and 7 Waste Management: 8 and 9 Fuel and Chemical Storage: 10 through 17
Related Acts and/or Regulations:	The <i>Nunavut Act</i> (http://laws-lois.justice.gc.ca/eng/acts/N-28.6/).

Valued Component	Potential adverse affects to public and traditional land use activities in the area from the research activities.
Potential effects:	No specific concerns or impacts to public and traditional land use activities in the area have been identified, however, the Board is

	recommending terms and conditions to ensure project activities are informed by available Inuit Qaujimaningit and that project activities do not interfere with Inuit wildlife harvesting or traditional land use activities.
Nature of Impacts:	
Mitigating Factors:	The proposed project is located in the vicinity of Cambridge Bay with minimal activities and physical footprint. Therefore, the proposed project is unlikely to result in impacts on local human and animal populations.
Proposed Terms and Conditions:	Other: 30 and 31
Related Acts and/or Regulations:	1. The <i>Nunavut Act</i> (http://laws-lois.justice.gc.ca/eng/acts/N-28.6/).

Socio-economic effects on northerners:

Valued Component	Local Economic Benefits
Potential effects:	The Proponent will be based out of Cambridge Bay and may provide positive economic effects through local purchasing, hiring locals, and use of accommodations.
Nature of Impacts:	The potential for impacts is considered positive to Cambridge Bay.
Mitigating Factors:	N/A
Proposed Terms and Conditions:	Other – 32
Related Acts and/or Regulations:	N/A

Significant public concern:

Valued Component	Public concern
Potential effects:	No significant public concern was expressed during the public commenting period for this file; however, the Board is recommending terms and conditions to ensure that to the extent possible hire local people and access local services where possible, and to ensure planned activities in the area utilizes available Inuit Qaujimaningit.
Nature of Impacts:	The potential for impacts is considered to be minimal as long as the Proponent follow the recommended terms and conditions.
Mitigating Factors:	Recommended terms and conditions
Proposed Terms and Conditions:	Other – 30 and 31
Related Acts and/or Regulations:	N/A

Technological innovations for which the effects are unknown:

- No specific issues have been identified associated with this project proposal.

Administrative Conditions:

Responsible authorities or the Proponent shall notify the Nunavut Planning Commission and the NIRB of any changes in operating plans or conditions, including phase advancement, associated with this project prior to any such change.

To encourage compliance with applicable regulatory requirements and assist the Board and responsible authorities with compliance and effects monitoring for project activities, the following project-specific terms and conditions have been recommended: 1-5.

In considering the above factors and subject to the Proponent's compliance with the terms and conditions necessary to mitigate against the potential adverse environmental and social effects, the Board is of the view that the proposed project is unlikely to cause significant public concern and its adverse ecosystemic and socioeconomic impacts are unlikely to be significant or are highly predictable and can be adequately mitigated by known technologies.

RECOMMENDED PROJECT-SPECIFIC TERMS AND CONDITIONS

The Board is recommending the following specific terms and conditions to apply in respect of the project:

General

1. Real Ice Development Company Limited (the Proponent) shall maintain a copy of the Project Terms and Conditions at the site of operation at all times and make it accessible to enforcement officers upon request.
2. The Proponent shall operate in accordance with all commitments stated in correspondence provided to the Nunavut Planning Commission (NPC File No.: 150112), and the NIRB (Online Application Form, September 14, 2023). This information should be accessible to enforcement officers upon request.
3. The Proponent shall operate the site in accordance with all applicable Acts, Regulations and Guidelines.
4. The Proponent shall ensure that it meets the standards and/or limits as set out in the authorizing agencies' permits or licences as required for this project.
5. The Proponent shall ensure that all personnel, staff and contractors are adequately trained prior to commencement of all project activities, and shall be made aware of all operational plans, management plans, guidelines and Proponent commitments relating to the project.

Water courses/Water bodies (including fresh and marine waters)

6. The Proponent shall ensure that water extraction from any fish-bearing waterbody is done with appropriate care and caution.
7. The Proponent shall not deposit, nor permit the deposit of any fuel, chemicals, wastes (including wastewater) or sediment into any water body. The Proponent should have in place an Emergency Spill Response Plan that is approved by the appropriate authorizing agency(ies).

Waste Management

8. The Proponent shall manage all hazardous and non-hazardous waste including food, domestic wastes, debris and petroleum-based chemicals (e.g., greases, gasoline, glycol-based antifreeze) in such a manner to avoid release into the environment and access to wildlife at all times until disposed of appropriately or at an approved facility.
9. The Proponent shall dispose of all combustible wastes as required by the appropriate authorizing agencies. All non-combustible wastes from the project site shall be removed to an approved facility for disposal.

Fuel and Chemical Storage

10. The Proponent shall locate all fuel and other hazardous materials a minimum distance away from the high-water mark of any water body and environmentally sensitive areas as required by the appropriate authorizing agencies. The materials shall be stored in such a manner as to prevent their release into the environment.
11. The Proponent shall use adequate secondary containment or a surface liner (e.g., self-supporting insta-berms and fold-a-tanks) when storing barreled fuel and chemicals at all locations.
12. The Proponent shall ensure that re-fuelling of all equipment occurs a minimum distance away from the high-water mark of any water body as required by the appropriate authorizing agencies.
13. All fuel and chemical storage containers must be clearly marked with the Proponent's name for ease of identification.
14. The Proponent shall have a Spill Contingency Plan in place at all fuel storage or transfer locations and shall ensure that appropriate spill response equipment and clean-up materials (e.g., shovels, pumps, barrels, drip pans, and absorbents) are readily available.
15. The Proponent shall follow the authorizing agencies' direction for management and removal of hazardous materials and wastes (e.g., contaminated soils, sediment and waste oil).
16. The Proponent shall ensure that wildlife deterrent systems are utilized at the time of a spill incident in order to avoid wildlife (terrestrial or marine) and migratory birds from being contaminated.
17. The Proponent shall ensure that all spills of fuel or other deleterious materials of 100 litres or more must be reported immediately to the 24-hour Spill Line at (867) 920-8130.

Wildlife – General

18. The Proponent shall not substantially alter or damage or destroy any wildlife habitat in conducting this operation unless otherwise authorized by the appropriate authorizing agencies.
19. The Proponent shall not chase, weary, harass or molest wildlife. This includes persistently circling, chasing, hovering over, pursuing or in any other way harass wildlife, or disturbing large groups of animals.
20. The Proponent shall not hunt or fish, unless proper Nunavut authorizations have been acquired.

Caribou and Muskoxen Disturbance

21. The Proponent shall avoid interfering with any paths or crossings known to be frequented by caribou during periods of migration as identified by current land use plans in place and/or by Inuit Qaujimaningit.
22. The Proponent shall not locate any operation or undertake activities that could block or cause any diversion to migration of caribou or muskoxen.
23. The Proponent shall immediately cease activities likely to interfere with the migration or calving of caribou or muskoxen until such time as the caribou or muskox have passed.

Road and Ground Disturbance

24. The Proponent shall not move any equipment or vehicles without prior testing the thickness of the ice to ensure the ice is in a state capable of fully supporting the equipment or vehicles.

Land Use and Restoration of Disturbed Areas

25. The Proponent shall remove all garbage, fuel and equipment at the end of each field season and/or upon completion of work and/or upon abandonment.
26. The Proponent shall ensure that all disturbed areas are restored to a stable or pre-disturbed state using Best Available Technology Economically Achievable (BATEA) upon completion of work and/or abandonment.
27. The Proponent shall suspend all project activities should any dead fish or wildlife (both marine and terrestrial), or any injured wildlife be observed during any works or activities in and around the marine waters. Activities may only be resumed on the recommendation of the authorizing agencies.
28. The Proponent shall report all incidents, injuries or sightings of marine mammals to the appropriate authorizing agencies.
29. The Proponent shall implement measures designed to minimize disturbance to seabed sediments and benthic communities and marine wildlife when carrying out project activities within the marine environment.

Other

30. The Proponent should engage with local residents regarding planned activities in the area and should solicit available Inuit Qaujimaningit and information regarding current recreational and traditional usage of the project area which may inform project activities. Posting of translated public notices and direct engagement with potentially interested groups and individuals prior to undertaking project activities is strongly encouraged.
31. The Proponent shall ensure that project activities do not interfere with Inuit wildlife harvesting or traditional land use activities.
32. The Proponent should, to the extent possible, hire local people and access local services where possible.

OTHER NIRB CONCERNS AND RECOMMENDATIONS

In addition to the project-specific terms and conditions, the Board is recommending the following:

Copy of licences, etc. to the Board and Commission

1. The NIRB respectfully requests that responsible authorities submit a copy of each licence, permit or other authorization issued for the Project to the NIRB to assist in enabling possible project monitoring that may be required. Please forward a copy of the licences, permits and/or other authorizations to the NIRB directly at info@nirb.ca or upload a copy to the NIRB's online registry at www.nirb.ca.

Use of Inuit Qaujimaningit

2. The Proponent is encouraged to work with local communities and knowledge holders to inform project design, to carry out the project, and to confirm or validate the perspectives represented in publications produced as part of the project. Care should be taken to ensure that Inuit Qaujimaningit and local knowledge collected for the project is used with permission and is accurately represented.

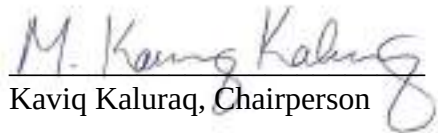
Species at Risk

3. The Proponent review Environment and Climate Change Canada's "Environment Assessment Best Practice Guide for Wildlife at Risk in Canada", available at the following link: http://www.sararegistry.gc.ca/virtual_sara/files/policies/EA%20Best%20Practices%202004.pdf. The guide provides information to the Proponent on what is required when Wildlife at Risk, including *Species at Risk*, are encountered or affected by the project.

CONCLUSION

The foregoing constitutes the Board's screening decision with respect to the Real Ice Development Company Limited's (Real Ice) "Real Ice-November Field Test in Cambridge Bay, Canada". The NIRB remains available for consultation with the Minister regarding this report as necessary.

Dated October 31, 2023, at Baker Lake, NU.


Kaviq Kaluraq, Chairperson

Attachments: Appendix A: Species at Risk in Nunavut

APPENDIX A: SPECIES AT RISK IN NUNAVUT

Due to the requirements of Section 79(2) of the Species at Risk Act (SARA), and the potential for project-specific adverse effects on listed wildlife species and its critical habitat, measures should be taken as appropriate to avoid or lessen those effects, and the effects need to be monitored. Project effects could include species disturbance, attraction to operations and destruction of habitat. This section applies to all species listed on Schedule 1 of SARA, as listed in the table below, or have been assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), which may be encountered in the project area. This list may not include all species identified as at risk by the Territorial Government. The following points provide clarification on the applicability of the species outlined in the table.

- Schedule 1 is the official legal list of Species at Risk for SARA. SARA applies to all species on Schedule 1. The term “listed” species refers to species on Schedule 1.
- Schedule 2 and 3 of SARA identify species that were designated at risk by the COSEWIC prior to October 1999 and must be reassessed using revised criteria before they can be considered for addition to Schedule 1.
- Some species identified at risk by COSEWIC are “pending” addition to Schedule 1 of SARA. These species are under consideration for addition to Schedule 1, subject to further consultation or assessment.

If species at risk are encountered or affected, the primary mitigation measure should be avoidance. The Proponent should avoid contact with or disturbance to each species, its habitat and/or its residence. All direct, indirect, and cumulative effects should be considered. Refer to species status reports and other information on the species at risk Registry at <http://www.sararegistry.gc.ca> for information on specific species.

Monitoring should be undertaken by the Proponent to determine the effectiveness of mitigation and/or identify where further mitigation is required. As a minimum, this monitoring should include recording the locations and dates of any observations of species at risk, behaviour or actions taken by the animals when project activities were encountered, and any actions taken by the proponent to avoid contact or disturbance to the species, its habitat, and/or its residence. This information should be submitted to the appropriate regulators and organizations with management responsibility for that species, as requested.

For species primarily managed by the Territorial Government, the Territorial Government should be consulted to identify other appropriate mitigation and/or monitoring measures to minimize effects to these species from the project.

Mitigation and monitoring measures must be undertaken in a way that is consistent with applicable recovery strategies and action/management plans.

Schedules of SARA are amended on a regular basis, so it is important to check the SARA registry (www.sararegistry.gc.ca) to get the current status of a species.

Updated: September 2019

Terrestrial Species at Risk¹	COSEWIC Designation	Schedule of SARA	Government Organization with Primary Management Responsibility²
Migratory Birds			
Buff-breasted Sandpiper	Special Concern	Schedule 1	Environment and Climate Change Canada (ECCC)
Common Nighthawk	Threatened	Schedule 1	ECCC
Eskimo Curlew	Endangered	Schedule 1	ECCC
Harlequin Duck	Special Concern	Schedule 1	ECCC
Harris's Sparrow	Special Concern	Schedule 1	ECCC
Horned Grebe	Special Concern	Schedule 1	ECCC
Ivory Gull	Endangered	Schedule 1	ECCC
Olive-sided Flycatcher	Threatened	Schedule 1	ECCC
Peregrine Falcon	Special Concern	Schedule 1	ECCC
Red Knot Islandica Subspecies	Special Concern	Schedule 1	ECCC
Red-necked Phalarope	Special Concern	Schedule 1	ECCC
Ross's Gull	Threatened	Schedule 1	ECCC
Rusty Blackbird	Special Concern	Schedule 1	ECCC
Short-eared Owl	Special Concern	Schedule 1	ECCC
Vegetation			
Porsild's Bryum	Threatened	Schedule 1	Government of Nunavut (GN)
Arthropods			
Transverse Lady Beetle	Special Concern	No Schedule	GN
Terrestrial Wildlife			
Caribou (Dolphin and Union Population)	Endangered	Schedule 1	GN
Caribou (Barren-ground Population)	Threatened	No Schedule	GN
Caribou (Torngat Mountains Population)	Endangered	No Schedule	GN
Grizzly Bear (Western Population)	Special Concern	Schedule 1	ECCC
Peary Caribou	Endangered	Schedule 1	GN
Polar Bear	Special Concern	Schedule 1	ECCC
Wolverine	Special Concern	Schedule 1	GN
Marine Wildlife			
Atlantic Walrus (High Arctic Population)	Special Concern	No Schedule	Fisheries and Oceans Canada (DFO)
Atlantic Walrus (Central/Low Arctic Population)	Special Concern	No Schedule	DFO
Beluga Whale (Cumberland Sound Population)	Threatened	Schedule 1	DFO
Beluga Whale (Eastern Hudson Bay Population)	Endangered	No Schedule	DFO

1 The Department of Fisheries and Oceans has responsibility for aquatic species.

2 Environment and Climate Change Canada (ECCC) has a national role to play in the conservation and recovery of Species at Risk in Canada, as well as responsibility for management of birds described in the Migratory Birds Convention Act (MBCA). Day-to-day management of terrestrial species not covered in the MBCA is the responsibility of the Territorial Government. Populations that exist in National Parks are also managed under the authority of the Parks Canada Agency.

Terrestrial Species at Risk¹	COSEWIC Designation	Schedule of SARA	Government Organization with Primary Management Responsibility²
Beluga Whale (Eastern High Arctic-Baffin Bay Population)	Special Concern	No Schedule	DFO
Beluga Whale (Western Hudson Bay Population)	Special Concern	No Schedule	DFO
Fish			
Atlantic Cod (Arctic Lakes Population)	Special Concern	No Schedule	DFO
Fourhorn Sculpin (Freshwater Form)	Data Deficient	Schedule 3	DFO
Lumpfish	Threatened	No Schedule	DFO
Thorny Skate	Special Concern	No Schedule	DFO

SCIENTIFIC RESEARCH LICENSE

LICENSE NUMBER 04 001 26R-M

ISSUED TO: Cian Sherwin
Real Ice Development Company LTD.
29 Lon Ogwen
Bangor, Gwynedd
LL57 2UD United Kingdom

TEAM MEMBERS: A.Ceccolini,A.Smith,A.Woods,S.Woods,P.M-Daguet

TITLE: Real Ice-January Field Test in Cambridge Bay, Canada

OBJECTIVES OF RESEARCH:

The project explores scientific and engineering methods to preserve and restore Arctic Sea ice, which is vital for both global climate regulation and local community life. In partnership with community members in Cambridge Bay, the research focuses on sea ice thickening using simple, zero-emission devices. The system employs a submersible pump lowered through an auger-drilled hole, drawing seawater to the surface. In the extreme cold, this water freezes rapidly, thickening the ice and flooding surface snow. This increases heat transfer between air and ice, supporting further natural growth. This will be our third Cambridge Bay field study, following the successful completion of our second in July 2025. For the 2026 season, operations will take place on a 1 km² site about 7 km from the hamlet, chosen in consultation with the local HTO and previously used during the 2024/25 trials. Approximately one-quarter of the site will be dedicated to experiments, with the remainder maintained as a control. Key data collected will include water displacement, ice thickness and salinity, and the temperatures of air, snow, and ice. Monitoring will continue until spring breakup to assess the long-term impacts of thickening operations.

TERMS & CONDITIONS:

The holder of the license will be bound by the terms and conditions of the Nunavut Impact Review Board Screening Decision Report (NIRB File #25YN033)and the Department of Culture & Heritage archaeological sites terms and conditions. These terms and conditions will form part of this license.

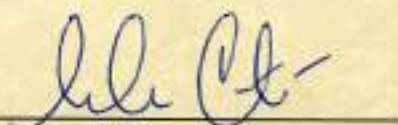
DATA COLLECTION IN NU:

DATES: January 10,2026 to August 1,2026

LOCATION: Bay of Iqaluktutiak

Scientific Research License 04 001 26R-M expires on December 31,2026

Issued at Iqaluit, NU on August 26,2025


James Shirley
Science Advisor

PER





ARIA

mark.symes@aria.org.uk

7 January 2026

Dear Exploring Climate Cooling programme team,

In his decision letter for Real Ice's outdoor experiments in January-July 2026 as part of the ARIA-funded Re-thickening Arctic Sea Ice (RASI) project, ARIA's CEO asked for the following as conditions 2b(i) and 2b(ii):

That the RASI team documents and shares with local communities the following before the experiments start, in a manner that is accessible for those communities:

- i. Information on their process(es) for achieving consent, for confirming continued consent, and for discerning/accepting withdrawal of consent. This information should include in particular how any dissent within the community and from Elders will be documented and handled.*
- ii. Information on practices related to community benefit, including the approach to co-authorship that will be followed and the approach that they will take to other forms of recognition of contributions (including, for example: instruments, guidance on experiments, and insights from Elders and others).*

I am writing to confirm that Real Ice believe that they have met these conditions as follows:

On condition 2b(i): Achieving and Withdrawal of Consent

Over the 2.5 years that Real Ice has been engaged with the community at Cambridge Bay the team has looked to secure consent for research through consistent engagement locally. In total the Real Ice team has spent more than 8 months in the community over this period engaging with stakeholder groups in structured board meetings and presentations and informal Q&A and social gatherings.

These consistent interactions allow the team to check in constantly with Cambridge Bay community members on the buy-in for the Real Ice research. This has been documented by Real Ice (the Elders video they shot in May 2025 is a good example), by independent journalists (e.g. the Narwhal articles) and by the participation of members of the community at events showcasing the Real Ice research such as at the Vatican in July 2024 with Real Ice's CEO.



Real Ice has explicitly asked community members how they would know if consent is withdrawn. This is a summary of what Real Ice heard:

If the community decides that they no longer want to contribute to, participate in or host the Real Ice research in Cambridge Bay, Real Ice would receive a letter from either the Mayor and Hamlet Council or the Elders, and Hunters and Trappers Organizations (EHTO) formally asking Real Ice to leave the community. Before such a drastic occurrence (this has never happened in the memory of any community members interviewed) there would be opportunities to address whatever concerns have been raised.

Concerns would be raised directly by the community members with whom Real Ice interacts most frequently – the members of the EHTO that are out on the sea ice every day with the Real Ice team.

On condition 2b(ii): Recognition of research contributions by local community members

Real Ice is committed to recognising the contributions of their co-researchers in the Cambridge Bay community, specifically the members of EHTO that contribute to the planning, design and execution of the research out on the sea ice. Evidence of this commitment is the recently published pre-print of the 2024/5 research results in which the local community co-researchers are named: see Real Ice's [recent preprint of results](#) from 2024/25.

Yours sincerely

Professor Shaun Fitzgerald OBE FREng (Director)

Principal Investigator of RASI project

Centre for Climate Repair



COMMUNITY ENGAGEMENT AND PERMITTING UPDATE FOR WINTER 25'/'26 FIELD TESTS ARCTIC REFLECTIONS – NOVEMBER 14th, 2025

A. Introduction

As part of the ARIA-funded RASi project, Arctic Reflections is planning to undertake sea ice thickening field testing in coming winters in the Baffin Bay / Qikiqtani region, Nunavut, Canada. These field tests are informed by previous field tests in winter 2024 in Svalbard and in winter 2025 in Newfoundland, Canada, both of which have involved extensive cooperation and engagement with local community representatives as well as formal permit procedures.

What is new for the upcoming field test is that this is planned to take place in the Inuit self governed region of Nunavut. Arctic Reflections recognizes the vital importance of engaging Inuit communities ethically and equitably in our work, for mutual benefit. As we explore sea ice thickening as a climate intervention, we are committed to aligning our practices with the Circumpolar Inuit Protocols for Equitable and Ethical Engagement, developed by the Inuit Circumpolar Council. These protocols, such as the adherence to Free, Prior, Informed Consent (FPIC) are a foundational guide for collaboration based on respect, mutual benefit, and the recognition of Inuit sovereignty and knowledge. Note that on our website, following the feedback of an Inuit representative, we explicitly state as guidelines the 8 [Inuit Qaujimajatuqangit Principles](#) that are being used in Nunavut. Public participation is also one of the principles of the American Geophysical Union's (2024) ethical framework for climate intervention research.

Within the Canadian Arctic context, community consultation is also an integral and essential part of the permitting process. In this document, we will briefly outline our field test plans, give a status update on our community engagement so far and our plans on this going forward, and give a status update on the permitting process.

B. Field test plan 2026/2027

The field test is planned on the sea ice around Broughton Island, near Qikiqtarjuaq. This is a community of about 600 inhabitants, predominantly Inuit, and is a suitable location for a field test because it has a research center, there is operational capacity, access to a workshop (for repair and maintenance), relevant ice conditions in an area protected from the drift ice, and a generally welcoming, engaged community. The exact spot of the field test will be chosen in collaboration with the Hunters & Trappers Organization, staying away from areas where animals are known to gather.



The objective is to thicken sea ice by pumping water from underneath on top of it, within an area of at most 1 km². Scientifically, we aim to show that this ice lasts longer and reflects more sunlight than ice that is not thickened. We plan to do most of the work in February 2026 (as well as 2027), when there is enough daylight and the sea ice is thick and safe. The work will take about 4–5 weeks each year, including setup, pumping, and cleanup. Monitoring of the ice will continue until summer, using equipment that can float and be tracked by GPS.

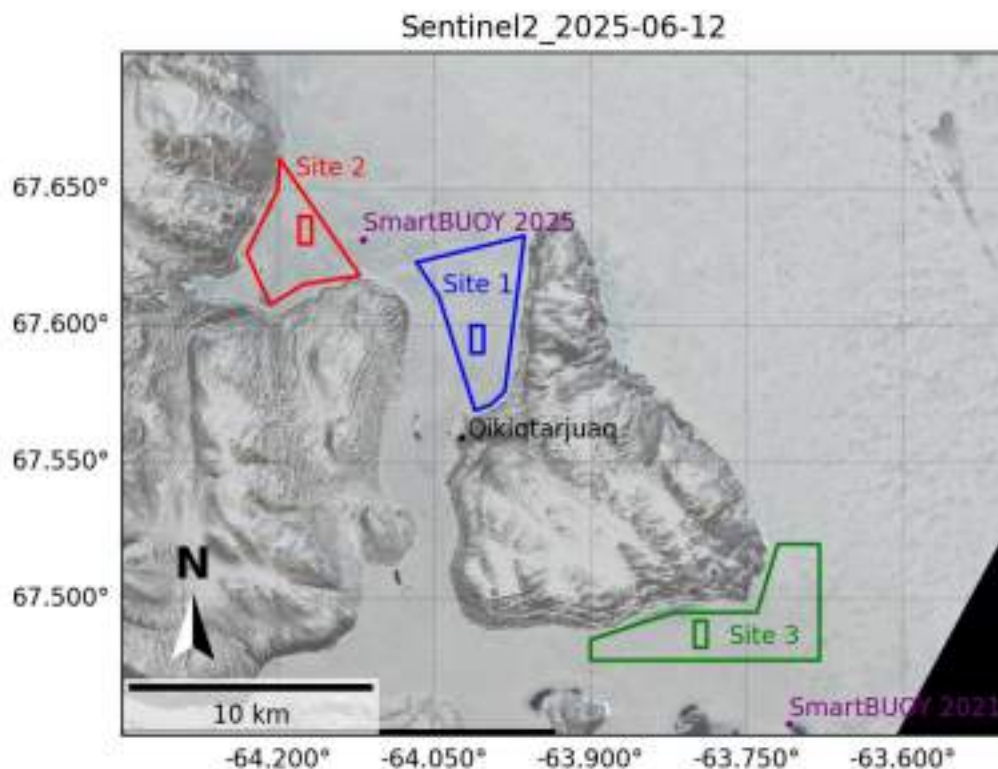


Figure 1: Overview of potential field test locations – initially we only had site 1 and site 2, after the community consultation site 3 was added

Our team (4-7 people at any one time, with the crews consisting of Arctic Reflections personnel, personnel from academic partners within the RASi projects, and local hires) will:

- Use snowmobiles and sleds to carry pumps and equipment
- Drill holes in the ice and pump seawater onto the surface
- Repeat this over an area of at most 1 km²
- Monitor ice thickness using smart sensors, weather stations, and visual checks, both of the thickened area as for non-thickened ice for comparison reasons



- Work only during the day, to avoid disturbing wildlife. All travel to and from the site will use the same marked path. Waste will be brought back each day. Refueling of snowmobiles will only happen in Qikiqtarjuaq, not on the ice. For the pumps we will only have to replace jerrycans to refuel to avoid spills.

We are committed to working closely with the Qikiqtarjuaq community. Besides hiring local wildlife monitors/guides and field ice observers during the operational phase of the field test as well as the monitoring phase, we are committed to:

- Share our results with the Qikiqtarjuaq Hunters & Trappers Organization
- Provide summaries in plain, local language and visual formats
- Visit Qikiqtarjuaq before the start of the field test for further community consultation (done) and afterwards to present findings and hear community feedback
- Have an ongoing public engagement process, planned in collaboration with the Hamlet council and the HTO Qikiqtarjuaq. We are committed to offer that this will include a school presentation, and a public event on sea ice thickening including offering soup lunch
- Co-investigate local ideas on sea ice thickening, with the local community members.
- Make our data available to Nunavut researchers and decision-makers and investigate if we can make all ice thickness data available via the Siku platform to the local community.

C. Community Consultation

After an introductory call with the Manager Research Licensing at the Nunavut Research Institute (NRI) in Iqaluit, we reached out to the Hunters & Trappers Organizations (HTOs) of 2 different communities in the Baffin Bay area, since they have an important say in (and could be affected by) field research: Pond Inlet and Qikiqtarjuaq. These are both communities with some research infrastructure and operational capacity, access to a workshop, relevant ice conditions and a generally welcoming community. Both communities are part of another field programme of RASi-participant Michel Tsamados from UCL, who has given valuable input in the context, and with him, we have identified ways about how the 2 research projects could potentially strengthen each other. Next to this, we contacted the research station in Qikiqtarjuaq from Laval University, and contacted SmartICE, a Canadian social enterprise working with Inuits from over 30 communities on ice safety and measurements.

After initial conversations, the Laval University contact person helped facilitate a digital meeting with the Qikiqtarjuaq Hunters & Trappers, in which we explained our project plans and asked for their feedback. The feedback in the meeting was very positive, which led us to start the formal permit applications, and plan for a trip to Qikiqtarjuaq in September. Next



to this, we talked to a representative of the Pond Inlet HTO, who also invited us to come give a presentation in September. We decided to combine this with broader community consultation on ice thickening and also on the ice arch project, to create synergy for ourselves and at the same time avoid overwhelming them with many different individual meetings. In the same trip, we also visited the Nunavut Trade Show in Iqaluit, to meet more local organizations, and present our approach in order to get more feedback.

Tom Meijeraan and Fonger Ypma from Arctic Reflections led the broader community consultation trip. We also invited Dr Geoff Evatt, collaborator from University of Manchester, to join us, specifically for the ice arch community consultation. Next to this, we decided to temporarily employ Ilona Mettiäinen, an environmental social scientist from the Arctic Centre of the University of Lapland with a lot of expertise in engagement and participatory research with Arctic communities (indigenous and non-indigenous) on climate interventions and climate adaptation related topics (in Greenland and Scandinavia), to assist with the community consultation and preparations.

Where When What		
Qikiqtarjuaq	8-12 September	Community consultation meetings, trust building, and field test preparation
Pond Inlet	13-16 September	Community consultation and trust building with more focus on ice arch
Iqaluit	16-18 September	Nunavut Trade Fair with opportunities to meet many relevant local Nunavut organizations and present our project

The purpose and goal of the community consultation meetings (in particular in Qikiqtarjuaq) was to ask for community consent, to fulfill the requirements of research permit applications, to receive input from the local communities regarding the potential field experiment sites and other local factors to be considered in designing the field experiments in these locations, and to ensure that the project activities are mutually beneficial as well as aligned with IQ principles and EEE principles and respect Inuit rights. Hence, we organized community consultation meetings and met other local and regional stakeholders and rightsholders and relevant authorities and policymakers at the planned host communities in Nunavut, Qikiqtarjuaq and Pond Inlet (Mittimatalik), and presented at the Iqaluit Trade Fair in September 2025. All of these communities are located in the Qikiqtaaluk or Qikiqtani Region, also known as Baffin Island.



For the purpose of this document, we will focus on the community consultation directly related to the upcoming field test in winter starting early 2026, in Qikiqtarjuaq.



Qikiqtarjuaq

The community consultation meeting in Qikiqtarjuaq took place on 10.9.2025. The meeting was organized at the research center of Laval University as an in-person meeting. Four Arctic Reflections team members were present in person. Consent to take notes was asked and granted orally by all participants by putting up hands. We had also printed consent forms just in case, but these were not needed/used after all. We had also sent out a participant information sheet beforehand to ensure FPIC – see attached document.

Altogether 13 local participants attended the meeting, of which 5 were women. This is a very good number of participants considering the smallness of the community, and a broad representation: the participants were community leaders and elders from the HTO and the Hamlet council including the Senior Administrative Officer and Mayor. Some participants had roles in both. Moreover, the representative of SmartICE and the manager of the research center (a younger Inuit woman) actively participated in the meeting. Some of the visiting scientists at the research center observed the meeting but did not actively participate.

We had prepared a presentation for introducing the project and for asking about local observations of changes in sea ice, as well as local preferences, interest and advice on testing the method in a mutually beneficial way, including in terms of the test site. After



introducing ourselves and hearing the participants introduce themselves, we continued by introducing the project including the funding source and the objectives of the project (including the intent to research climate cooling), explaining the method, and by showing videos of the earlier field experiments in Newfoundland and Svalbard. We also asked for the participants' views on the locally observed changes in sea ice. They openly discussed the observed impacts in their use of the sea ice. We presented a map of potential field experiment sites (drawn based on earlier dialogue), and the participants commented on that and suggested a new, more suitable location for the field experiments on the southern side of the island.

Moreover, it was discussed what the project would need from / in the community, and the employment opportunities in the project. The field experiments were welcomed, and we have since received a formal support letter from the Qikiqtarjuaq Hamlet. The HTO and Hamlet council will be our contact points in the community and will inform the community more widely about the project.

Both the HTO and Hamlet Council suggested ways to engage with the community in the interim (between the consultation and the actual field experiment in February 2026). The recommended channels include using the local radio channel for informing the community about the project in Inuktitut, for which we provided a translated project description, and the local Facebook group. The community also brought up their own ideas on how to improve the ice conditions locally, and we received valuable practical advice on preparing for the field experiments and who could be hired. During the meeting, two people already indicated enthusiasm to participate in the field tests.

We offered delicacies from the Netherlands and Finland and locally purchased delicacies. Hosted by the University of Laval research center, and enabled by the kelp research team, we got to taste kelp, a local delicacy. We believe this cultural exchange also helped create contacts to the local community.



The results of the meeting

Beyond gaining local acceptance and meeting the requirements of the research permit applications, the meeting was successful in a number of other ways as well.

1. The community welcomes the project and field experiment to Qikiqtarjuaq

As a key result of the meeting, the field experiments were welcomed to Qikiqtarjuaq in February 2026 by the community leaders and elders. The representative of the hamlet/municipality has signed a support letter, and the HTO has verbally indicated their support, to be formalized in their response as contact person for the NIRB permit application.

It was stated that ice thickening could be a well-liked climate change adaptation measure in the community. For instance, the locals wished that they could safely go ice fishing for longer. Hence there is a clear local demand for solutions like sea ice thickening on the community level (substantive engagement). For the avoidance of doubt, we did however make clear that they shouldn't expect any of these potential positive benefits in the near term from the research itself (which was clear to the community, since the field testing is on purpose scheduled in a remote area where limited travel takes place).



Wider applications of the ice thickening method were also discussed at the meeting, and there was one question on what the ultimate objective of the research was, to which we have answered that we are researching whether this could work to preserve Arctic sea ice at scale and help cool the climate, while also providing local benefits. All in all, this raised less attention than the immediate local needs during and soon after the field experiment phase. A meeting participant also wanted to discuss their idea of spurring sea ice growth, which we look forward to co-creating further on with him - since the meeting, we exchanged already several emails with this meeting participant on a potential research experiment.

In addition to the actual consultation meeting with the HTO, Hamlet Council and SmartICE, we also built trust by meeting local community members such as Parks Canada, the Co-op shopkeeper, municipality office workers, the Royal Canadian Mountain Police, healthcare professionals, staff of the local hotel-restaurant, local handicraft makers and artists, and the other visiting scientists and the permanent staff of the research center of the University of Laval.

2. Choosing a field experiment site together, based on IQ and community preferences

Based on the consultation, the location of the field experiment site was redefined: instead of the preliminarily planned sites north of the island, a site south of the island was selected instead. The preliminarily planned sites were discussed by the meeting participants in Inuktitut and deemed as unsuitable for field experiments, as the sites proved to be seal birthing sites in the spring, and hence not to be disturbed. A location south of the island was suggested by the participants instead. The new location that came out of this co-creation process meets the criteria of the Arctic Reflections team, including enough water depth, no harm to wildlife, outside of community transportation routes and hunting grounds, and preferably within 5-10 km of the community to facilitate transport. The new location meets these criteria and is approved by the community leaders and elders. It was decided that the exact location of the 1 km² field experiment site will be decided when the team arrives in Qikiqtarjuaq in February 2026, based on the conditions and other observations then.

3. Identifying available community members to work for the project

During the consultation meeting and otherwise during our visit, we were already able to identify some individuals who would like to work with us in February 2026 during the field experiment e.g. as guides and wildlife observers. The consultation meeting participants also had other people in mind that could be hired to the project in various roles, including as technicians and drone pilots.



As we had pleasant discussions with local community members also outside of the community consultation meeting, some expressed their interest towards being hired by the project.

We will primarily follow the recommendations of the HTO and SmartICE on the hirings, but it is good to know that there are active and interested community members that could work for the project.

It can be estimated that the project will bring some welcome economic opportunities for some community members.

Directly and indirectly, already the community consultation meeting benefited the community economically. We made sure to leave money in the community by e.g. using local services (restaurant, grocery store, local tour guide, local hotel and AirBnB accommodation) and buying local handicrafts and art. Several team members bought art and bone carvings from local artists and craftsmen. However, the CITES rules limited our possibilities to buy local handicrafts, as many were made from narwhal or walrus ivory.

4. Practical advice on the field experiment and on the available support in the community

We also received advice on how to prepare for the field experiment. Particularly bringing any necessary spare parts was a key recommendation. There is also a garage available in the village for assembling the equipment in the middle of winter.

5. Guidelines and collaboration on community's wishes on future engagement

The HTO and Hamlet Council participants, the Senior Administrative Officer, and the HTO president and the mayor of Qikiqtarjuaq, promised to spread the word among the community on the project and the upcoming field experiments, including via the local Facebook group and in the local radio. They also promised to inquire on whether the community members would like to have a public meeting on the project when the team returns in February 2026.

Meanwhile, the project can be in touch with the community via Facebook that is a key communications channel at the community. Moreover, local information channels like the local radio can also be used for communications in Inuktitut. The HTO and SAO are now central contact points between the community and the project.

We took a lot of photographs in the community and its environment. We did not take photographs of the consultation meeting out of respect for the participants, but a meeting participant took some photographs and shared these with us with permissions to use them in our work.



Based on our dialogue with and observations of the community and its practices, we also identified the following as potential ways to engage with the local community:

- Public event at the community during field test period; for instance, offering soup lunch at the municipality hall (an on-going practice that depends on the availability of funds for it) and telling people about the project during the lunch event. This will be a key event to solicit further feedback from the broader community on our field experiments.
- Visiting local school and giving presentations there during field test period, which is also a good opportunity to solicit feedback.
- The local research centre (by Laval University) seems to be a well-liked hub and meeting place where local handicraft makers and other locals come to meet scientists; being available at the research centre during the field experiment for any discussions may be a good idea
- Training community members in useful skills such as drone flying, measurements and observation, technical maintenance etc.; all skills that would probably prove essential in further research collaborations

Other potential ways of making research benefit the community, but which are not within the reach of this project or for the upcoming field season:

- Building housing in Qikiqtarjuaq that the research team could use for lodging while on site, also alleviating local housing shortage and lack of hotel accommodation for visitors
- Buying new skidoos and selling them in good condition to local users after the field season or the entire field experiment / project

Further community feedback opportunities

We were very happy with the feedback during the meeting, including the concerns about the location due to the presence of seals when we explicitly mentioned the noise of the operation, and the joint resolution where they proposed a new location. Also, the positive feedback on willingness to be employed as part of this project, as well as practical ice preservation ideas and knowledge about issues with the sea ice (such as the shortening ice fishing season) were welcomed. During the meeting, we have stressed that we would love to come, but we would of course respect their decision, and we feel that this was appreciated.

In order to give the community members ample opportunity to provide feedback on our field experiments, the townhall meeting and the school visit in February will be excellent opportunities, as mentioned above. This would enable to incorporate this feedback in further iterations of our approach. In the meantime, we will coordinate with the hamlet to



provide information about the project including our contact details via social media groups and the local radio station.

Next to this, as part of the formal permitting process (see below), there is an open process by the Nunavut Impact Review Board (NIRB) where stakeholders within Nunavut (and in particular within the community) have the opportunity to provide feedback on all research proposals that apply for a permit.



Finally, after the field testing, we will plan a visit (around the summer) to have a meeting with HTO and Hamlet to discuss initial results and cooperation, as well as future cooperation, and during that visit, we intend to also hold a broader town hall meeting again.

Other notions from Qikiqtarjuaq

Another research team focusing on studying kelp happened to be visiting Qikiqtarjuaq at the same time with us. This was unforeseen, and they also had community engagement plans and activities going on. To avoid overwhelming the local community, we coordinated with the other researchers to ensure that we both can have our consultation meetings with the hamlet and the HTO. Our public event (possibly in the form of a soup lunch event) and school visit will be scheduled to take place in February when the field experiment team is present.

Trust had already been built during the email correspondence with Qikiqtarjuaq HTO and hamlet council during the spring and summer 2025, including the HTO meeting to which Tom presented and participated online, and which was facilitated by the Laval University research coordinator.

All in all, we felt welcomed by the local community. As we were leaving, several people wanted to ensure we return in February. We believe that the hamlet and the HTO will support our application for the field research permit. We already even discussed coming back in 2027 as well.

We also learned about local ideas on spurring ice growth, which we will look into during the field experiment.

Pond Inlet / Mittimatalik

The consultation meeting at Mittimatalik took place on 15.9.2025. The participants included two members of the HTO board including the vice president who also interpreted, the elder contact person of the HTO, the secretary of the HTO, a representative of SmartICE, and three Arctic Reflections team members.

We again offered delicacies from the Netherlands and Finland.

The focus in this meeting was on the Nares Strait and NOW Polynya, but we talked about aligning issues as in Qikiqtarjuaq. Locally interesting test sites were preliminarily identified also here, some of them very close to the town. This meeting was great as an investment in relation building for the future.

Iqaluit

Participation in the Iqaluit Trade Fair on 15.-18.9.2025 proved very useful in terms of informing Nunavut key organizations about the project and the sea ice thickening method. We met several key people and have plans to engage with them online. Meeting the people face to face was a key to getting in touch with them.

The public feedback from the event was very positive.

Following guidelines related to ethical and equitable research in Arctic communities

In our consultations, we follow the guidelines and principles related to climate intervention research (AGU 2024) and specifically related to ethical and equitable research with Arctic communities, particularly the Inuit. These include the Ethical, Equitable Encounters principles by the Inuit Circumpolar Council (2022) and the Inuit Qaujimajatuqangit principles (<https://www.nirb.ca/inuit-qaujimajatuqangit>). Moreover, the International Arctic Social Sciences Association's principles on ethical Arctic research (2020) and recent publications on stakeholder engagement in the Arctic (Latola et al. 2020) and decolonial Arctic research (Holmberg et al. 2023, Herrmann et al. 2023) are applied. To conclude, we follow the key recommendations from these documents in the following way:

- Appreciation of Indigenous Knowledge / Inuit Qaujimajatuqangit as an equal knowledge system to Western science. We rely on IQ on scoping local motivations and benefits from participating in this research, particularly regarding the observations of changes in sea ice conditions. Moreover, the field experiment site in Qikiqtarjuaq was selected by an integration of the criteria and IQ to a place that is acceptable and desirable for the local community, including regarding no disturbance to wildlife (seals).

- Establishing mutually beneficial research relationships. During the consultation meetings, we were able to identify locally relevant and meaningful uses for sea ice thickening, including for potentially enabling safe fishing during summer months when ice has become unstable due to climate change (for the avoidance of doubt, we clearly indicated that these benefits cannot be expected from doing the research itself). Locally suitable test sites were identified based on IQ. Moreover, local employment opportunities were identified, and locals expressed interest towards working for the project. We also promised to openly share the data with the local community. Moreover, sea ice strengthening methods were suggested by local community members, and we will co-investigate these. We used local services including restaurant and accommodation services, local guide, grocery stores, and bought local art and handicrafts. We compensated the local community members for the time they used towards talking with us (honoraria). We also identified potential ways in which our engagement with the community could be beneficial.
- We had familiarized ourselves with relevant literature on the case study sites and communities beforehand, including the IQ maps on sea ice by SmartICE and the Nunavut Coastal Resources Inventory documents. The existing document and the discussions at the consultation meeting confirmed that the changes in sea ice conditions are a locally relevant topic, and our project was wished welcome.
- We respect Inuit rights by centering asking for their consent and permission to do the study in their lands and by co-designing research operations for also local benefit in establishing research relationship. We co-designed the field experiment sites with the local HTO and Hamlet council. We have funding for local participation and partnership.
- We have contacted the communities in timely manner, which has enabled them to influence the design of the field experiment, particularly choosing the field experiment site. We sought to build trust by continuous communications and by our personal visit. We also shared delicacies from our homelands with the communities and tried their traditional foods.
- We coordinated engagement efforts with the kelp research team in order to avoid research fatigue or overwhelming the community.
- The local HTO and Hamlet Council and SAO and SmartIce are key stakeholders and rightsholders (also contact points and intermediaries) for the project. They will help us with further engagement and recruitment.
- Respecting elders. We talked with community elders and leaders at the HTO and Hamlet Council, to rely on their leadership and IQ. We actively sought to include also women in the dialogue.
- We will communicate about the results of the study in a way that will be later on defined together with the host communities. We will engage with the community in various ways (e.g. school collaboration such as youth science-art workshop; soup lunch; radio; Facebook) that are locally relevant.

D. Permit status

For research in Nunavut, there are different permits that need to be in place, some of which are only for specific types of research. See the overview below as per NRI (Nunavut Research Institute), where we have indicated which ones are relevant for us.

CONDUCTING RESEARCH IN NUNAVUT

Depending on the nature of your research activities, receiving **regulatory approval** or exemption is the first step in the application process. Next, applicants must seek the appropriate **research license(s) and/or permit(s)**. Prior to conducting field research, you may also need the appropriate **land use/access permit(s)** or exemption. For research taking place in Nunavut schools, applicants must submit a proposal to the Government of Nunavut Department of Education in addition to the Nunavut Research Institute.

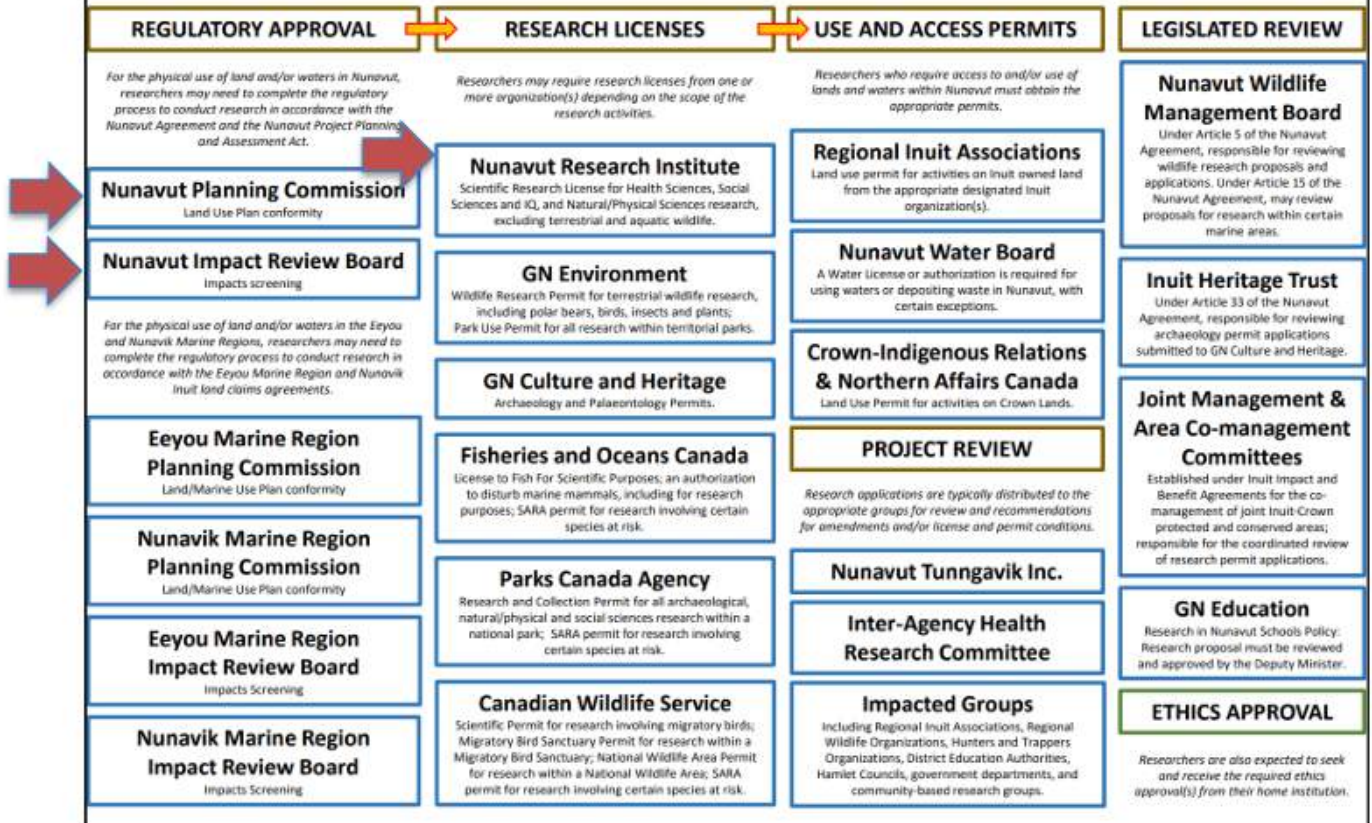


Figure 2: Overview of required permissions for research, from https://www.nri.nu.ca/sites/default/files/Research_Authorizations_Nunavut.pdf

For all permits, having community support is a pre-requisite. This can be in the form of a formal letter of support, but that is not necessary. The authorities will contact local communities (Hamlet and HTO) during the permit application process.

Required approval bodies	Status per Nov 14th	Comments
Nunavut Planning Commission (NPC)	Start: NPC File #150895. 12-08-2025: NPC determined that the project proposal is outside the area of an applicable regional land use plan. After changing location (due to input of local	NPC checks for regional Inuit lands use. For us this is not the case. After this decision the project proposal was forwarded to the NIRB.

	community), we amended the application. New NPC File # 150932. 17-10-2025: NPC again determined this proposal is outside the area of an applicable regional land use plan.	
Nunavut Impact Review Board (NIRB)	Accepted for screening, NIRB file No. 25YN078. 27-10-2025: the NIRB confirmed by email everything was complete, and no changes were required (after the change of location). The application is currently in “active screening” status, and according to their process, they should complete screening within 45 days of receiving referral by NPC (17-10-‘25), so by Dec 1st.	Oversees potential environmental and community impacts for projects in Nunavut
Nunavut Research Institute (NRI)	Formally pending, informally agreed upon only subject to receiving the other required licences	Licence to be able do research in Nunavut

To formalize the positive reaction by the local community, we have obtained a formal Letter of Support from a representative of the Hamlet (in the appendix). We have also obtained verbal support by the Hunters & Trappers Organization.

Following a change in the proposed field test location due to the community consultation, our permit application required clarification from the Nunavut Planning Commission (NPC), which is responsible for land use determinations. For this, we have done an amendment to the NPC application, which has led to a new, positive decision, and a new referral to the NIRB. Based on NIRB’s timelines, we anticipate that the permit could be obtained within 45 days after the NPC’s second referral date (17-10-2025), which would mean NIRB screening should be complete by 1-12-2025 (Dec 1st).

Finally, informally we have already heard that the Research permit (NRI) would be granted once the other permits have been obtained.

As part of the permit application, it is required to investigate potential impacts and mitigation measures, which are outlined in the following. Due to the limited area (1km²) where we plan to thicken the ice, the impact on the physical environment is expected to be minimal, and can in nature be compared to the creation of ice roads. A hole is drilled through the ice, after which a pump is placed into the hole to pump water on top of the ice, which will freeze rapidly and leads to thicker ice. Both drilling and pumping will make noise, which could disturb local wildlife and thus also local hunting and trapping activities. To avoid such disruption, we took into account local input on the optimal field test area, and agreed that the exact field test location will be determined in close collaboration with the Hunters & Trappers Organization just before the beginning of the test. Wildlife monitors will continuously assess the site during operations, and all activities will pause if wildlife is observed nearby, resuming only after they've left. Operations are planned for February to avoid disturbance due to artificial light in the polar night. High-flow pumps and electric drills will minimize operational time and noise. Snowmobile traffic will be limited to a single, marked route to reduce disturbance. All waste will be collected and returned to Qikiqtarjuaq daily. Any measurement equipment left on the ice will be properly secured, floatable, GPS-trackable, and clearly marked with our contact information to ensure safe recovery after the test period. Snowmobile refueling will only occur in the village, eliminating spill risks on the sea ice. The gasoline-powered pumps, designed for ice thickening, hold 20 liters of fuel and require at most one refueling per day. This will be done by swapping full 20-liter steel jerrycans, avoiding the need to pour fuel on the ice. At the end of the season, we will recover all remaining buoys and floating monitoring platforms to ensure minimal environmental impact. We have prepared our own more elaborate EIA (as a separate document).

F. Next steps

In further preparation of the field test, we will continue engagement with Qikiqtarjuaq local community, see above for some ideas; further contacts with the Qik SAO and HTO and asking them to put us in contact e.g. with the school, and planning the public event; producing posters in Inuktitut on the project; presence on social media and local radio.

For the preparation of the field test, we will continue with the engineering of our system with our engineering partners, and do an equipment test in December on a frozen lake in Canada (for which we have also acquired the required permits, and have liaised with the relevant municipality representatives on how to best engage the local community), to ensure everything works properly during the field test, and we have the right spare parts with us. We are furthermore organizing the logistics for the field test, preparing the operational plan, including updating our safety policy.

For the execution of the field test, we have agreed that we will employ local people as part of the team, specifically for safety (wildlife monitoring, ice & weather conditions) during the field test itself, and for measurements and monitoring during the period until the ice has melted. For this, we will provide training on the job. We are in the process of hiring the required people via SmartICE, to handle liabilities, and ensure they are properly trained and equipped (this was also separately recommended to us by the Laval Research Centre representative). This may evolve in a broader partnership where we can further co-develop our ice-thickening methods together with the local community representatives – the aim is to discuss this after the joint field test cycle evaluation, next summer.

We will periodically update the ARIA team on engagement activities and community inputs in our quarterly project check-ins, to ensure that ARIA's role in facilitating conversations with both national and supra-national Inuit organizations are closely coordinated, and to minimize inconsistencies or misunderstandings.

Appendix

Documents informing our consultation meetings

- Nunavut research strategy mostly underlines local benefit from research - Inuit Circumpolar Council (2022) EEE protocols: nothing about us without us, research benefiting Greenland, respect and appreciation of Indigenous Knowledge and Inuit rights, applying Inuit methodologies including patient listening; co designing projects
- Inuit Qaujimajatuqangit principles
- ITK and NRI (2006) Negotiating Research Relationships with Inuit Communities. Scot Nickels, Jamal Shirley, and Gita Laidler (eds). Inuit Kanatami and Nunavut Research Institute: Ottawa and Iqaluit. 25 pp.
- Publications on decolonial Arctic research: Herrmann et al. 2023, Holmberg et al. 2022, that highlight that indigenous peoples need to be funded and included in project planning as partners and leaders; need to ensure funding for participation (preferably starting from since the funding programmes are planned, but this is not always possible in the present situation)
- Ellam Yua et al. 2022 on knowledge co-production and Indigenous Knowledge
- American Geographical Union (2024) Ethical Framework Principles for Climate Intervention research: justice and public participation

Attachment

Letter of Support by Senior Administrative Officer of the Hamlet of Qikiqtarjuaq



MUNICIPALITY OF QIKIQTARJUAQ

P. O. Box 4

Qikiqtarjuaq, NU X0A 0B0

Tel. (867) 927-8832 Fax (867) 927-8120

September 16, 2025

To Whom It May Concern,

This letter is to confirm that the Hamlet of Qikiqtarjuaq supports the Arctic Ice Thickening research project proposed by Arctic Reflections, scheduled to take place in the winters of 2026 and 2027.

The planned fieldwork will be conducted on the sea ice directly off the coast of Qikiqtarjuaq. For each year, the exact location will be selected in close consultation with and agreement of the Qikiqtarjuaq community.

We welcome Arctic Reflections' plan to work closely with the Qikiqtarjuaq community—using local services like guiding and including Inuit knowledge about the sea ice in their work.

The project will thicken about 1 km² of sea ice by pumping seawater onto the surface. This will take 3 to 4 weeks in winter. After that, small instruments like smart buoys will track how long the ice lasts and how much sunlight it reflects, compared to nearby non-thickened ice. Monitoring will continue through the melting season using local sensors and satellites.

We understand that the project is intended as a scientific field test and monitoring campaign, and we support this effort to better understand how Arctic sea ice preservation could contribute to climate resilience.



SCREENING DECISION REPORT NIRB FILE No.: 25YN078

NPC File No.: 150932

January 12, 2026

Following the Nunavut Impact Review Board's (NIRB or Board) assessment of all materials provided, the NIRB is recommending that a review of Arctic Reflections' "Arctic Ice Thickening Field Test Qikiqtarjuaq" is not required pursuant to Article 12, Section 12.4.4(a) of the *Agreement between the Inuit of the Nunavut Settlement Area and Her Majesty the Queen in right of Canada (Nunavut Agreement)* and s. 92(1)(a) of the *Nunavut Planning and Project Assessment Act*, S.C. 2013, c. 14, s. 2 (*NuPPAA*).

Subject to the Proponent's compliance with the terms and conditions as set out in below, issued in accordance with s. 92(2)(a) of *NuPPAA*, the NIRB is of the view that the project proposal is not likely to cause significant public concerns, and it is unlikely to result in significant adverse environmental and social impacts. The NIRB therefore recommends that the responsible Minister accepts this Screening Decision Report.

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REGULATORY FRAMEWORK

The primary objectives of the NIRB are set out in Article 12, Section 12.2.5 of the *Nunavut Agreement* and are confirmed by s. 23 of the *NuPPAA*. The purpose of screening is provided for under Article 12, Section 12.4.1 of the *Nunavut Agreement* and s. 88 of the *NuPPAA*.

As set out under Article 12, Section 12.4.4 of the *Nunavut Agreement* and s. 92(1) of the *NuPPAA*, upon conclusion of the screening process, the Board must provide its written report the Minister indicating one of three options:

- (a) a review of the project is not required;
- (b) a review of the project is required; or
- (c) the project should be modified or abandoned.

PROJECT OVERVIEW & THE NIRB ASSESSMENT PROCESS

On October 17, 2025, the NIRB received a referral to screen Arctic Reflections' "Arctic Ice Thickening Field Test Qikiqtarjuaq" project proposal (NIRB File No: 25YN078) from the Nunavut Planning Commission (Commission), which noted that the project proposal is outside the area of an applicable land use plan. All documents received and pertaining to this project proposal can be accessed from the NIRB's Public Registry by using any of the following search criteria or www.nirb.ca/project/126244.

- Project Name: Arctic Ice Thickening Field Test Qikiqtarjuaq
- NIRB File No.: 25YN078
- NIRB Application No.: 126244

Table 1: NIRB's Assessment Process

Date	Stage
October 17, 2025	Receipt of project proposal which noted that the project proposal is outside the area of an applicable land use plan.
October 17, 2025	Pursuant to s. 144(1) of the <i>NuPPAA</i> the NIRB requested the Proponent complete an online application to address information required for Screening
October 21, 2025	Receipt of online application from Proponent
November 6, 2025	Scoping pursuant to s. 86(1) of the <i>NuPPAA</i>
November 19, 2025	Translated Public engagement and comment request (which included terms and conditions) was issued to the following community of Qikiqtarjuaq
December 1, 2025	Receipt of public comments
January 12, 2026	Issuance of Screening Decision Report

1. Project Scope

Location	Qikiqtani region, within 10 km of Qikiqtarjuaq
Objective	The Proponent intends to conduct a field test of Arctic Ice Thickening by pumping seawater onto the sea ice surface to increase ice thickness, and to

	measure whether the method is effective under Nunavut conditions, how long the thickened ice persists, and whether there are environmental or wildlife impacts.
Timeline	Start: February 1, 2026 End: July 31, 2026

As required under s. 86(1) of the *NuPPAA*, the Board accepted the scope of the project as set out by Arctic Reflections in the proposal. The scope of the project proposal includes the following undertakings, works, or activities:

Transportation & Access

- Three (3) snowmobiles
- Three (3) sleds for transporting equipment

Ice Drilling & Pumping Operations

- Three (3) drills to create holes in the sea ice
- Three (3) gasoline-powered pumps to pump seawater onto the ice surface for thickening

Monitoring & Measurement Equipment

- Two (2) Smart buoys (ice thickness, solar reflection)
- Two (2) SAMS SIMBA sensors (snow/ice thickness, water & air temperatures)
- One (1) anemometer (wind speed, direction, temperature)
- Two (2) radiometers (shortwave & longwave radiation)
- Two (2) data loggers (store/transfer monitoring data)
- Two (2) time-lapse cameras (ice melt and visual validation)
- Two (2) floating platforms to support instruments during melt season

Sampling Equipment

- One (1) Mark II Kovacs Ice Corer (ice thickness, temperature, salinity sampling)

Fuel Requirements

- 2,500 L gasoline for pumps (125 × 20 L jerrycans)
- 200 L gasoline for snowmobiles (10 × 20 L jerrycans)
- **Total: 2,700 L**

2. Inclusion or Exclusion to Scoping List

The NIRB has identified no additional works or activities in relation to the project proposal. As a result, the NIRB will proceed with screening the project based on the scope as described above.

3. Public Comments and Concerns

As outlined in Table 1 above, notices regarding the NIRB's screening of this project proposal were distributed to community organizations as well as to relevant federal and territorial government agencies, Inuit organizations and other parties with a request for interested parties to provide the Board with any comments or concerns regarding:

- Whether the project proposal is likely to arouse significant public concern; and if so, why;
- Whether the project proposal is likely to cause significant adverse eco-systemic or socio-economic effects; and if so, why;
- Whether the project proposal is likely to cause significant adverse impacts on wildlife habitat or Inuit harvest activities; and if so, why;

- Whether the project proposal is of a type where the potential adverse effects are highly predictable and mitigable with known technology, (and providing any recommended mitigation measures); and
- Any matter of importance to the Party related to the project proposal.

Additionally, proposed project-specific terms and conditions, should the project proceed, were attached for consideration and comment.

On or before December 1, 2025, the NIRB received comments from the following interested parties:

Table 2: Comments Received

Commenting Party	NIRB Doc ID No.
Transport Canada	358300

a. Summary of Comments and Concerns Received

The following provides a summary of the comments and concerns received by the NIRB in relation to the Arctic Ice Thickening Field Test Qikiqtarjuaq project proposal:

Transport Canada

- The project proposes to use two (2) floating platforms to keep scientific instruments floating when the ice starts to melt in summer. The Arctic Ocean is a navigable waterway and works in navigable waterways are subject to the *Canadian Navigable Waters Act* (CNWA) and in some cases may require an approval under the CNWA.
- Recommended the Proponent should self-assess using the Transport Canada Navigation Protection Program (NPP)'s Project Review Tool (<https://npp-submissions-demandes-ppn.tc.canada.ca/projectreview-outildexamenduprojet>) to determine if the CNWA applies while the platforms are floating in open, navigable waters.
- Recommended the Proponent should contact the NPP at NPPPNR-PPNRPN@tc.gc.ca directly for further advice.

4. b. Comments and Concerns with respect to Inuit Qaujimaningit, Indigenous and Community Knowledge

No concerns or comments were received with respect to Inuit Qaujimaningit or Indigenous and Community knowledge in relation to the proposed project. However, Inuit Qaujimaningit and Indigenous and community knowledge is incorporated into the terms and conditions recommended below based on information collected from prior and similar projects, data collected and mapped by the Commission, and other available sources.

ASSESSMENT OF THE PROJECT PROPOSAL IN ACCORDANCE WITH PART 3 OF NUPPAA

In determining whether a review of the project is required, the Board considered whether the project proposal had potential to result in significant ecosystemic or socio-economic impacts. Table 3. The Board took particular care to consider Inuit Qaujimaningit, Indigenous and

Community Knowledge in carrying out its assessment and determination of the significance of impacts.

Table 3: Summary of the Board's Assessment of Factors s. 90 NuPPAA

Factor	Comment
The size of the geographic area, including the size of wildlife habitats, likely to be affected by the impacts.	▪ The project footprint is limited to a maximum of 1 km² of seasonal sea ice. ▪ The project is not located within identified or critical wildlife habitat. While far-ranging species (e.g., polar bear, migratory birds) may occur within the broader regional range, any potential interactions are expected to be localized and temporary.
The ecosystemic sensitivity of that area.	▪ No specific areas of ecosystemic sensitivity have been identified by the Proponent within the physical footprint of the proposed project.
The historical, cultural and archaeological significance of that area.	▪ No specific areas of historical, cultural and archaeological significance have been identified by the Proponent within the physical footprint of the proposed project.
The size of the human and the animal populations likely to be affected by the impacts.	▪ The proposed project is unlikely to result in impacts to local human and animal populations.
The nature, magnitude and complexity of the impacts; the probability of the impacts occurring; the frequency and duration of the impacts; and the reversibility or irreversibility of the impacts.	▪ A zone of influence of up to 1 km² from the most potentially-disruptive project activities was selected for the NIRB's assessment. ▪ With adherence to the relevant regulatory requirements and application of the mitigation measures recommended by the NIRB, no significant residual effects are expected to occur.
The cumulative impacts that could result from the impacts of the project combined with those of any other project that has been carried out, is being carried out or is likely to be carried out.	▪ Table 4 is a list of past, present and reasonably foreseeable projects. The Board recommended terms and conditions along with mitigation measures designed with consideration for the potential for cumulative effects in the Board Views section.
Any other factor that the Board considers relevant to the assessment of the significance of impacts.	▪ No other relevant factors were identified; however, see below for Regulatory Requirements mandating mitigation and/or reporting.

Regulatory Requirements

The Proponent is also advised that the following legislation may apply to the Project:

Acts and Regulations

1. The *Fisheries Act* (<http://laws-lois.justice.gc.ca/eng/acts/F-14/index.html>).

2. The *Species at Risk Act* (<https://laws-lois.justice.gc.ca/eng/acts/s-15.3/>). Attached in **Appendix A** is a list of Species at Risk in Nunavut.
3. The *Wildlife Act (Nunavut)* and its corresponding regulations (<http://www.canlii.org/en/nu/laws/stat/snu-2003-c-26/latest/snu-2003-c-26.html>).
4. The *Nunavut Act* (<http://laws-lois.justice.gc.ca/eng/acts/N-28.6/>). The Proponent must comply with the proposed terms and conditions listed in the attached **Appendix B**.
5. The *Arctic Waters Pollution Prevention Act* (<http://laws-lois.justice.gc.ca/eng/acts/A-12/>) and the *Arctic Shipping Safety and Pollution Prevention Regulations* (<https://laws-lois.justice.gc.ca/eng/regulations/SOR-2017-286/index.html>).

Table 4: Past, Present, and Reasonably Foreseeable Projects Considered

NIRB Project Number	Project Title	Project Type
<i>Present Projects – approved or in operation</i>		
25YN018	Physiological response of soft-shell clam <i>Mya truncata</i> to spring microgal blooms	Research
25YN020	Assessing Oil related contaminants in the softshell clam and characterization of invertebrate communities near Qikiqtarjuaq	Research
25YN045	Arctic Coast – Nunavut Community-based Monitoring 2025/2026	Research (seasonal)
25YN066	Coastal Baseline Inventory: Benthic community composition and food web structure in waters adjacent to Qikiqtarjuaq, NU 2025	Research

Views of the Board

In considering the above factors, the Board has identified the following and respectfully provides its views regarding whether or not the proposed project has the potential to result in significant impacts. The NIRB has also proposed terms and conditions that would mitigate the potential adverse impacts identified.

Ecosystem, wildlife habitat and Inuit harvesting activities:

Valued Component	Migratory and non-migratory birds, terrestrial wildlife and Species at Risk
Potential effects:	Minimal potential interaction as the project is offshore and does not overlap with terrestrial habitat or known nesting or staging areas. Temporary disturbance may occur during short deployment of water pumps.
Nature of Impacts:	Low magnitude, short-duration and unlikely to occur. No long-term displacement or habitat alteration expected.

Mitigating Factors:	Small stationary footprint, no lighting, no repeated disturbance, and compliance with SARA and Nunavut Wildlife Act.
Proposed Terms and Conditions:	Fuel and Chemical Storage – 8 through 10 Wildlife – General – 12 through 15

Valued Component	Fish and fish habitat and marine sea ice environment, marine mammal
Potential effects:	Potential adverse impacts to fish, water, the aquatic environment, and marine mammals due to use of water pumps.
Nature of Impacts:	The potential for impacts is considered to be limited and mostly reversible if regulations and best practices for use of fuel are followed.
Mitigating Factors:	The Board is recommending terms and conditions and it is expected that these terms and conditions would mitigate any potential adverse impacts to water quality, fish and fish habitat, and marine mammals in the direct project area and areas adjacent to the proposed project.
Proposed Terms and Conditions:	Water courses/Water bodies – 6

Valued Component	Public and traditional land use activities
Potential effects:	No specific concerns or impacts to public and traditional land use activities in the area have been identified; however, potential adverse impacts to the public and traditional land-use activities may result from proposed project activities such as snowmobile transportation.
Nature of Impacts:	The potential for impacts is considered to be minimal due to the temporary and low-impact nature of the activities, and any resulting impacts would be expected to be reversible.
Mitigating Factors:	Community engagement already initiated with HTA; data generated may improve long-term marine safety and spill response planning.
Proposed Terms and Conditions:	Public Consultation – 16 and 17

Socio-economic effects on northerners:

Valued Component	Economic impact, local business, employment and hiring
Potential effects:	Potential positive impacts to the community of Qikiqtarjuaq resulting from proposed research activities. There is also the potential of non-local workers purchasing arts and crafts from local artisans.
Nature of Impacts:	The potential for positive economic benefits in relation to the research activities are likely but short-term for the duration of activities.
Mitigating Factors:	Board is recommending the Proponent continues to inform the communities of the research activities and ensure potential local hiring opportunities
Proposed Terms and Conditions:	Other - 18

Significant public concern:

Valued Component	Public concern
Potential effects:	No significant public concern was expressed during the public commenting period for this file.
Nature of Impacts:	Each of the potential concerns were discussed in previous sections and the potential for impacts is considered to be minimal as long as the Proponent follow the recommended terms and conditions.
Mitigating Factors:	The Board is recommending terms and conditions to ensure that to the extent possible, the Proponent hire locally and access local services where possible, and to ensure planned activities in the area utilizes available Inuit Qaujimaningit.
Proposed Terms and Conditions:	Other – 16 and 17

Technological innovations for which the effects are unknown:

- No specific issues have been identified associated with this project proposal.

Administrative Conditions:

To encourage compliance with applicable regulatory requirements and assist the Board and responsible authorities with compliance and effects monitoring for project activities, the following project-specific terms and conditions have been recommended: 1-5.

In considering the above factors and subject to the Proponent's compliance with regulatory requirements and the terms and conditions necessary to mitigate against the potential adverse environmental and social effects, the Board is of the view that the proposed project is unlikely to cause significant public concern and its adverse ecosystemic and socioeconomic impacts are unlikely to be significant, or are highly predictable and can be adequately mitigated by known technologies.

RECOMMENDED PROJECT-SPECIFIC TERMS AND CONDITIONS

The Board is recommending the following specific terms and conditions to apply in respect of the project:

General

1. Arctic Reflections (the Proponent) shall maintain a copy of the Project Terms and Conditions at the site of operation at all times and make it accessible to enforcement officers upon request.
2. The Proponent shall operate in accordance with all commitments stated in correspondence provided to the Nunavut Planning Commission (NPC File No.: 150932, and the NIRB (Online Application Form, October 21, 2025. This information should be accessible to enforcement officers upon request.
3. The Proponent shall operate the site in accordance with all applicable Acts, Regulations and Guidelines.

4. The Proponent shall ensure that it meets the standards and/or limits as set out in the authorizing agencies' permits or licences as required for this project.
5. The Proponent shall ensure that all personnel, staff and contractors are adequately trained prior to commencement of all project activities, and shall be made aware of all operational plans, management plans, guidelines and Proponent commitments relating to the project.

Water courses/Water bodies (including fresh and marine waters)

6. The Proponent shall not deposit, nor permit the deposit of any fuel, chemicals, wastes (including wastewater) or sediment into any water body. The Proponent should have in place an Emergency Spill Response Plan that is approved by the appropriate authorizing agency(ies).

Waste Management

7. The Proponent shall manage all hazardous and non-hazardous waste including food, domestic wastes, debris and petroleum-based chemicals (e.g., greases, gasoline, glycol-based antifreeze) in such a manner to avoid release into the environment and access to wildlife at all times until disposed of appropriately or at an approved facility.

Fuel and Chemical Storage

8. The Proponent shall have a Spill Contingency Plan in place at all fuel storage or transfer locations and shall ensure that appropriate spill response equipment and clean-up materials (e.g., shovels, pumps, barrels, drip pans, and absorbents) are readily available.
9. The Proponent shall follow the authorizing agencies' direction for management and removal of hazardous materials and wastes (e.g., contaminated soils, sediment and waste oil).
10. The Proponent shall ensure that all spills of fuel or other deleterious materials of 100 litres or more must be reported immediately to the 24-hour Spill Line at (867) 920-8130.

Air Quality

11. The Proponent shall eliminate unnecessary idling to reduce greenhouse gas emissions as much as possible.

Wildlife – General

12. The Proponent shall not substantially alter or damage or destroy any wildlife habitat in conducting this operation unless otherwise authorized by the appropriate authorizing agencies.
13. The Proponent shall not chase, weary, harass or molest wildlife. This includes persistently circling, chasing, hovering over, pursuing or in any other way harass wildlife, or disturbing large groups of animals.
14. The Proponent shall not hunt or fish, unless proper Nunavut authorizations have been acquired.
15. The Proponent shall ensure that all wildlife have the right-of-way on any roads or trails. Vehicles are required to slow down or stop and wait to permit the free and unrestricted movement of wildlife across roads or trails at any location.

Other

16. The Proponent should engage with local residents regarding planned activities in the area and should solicit available Inuit Qaujimaningit and information regarding current recreational and traditional usage of the project area which may inform project activities. Posting of translated public notices and direct engagement with potentially interested groups and individuals prior to undertaking project activities is strongly encouraged.
17. The Proponent shall ensure that project activities do not interfere with Inuit wildlife harvesting or traditional land use activities.
18. The Proponent should, to the extent possible, hire local people and access local services where possible.

OTHER NIRB CONCERNS AND RECOMMENDATIONS

In addition to the project-specific terms and conditions, the Board is recommending the following:

Change in Project Scope

1. Responsible authorities or Proponent shall notify the Nunavut Planning Commission and/or Parks Canada as appropriate, and the NIRB of any changes in operating plans or conditions, including phase advancement, associated with this project prior to any such change.

Copy of licences, etc. to the Board and Commission

2. The NIRB respectfully requests that responsible authorities submit a copy of each licence, permit or other authorization issued for the Project to the NIRB to assist in enabling possible project monitoring that may be required. Please forward a copy of the licences, permits and/or other authorizations to the NIRB directly at info@nirb.ca or upload a copy to the NIRB's online registry at www.nirb.ca.

Use of Inuit Qaujimaningit

3. The Proponent is encouraged to work with local communities and knowledge holders to inform project design, to carry out the project, and to confirm or validate the perspectives represented in publications, and reports produced as part of the project. Care should be taken to ensure that Inuit Qaujimaningit and local knowledge collected for the project is used with permission and is accurately represented.

Bear and Carnivore Safety

4. The Proponent should review the Government of Nunavut's booklet on Bear Safety, which can be downloaded from this link: http://gov.nu.ca/sites/default/files/bear_safety_-_reducing_bear-people_conflicts_in_nunavut.pdf. Further information on bear/carnivore detection and deterrent techniques can be found in the "Safety in Grizzly and Black Bear Country" pamphlet, which can be downloaded from this link: https://www.enr.gov.nt.ca/sites/enr/files/resources/safety_in_grizzly_and_black_bear_country_english.pdf.

5. There are polar bear and grizzly bear safety resources available from the Bear Smart Society with videos on polar bear safety available in English, French and Inuktitut at <http://www.bearsmart.com/play/safety-in-polar-bear-country/>. Information can also be obtained from Parks Canada's website on bear safety at the following link: <http://www.pc.gc.ca/eng/pn-np/nu/quttinirpaaq/visit/visit6/d.aspx> or in reviewing the "Safety in Polar Bear Country" pamphlet, which can be downloaded from the following link: http://www.pc.gc.ca/eng/pn-np/nu/quttinirpaaq/visit/visit6/~media/pn-np/nu/auyuittuq/pdf/shared/PolarBearSafety_English.ashx.
6. Any problem wildlife or any interaction with carnivores should be reported immediately to the local Government of Nunavut, Department of Environment Conservation Office (Conservation Officer of Qikiqtarjuaq, phone: (867) 927-8966.

CONCLUSION

The foregoing constitutes the Board's screening decision with respect to the Arctic Reflections' "Arctic Ice Thickening Field Test Qikiqtarjuaq". The NIRB remains available for consultation with the Minister regarding this report as necessary.

Dated January 12, 2026 at Iqaluit, NU.



Albert Ehloak, *Acting* Chairperson

Attachments: Appendix A: Species at Risk in Nunavut

APPENDIX A: SPECIES AT RISK IN NUNAVUT

Due to the requirements of Section 79(2) of the *Species at Risk Act*, S.C. 2002, c. 29 (SARA), and the potential for project-specific adverse effects on listed wildlife species and its critical habitat, measures should be taken as appropriate to avoid or lessen those effects, and the effects need to be monitored. Project effects could include species disturbance, attraction to operations and destruction of habitat. This section applies to all species listed on Schedule 1 of SARA, as listed in the table below, or have been assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), which may be encountered in the project area. This list may not include all species identified as at risk by the Territorial Government. The following points provide clarification on the applicability of the species outlined in the table.

- Schedule 1 is the official legal list of Species at Risk for SARA. SARA applies to all species on Schedule 1. The term “listed” species refers to species on Schedule 1.
- Schedule 2 and 3 of SARA identify species that were designated at risk by the COSEWIC prior to October 1999 and must be reassessed using revised criteria before they can be considered for addition to Schedule 1.
- Some species identified at risk by COSEWIC are “pending” addition to Schedule 1 of SARA. These species are under consideration for addition to Schedule 1, subject to further consultation or assessment.

If species at risk are encountered or affected, the primary mitigation measure should be avoidance. The Proponent should avoid contact with or disturbance to each species, its habitat and/or its residence. All direct, indirect, and cumulative effects should be considered. Refer to species status reports and other information on the Species at Risk Registry at <http://www.sararegistry.gc.ca> for information on specific species.

Monitoring should be undertaken by the Proponent to determine the effectiveness of mitigation and/or identify where further mitigation is required. As a minimum, this monitoring should include recording the locations and dates of any observations of Species at Risk, behaviour or actions taken by the animals when project activities were encountered, and any actions taken by the proponent to avoid contact or disturbance to the species, its habitat, and/or its residence. This information should be submitted to the appropriate regulators and organizations with management responsibility for that species, as requested.

For species primarily managed by the Territorial Government, the Territorial Government should be consulted to identify other appropriate mitigation and/or monitoring measures to minimize effects to these species from the project.

Mitigation and monitoring measures must be undertaken in a way that is consistent with applicable recovery strategies and action/management plans.

Schedules of SARA are amended on a regular basis, so it is important to check the SARA registry (www.sararegistry.gc.ca) to get the current status of a species.

Updated: September 2024

Terrestrial Species at Risk¹	COSEWIC Designation	Schedule of SARA	Government Organization with Primary Management Responsibility²
Buff-breasted Sandpiper	Special Concern	Schedule 1	Environment and Climate Change Canada (ECCC)
Common Nighthawk	Threatened	Schedule 1	ECCC
Eskimo Curlew	Endangered	Schedule 1	ECCC
Harlequin Duck	Special Concern	Schedule 1	ECCC
Harris's Sparrow	Special Concern	Schedule 1	ECCC
Horned Grebe	Special Concern	Schedule 1	ECCC
Ivory Gull	Endangered	Schedule 1	ECCC
Olive-sided Flycatcher	Threatened	Schedule 1	ECCC
Peregrine Falcon	Special Concern	Schedule 1	ECCC
Red Knot Islandica Subspecies	Special Concern	Schedule 1	ECCC
Red-necked Phalarope	Special Concern	Schedule 1	ECCC
Ross's Gull	Threatened	Schedule 1	ECCC
Rusty Blackbird	Special Concern	Schedule 1	ECCC
Short-eared Owl	Special Concern	Schedule 1	ECCC
Porsild's Bryum	Threatened	Schedule 1	Government of Nunavut (GN)
Transverse Lady Beetle	Special Concern	No Schedule	GN
Caribou (Dolphin and Union Population)	Endangered	Schedule 1	GN
Caribou (Barren-ground Population)	Threatened	No Schedule	GN
Caribou (Torngat Mountains Population)	Endangered	No Schedule	GN
Grizzly Bear (Western Population)	Special Concern	Schedule 1	ECCC
Peary Caribou	Endangered	Schedule 1	GN
Polar Bear	Special Concern	Schedule 1	ECCC
Wolverine	Special Concern	Schedule 1	GN
Atlantic Walrus (High Arctic Population)	Special Concern	No Schedule	Fisheries and Oceans Canada (DFO)
Atlantic Walrus (Central/Low Arctic Population)	Special Concern	No Schedule	DFO
Beluga Whale (Cumberland Sound Population)	Threatened	Schedule 1	DFO
Beluga Whale (Eastern Hudson Bay Population)	Endangered	No Schedule	DFO
Beluga Whale (Eastern High Arctic-Baffin Bay Population)	Special Concern	No Schedule	DFO
Beluga Whale (Western Hudson Bay Population)	Special Concern	No Schedule	DFO
Atlantic Cod (Arctic Lakes Population)	Special Concern	No Schedule	DFO
Fourhorn Sculpin (Freshwater Form)	Data Deficient	Schedule 3	DFO
Lumpfish	Threatened	No Schedule	DFO
Thorny Skate	Special Concern	No Schedule	DFO

¹ The Department of Fisheries and Oceans has responsibility for aquatic species.

² Environment and Climate Change Canada (ECCC) has a national role to play in the conservation and recovery of Species at Risk in Canada, as well as responsibility for management of birds described in the Migratory Birds Convention Act (MBCA). Day-to-day management of terrestrial species not covered in the MBCA is the responsibility of the Territorial Government. Populations that exist in National Parks are also managed under the authority of the Parks Canada Agency.





ARIA

mark.symes@aria.org.uk

26 January 2026

Dear Exploring Climate Cooling programme team,

In his decision letter for the outdoor experiments planned by Arctic Reflections in February-July 2026 as part of the ARIA funded Re-thickening Arctic Sea Ice (RASI) project, ARIA's CEO asked for the following as conditions 2b(i) and 2b(ii):

That the RASI team documents and shares with local communities the following before the experiments start, in a manner that is accessible for those communities:

i. Information on their process(es) for achieving consent, for confirming continued consent, and for discerning/accepting withdrawal of consent. This information should include in particular how any dissent within the community and from Elders will be documented and handled.

ii. Information on practices related to community benefit, including the approach to coauthorship that will be followed and the approach that they will take to other forms of recognition of contributions (including, for example: instruments, guidance on experiments, and insights from Elders and others).

I am writing to confirm that Arctic Reflections believe that they have met these conditions as follows:

On condition 2b(i): Achieving and Withdrawal of Consent

Since engaging with the community at Qikiqtarjuaq in June 2025, after a visit to the community involving meetings with key Hamlet and HTO (Hunters & Trappers Organization) representatives, the team has obtained formal letters of support by the Hamlet and HTO, as well as informal enthusiasm from key community members. In order to further formalize this and also provide a clear & transparent procedure for withdrawal of consent, they have set-up a clear policy outlining such procedures as well as how community members can raise concerns, how progress will be jointly evaluated, and how continued consent and trust by the community will need to be continually "earned". The policy document has been shared with key representatives of the community (see <https://arcticreflections.earth/local-communities/>). This is a live document which will be updated as feedback continues to be received.

On condition 2b(ii): Recognition of research contributions by local community members

Arctic Reflections is committed to recognising the contributions of their co-researchers in the Qikiqtarjuaq community, specifically the local co-workers that contribute to the research, planning and operation of the field tests. This commitment is also part of the policy document that has been shared with the community.



UNIVERSITY OF
CAMBRIDGE



Centre for
Climate Repair

Yours sincerely

Professor Shaun Fitzgerald OBE FREng (Director)

Principal Investigator of RASI project

Centre for Climate Repair

Environmental Impact Assessment (EIA)

By Arctic Reflections B.V., October 2025

Arctic Ice Thickening Field Test

Field Test in February 2026, Qikiqtarjuaq, Nunavut
(formerly known as Broughton Island)





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We contribute to
Sustainable Development Goals

1. Introduction and Purpose

This Environmental Impact Assessment (EIA) evaluates the potential environmental effects associated with the Arctic Ice Thickening (AIT) field test to be conducted directly off the southeast coast of Qikiqtarjuaq (Nunavut) in February. The purpose of this field test is to evaluate the scientific and technical feasibility of using AIT to thicken sea ice in order to enhance its seasonal persistence, reflectivity, and potential cooling effect. The overall goal is to assess whether AIT can contribute to mitigating Arctic sea ice loss and related ecosystem impacts caused by global warming.

The main body of this document will provide a summarized overview of potential impact and relevant mitigation measures. Annex I will provide a detailed overview for each species used to compile the summarized overview. This EIA was informed by a broader Environmental Risk Assessment of the Arctic Reflections' sea ice thickening methodology in the Canadian Arctic (M. Teunis, 2023).

2. Project Overview

Three tailor-made skid barges equipped with pumps will be towed to the site by snowmobiles. The pumps, mounted on lifting frames, will extract seawater from below the ice and discharge it onto the surface to promote controlled ice thickening. Two alternating crews of five to eight people each will conduct the operations over approximately four weeks. The first crew will install scientific instruments, commission the pumps, and initiate ice thickening. After 2.5 weeks, the second crew will continue the process, complete the thickening phase, and carry out cleanup and storage of the equipment. Scientific instruments will remain in place to monitor melting throughout the spring and summer seasons, after which they will be recovered.

3. Site Description and Baseline Conditions

The field test will take place off the southeast coast of Qikiqtarjuaq, located on the east coast of Baffin Island in Nunavut. We identified 2 zones within which our field test could take place. Following an in-person joint meeting with the Hunters and Trappers Organization (HTO) and the Hamlet of Qikiqtarjuaq on September 10th, 2025, we jointly decided to designate a new Zone 3 (south-east of Qikiqtarjuaq) as the preferred location for our upcoming field test. Zone 3 has been selected because the likelihood of disturbing wildlife is lower compared to the previously indicated Zones 1 and 2. Zone 2 will not be considered anymore. Zone 1 will remain only as a fallback option, to be considered solely in extraordinary circumstances and only if the HTO determines just before the start of the field test that Zone 1 takes preference over Zone 3. Figure 1 shows these three zones. For reference, we have included a rectangle within each zone to illustrate the size of the final 1 km² site relative to the overall zone. The exact location within this zone will be chosen just before the start of the field test in collaboration with the HTO, to avoid areas where animals are known to gather while staying clear of community travel routes.

The Qikiqtarjuaq region is part of the Qikiqtaaluk (Baffin) region and falls within Inuit Nunangat. The area is characterized by landfast sea ice in winter, rugged fjord coastlines, and proximity to the Davis Strait. The local community of Qikiqtarjuaq has a population of approximately 600 people, with livelihoods closely tied to traditional harvesting and marine resources (Kanatami, 2023, pp. 5-6). The area supports species including ringed seals, bearded seals, polar bears, Arctic char, seabirds, and occasionally narwhals and bowhead whales during open-water seasons. The nearest sensitive habitat

features include polynyas and floe-edge ecosystems located farther east, outside the operational area (Copernicus Climate Change Service, 2021). (Qikiqtani Inuit Association, 2018, p. 33)



4.2 Biological Environment

The biological environment includes ice-dependent mammals (ringed and bearded seals, polar bears), Arctic cod, seabirds, and microorganisms inhabiting the sea ice. Operations are planned for February, prior to the ringed seal pupping season (March–April) and before the peak biological productivity period (April–June). Disturbance to wildlife is expected to be temporary and localized. Noise from pumps and snowmobiles may cause avoidance behavior in nearby seals or polar bears, though mitigation measures will minimize this risk. The impact of artificial light will be minimal, as operations occur primarily under natural daylight conditions. No significant effect on fish populations or plankton communities is anticipated. Arctic char typically winter and spawn in lakes (Fisheries and Oceans Canada, 2023, p. 18) and Arctic cod spawn in deeper ice-covered offshore areas and the site is distant from known spawning grounds (e.g., Franklin and Darney Bays). (Geoffroy, 2023, p. 7).

4.3 Socioeconomic and Cultural Environment

Qikiqtarjuaq is an Inuit community with active subsistence hunting and fishing, primarily targeting seals, Arctic char, occasionally polar bears and seasonally narwhals (Qikiqtani Inuit Association, 2018, p. 29). The field test area lies outside the main local harvesting routes, reducing potential overlap. Noise and human activity could temporarily disturb seals, potentially affecting harvest

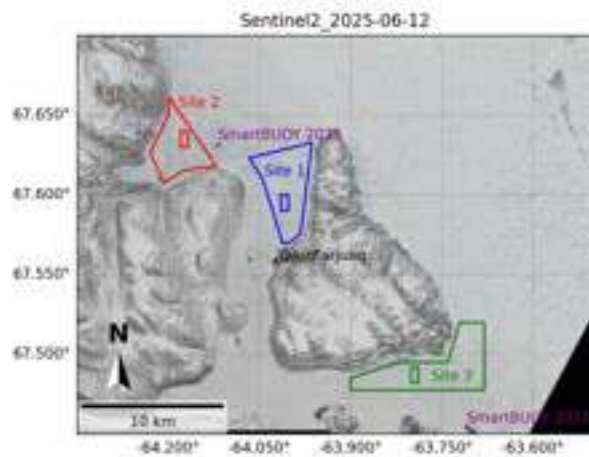


Figure 1: Potential field test sites zones, zone 3 being the preferred location

4. Analysis of Potential Environmental Impacts

4.1 Physical Environment

The physical disturbance from the AIT test will be minimal given its small (1 km²) footprint. Pumping seawater onto sea ice can be compared to constructing temporary ice roads in terms of physical impact. All activities are conducted during the winter season when the sea ice is stable and thick. No sediment disturbance is expected since pump inlets will be limited to a maximum depth of 50 cm below the ice surface, with local water depths easily exceeding 10 meters. No long-term alteration of the seafloor or hydrodynamic processes is anticipated. The thickened ice will eventually melt during summer, ensuring no lasting physical modification to the environment

Figure 2 Water depth (in meters) at the southern side of Qikiqtarjuaq, the location of our preferred field test zone 3.

opportunities, though this risk is minimal. The project will employ local wildlife monitors and engage community representatives to ensure culturally appropriate and environmentally sensitive operations, consistent with Inuit Tapiriit Kanatami's policy recommendations emphasizing Inuit participation in climate action initiatives (Inuit Tapiriit Kanatami (ITK), 2019, p. 4).

5. Mitigation Measures

- Select field site with input from Inuit wildlife monitors to avoid seal concentrations, denning sites, or key travel routes.
- Use high-flow rate pumps to minimize operational duration and noise.
- Restrict artificial lighting; operate mainly in daylight.
- Cease all operations if polar bears or other wildlife are observed nearby.

- Provide polar bear safety training for personnel.
- Prohibit any approaching or disturbance of wildlife by team members.
- Remove all non-essential equipment and waste after operations to avoid pollution.
- Always take the exact same route to and from the field test location to minimize disturbance caused by snowmobiles

6. Residual Impact Assessment

Due to the limited area and the timing of field test operations in February, no significant impact is expected. The most important mitigation is to minimize the disturbance of seals. Other than that, we think that the impact of our field test can best be compared with the impact of creating an ice road.

Biophysical resource	Potential impact	Proposed Mitigation	Residual impact	Predicted significance
Sea ice	Extended lifetime of sea ice	Limit to max 1 km ²	• low magnitude • localized geographic extent • frequent occurrence • short-term duration • fully reversible	Not significant
Sea water	Disturbance of sediment while pumping	Use of pumps with short water inlet pipe (< 0.5m) while water depth > 10m	• low magnitude • localized geographic extent • frequent occurrence • short-term duration • fully reversible	Not significant
Pinnipeds	Disturbance of ringed seals	• Exact field test area to be chosen based on topical information and advice from wildlife monitors, staying away from seal concentrations • Wildlife Monitors will continuously assess the proposed field test area and advise on any wildlife concerns • Avoid resting and foraging areas while travelling to and from field test area and always use the same route • Minimize use of artificial light / operate in February when there is daylight • Minimize use of artificial noise: use high flow rate pumps to reduce pumping time and limit vehicle movements • Operate in February before birthing period • Team will be instructed to stay away from wildlife and not feed, hunt, trap or disturb them	• low magnitude • localized geographic extent • infrequent occurrence • short-term duration • fully reversible	Not significant

Polar bear	Disturbance, negative human-bear encounters	- Exact field test area to be chosen based on topical information and advice from wildlife monitors, staying far away from known dens - Wildlife Monitors will continuously assess the proposed field test area and advise on any wildlife concerns - Activities will cease if polar bear observed in proximity of the field test site and will only resume after the bear has left the area - Team will receive polar bear training - Minimize use of artificial light / operate in February when there is daylight - Minimize use of artificial noise: use high flow rate pumps to reduce pumping time and limit vehicle movements - Team will be instructed to stay away from wildlife and not feed, hunt, trap or disturb them	- low magnitude - localized geographic extent - infrequent occurrence - short-term duration - fully reversible	Not significant
Fish	Disturbance of Arctic Cod	- Avoid pumping near known spawning areas. Known spawning areas in Canadian Arctic are Franklin and Darney Bays - Field test operations in February. By late spring (after operations) juvenile cod can be found in shallower waters	- low magnitude - localized geographic extent - infrequent occurrence - short-term duration - fully reversible	Not significant
Whales	Disturbance of whales	Field test operations in February when whales are not present	- low magnitude - localized geographic extent - infrequent occurrence - short-term duration - fully reversible	Not significant
Birds	Disturbance of birds	Field test operations in February when migratory birds are not present on the sea ice	- low magnitude - localized geographic extent - infrequent occurrence - short-term duration - fully reversible	Not significant
Phytoplankton and Zooplankton	Disturbance of algae growth and disturbance of zooplankton	- Operations in February avoid disrupting the critical bloom period - Minimize artificial light - Conduct measurements for future reference	- low magnitude - localized geographic extent - infrequent occurrence - short-term duration - fully reversible	Not significant
Impact on harvesting	Disturbance of seals	See mitigation to prevent disturbance of seals in this table	- low magnitude - localized geographic extent - infrequent occurrence - short-term duration - fully reversible	Not significant

7. Conclusion

The environmental impact of the proposed Arctic Ice Thickening (AIT) field test off the southeast coast of Qikiqtarjuaq is expected to be minimal. The activity is temporary, small in scale, and conducted during a period of low biological activity. With the mitigation measures in place, no significant adverse effects are anticipated on the physical, biological, or cultural environment. Continued collaboration with local Inuit organizations and wildlife monitors ensures that the project aligns with community values and respects Inuit rights under the Nunavut Agreement and UNDRIP.

8. References

Copernicus Climate Change Service. (2021). *Circumpolar map of known polynyas and ice conditions in the Arctic*.

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Nunavut department of Environment. (2010). *Nunavut Coastal Resource Inventory*.

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Annex I: Detailed overview per species

Potential Impacts on Pinnipeds around Qikiqtarjuaq (February – March)

Ringed Seals: Small pinnipeds (~1.5 m, 68 kg in winter) that depend on thick blubber layers for insulation and energy during the breeding season. They are key prey for polar bears and subsistence species for local communities. They primarily feed on arctic cod and crustaceans. Pupping starts at the end of March, but most born in April. To be found mainly to the Northwest of Qikiqtarjuaq year-round (Nunavut department of Environment, 2010, p. 52) (Qikiqtani Inuit Association, 2018, p. 70).

- Bearded Seals: Larger seals (~2.4 m, up to 340 kg in winter) that rely on benthic prey like crabs, shrimp, and clams. They birth pups on moving sea ice later in the year (April-May). Bearded seals can be found to the Northwest and to the South of Qikiqtarjuaq. The latter being the preferred location of our field test, but there they can only be found between August and November (Nunavut department of Environment, 2010, p. 26) (Qikiqtani Inuit Association, 2018, p. 70).

- Harbour Seals: not present in February-March (Qikiqtani Inuit Association, 2018, p. 71)

- Harp Seals: not present in February-March (Qikiqtani Inuit Association, 2018, p. 71)

- Hooded Seal: not present in February-March (Qikiqtani Inuit Association, 2018, p. 71)

- Walrus: not present in February-March (Qikiqtani Inuit Association, 2018, p. 71)

Potential Impacts of Operations:

1. Disturbance from Noise and Human Activity:

- Noise Stress: Seals are highly sensitive to sound. This could cause seals to flee their resting or foraging areas, leading to increased energy expenditure.

- Displacement: Disturbance might force seals away from preferred habitats near Qikiqtarjuaq, affecting their access to prey and increasing competition in less suitable areas.

- Artificial Light:

- Behavioral Disruption: Artificial lighting during winter could disturb seals' natural behavior, such as resting or hunting. Light may also attract or repel prey species, indirectly affecting seals' foraging success.

- Impact on Ice Habitat:

- Habitat Alteration: Pumping water onto sea ice could change ice thickness and dynamics, potentially impacting seal breathing holes and access to sub-ice habitats.

- Breeding Site Risk: February is before the birthing period for bearded seals, but altering ice conditions later in winter could impact future habitat suitability for denning and pupping later in the year.

	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Qikiqtarjuaq												
bearded seal	X	X	X	X	X	X	X	X	X	X	X	X
harbour seal (rare)			X	X								
harp seal	X	X	X	X	X	X						X
hooded seal	X	X	X	X	X							X
ringed seal	X	X	X	X	X	X	X	X	X	X	X	X
walrus	X	X	X	X	X	X						

Figure 3: Observations of seals and walruses Qikiqtarjuaq [5] (Qikiqtani Inuit Association, 2018, p. 64)



Table 7: Bearded Seal - Areas of Occupation

LABEL NUMBER	INTERVIEW CODE	SPECIES	MONTHS	COMMENTS
2_77	QIK_2_0310	Bearded Seal	Aug-Nov	
3_103	QIK_3_0310	Bearded Seal	Sep-Oct	
6_88A	QIK_6_0310	Bearded Seal	Aug-Sep	

Figure 6: Table showing presence of Bearded Seal to the south of Qikiqtarjuaq (area 2_77) (Nunavut department of Environment, 2010, p. 27)

Conclusion

Operations near Qikiqtarjuaq in February could potentially affect ringed seals; however, these animals are primarily found northwest of Qikiqtarjuaq and not in the southern area where our preferred field test Zone 3 is located. Other pinniped species are not present near the planned operations site.

To minimize any potential impact, a series of mitigation measures will be implemented, focusing on avoiding known resting and foraging areas. Wildlife monitors will be engaged to provide real-time observations

and guidance on selecting the precise field test location. They will continuously monitor the area during operations and promptly alert the team to any seal-related concerns. All team members will be instructed to avoid disturbing seals or other wildlife. Conducting operations in February enables the use of natural daylight—reducing the need for artificial lighting—and ensures that activities take place before the ringed seal birthing season. In addition, the use of high flow rate pumps will help shorten pumping duration, further limiting potential disturbance.

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	January to mid-March	mid-March to third week of May	end of May to mid-July	end of July / beginning of August to mid-September	end of September to November	end of November to end of December
Species						
Ringed seal	breathing holes (maybe at floe edge but harvesting is not done there. Ice too rough)	breathing hole; birthing lair; pupping starts at the end of March, but most born in April	present	present	present	present
Bearded seal	breathing holes (maybe at floe edge but harvesting is not done there. Ice too rough)	breathing hole; birthing lair; pupping starts at the end of March, but most born in April	floe edge; skins best this time of year for boots	present	present	present

Figure 7: Table showing Ringed and Bearded seal distribution around Oikiqtariuaq based on IQ (Oikiqtani Inuit Association, 2018, p. 71)

Potential Impacts on Polar Bears around Qikiqtarjuaq (February–March)

Polar Bears (*Ursus maritimus*): Apex predators of the Arctic that rely on sea ice for hunting, mainly targeting ringed seals. Females den from November to late March/early April, with average litter sizes of 1-3 cubs, and typically breed in late April or early May. Polar bears can be found along the entire Baffin, Devon, and Ellesmere islands coastlines. They have their cubs in dens before ringed seals give birth. Polar bear hunt ringed seal pups in their dens, or out on the open ice (Qikiqtani Inuit Association, 2018, p. 76).

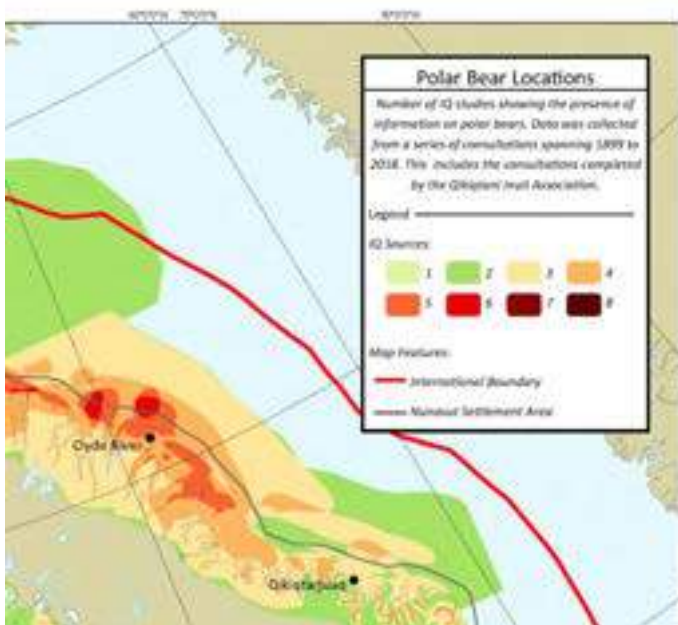


Figure 8 Location of polar bear based on Inuit hunting locations (Qikiqtani Inuit Association, 2018, p. 77)

Potential Impacts of Operations:

1. Disturbance from Noise and Human Activity:

- o Denning Females: Noise from pumping and associated activities near denning areas can disturb pregnant females or mothers with cubs, potentially causing den abandonment, which could lead to cub mortality.
- o Energetic Stress: Polar bears rely on conserving energy during winter. Human

activity that forces movement or alters behavior can increase energy expenditure, reducing survival chances.

2. Artificial Light:

- o Behavioral Disruption: Artificial light may disturb nocturnal hunting or resting patterns, potentially disorienting bears or altering their interaction with prey like ringed seals.
- o Impact on Hunting: Light may also affect the visibility of prey species, influencing hunting success.

3. Impact on Habitat and Prey Availability:

- o Prey Distribution: If ringed seals are displaced or their local populations are reduced due to operations, polar bears may struggle to find sufficient prey, increasing their travel distances and energy use.

4. Impact on Population and Reproduction:

- o Den Site Disruption: Operations in or near key denning areas may harm the reproductive success of females by causing abandonment or physical disturbance of dens.
- o Stress on Cubs: Disturbed females might fail to provide adequate care to cubs, affecting their survival.

Conclusion

Pumping operations, noise, and artificial light near Qikiqtarjuaq in February could impact polar bears, particularly denning females and hunting adults. The most critical concerns are disturbance to denning sites and disruption of hunting opportunities. Implementing mitigation measures will reduce these risks. The field test area will be selected based on current information and guidance from wildlife monitors, ensuring it remains distant from known dens. Wildlife monitors will continuously evaluate the site and provide advice on any concerns related to wildlife. If a polar bear is observed near the field test site, all activities will pause and only resume once the bear has left the vicinity. Additionally, the team will undergo polar bear safety training to ensure preparedness. We plan our

operations in February, so we can make use of daylight and minimize artificial light.

Potential Impacts on Fish Around Qikiqtarjuaq in February

In February, Arctic cod is the only fish species known to remain active under the sea ice near Qikiqtarjuaq. Arctic cod plays a critical role in the Arctic ecosystem, serving as a key prey species for marine mammals like seals and some seabirds. While Arctic char is a common species in the Arctic, they are not present directly in or under sea ice. They lack the necessary antifreeze proteins to survive the frigid saltwater temperatures and risk freezing. They therefore migrate to fresh water to overwinter or migrate to deep offshore areas. They spawn in September in lakes or rivers or streams connected to lakes.

Potential Impacts of Operations:

1. Direct Removal of Eggs or Larvae

- Risk: Arctic cod spawn during the winter, and their eggs and larvae may be present in the water column under the ice. Pumping seawater onto the ice risks unintentionally removing eggs or larvae from the local environment, which could reduce reproductive success in the immediate area. In general, it can be said that Arctic cod moves to deeper, ice-covered waters to release their eggs. The eggs and larvae then drift with the currents, eventually making their way into shallower coastal areas as they develop. By late spring and summer, juvenile cod can often be found in shallower waters

- Mitigation: Avoid pumping near known spawning areas or at depths where eggs and larvae are most concentrated. In the Canadian Arctic, spawning is suggested to occur near the Franklin and Darney Bays [(Geoffroy, 2023, p. 7).

2. Disturbance from Noise

- Risk: Arctic cod are sensitive to underwater noise, which can alter their behavior. Noise generated by pumping

equipment could cause cod to flee, leading to energy loss and potential displacement from optimal foraging grounds.

- Mitigation: limit operating time by using high flow rate pumps

3. Changes in Prey Availability

- Risk: Pumping operations might disturb zooplankton, a primary food source for Arctic cod. Any significant disruption to the local zooplankton population could impact cod feeding opportunities, particularly during the resource-scarce winter months.

- Mitigation: Maintain careful placement of pumping equipment / use short water inlet pipe to reduce the disturbance of zooplankton populations near the sea floor.

Broader Considerations

- Localized Impact: Arctic cod populations are highly adapted to dynamic and harsh conditions, so localized effects are unlikely to significantly impact the broader population.

- Ecosystem Dependency: Since Arctic cod are a cornerstone species, any significant disruption to their lifecycle could cascade through the food web, affecting higher predators like seals and seabirds.

Conclusion

By implementing precautionary measures, the potential risks to Arctic cod during February pumping operations can be minimized, ensuring minimal ecological disruption near Qikiqtarjuaq. Spawning occurs between September and April, and peaks between January and February, when our field test location is planned. We should thus stay away from the known spawning areas in the Canadian Arctic are Franklin and Darney Bays (Geoffroy, 2023, p. 7). By late spring (after our operations) juvenile cod can be found in shallower waters

Potential Impacts on Whales around Qikiqtarjuaq (February–March)

Given the absence of belugas, bowhead whales, and narwhals in the Qikiqtarjuaq region during February and March, the direct impact of Arctic Ice Thickening operations on these species is expected to be negligible.

These whales typically migrate to areas with polynyas or less dense ice during the winter months, avoiding the stable, heavy ice found near Qikiqtarjuaq.

ᐃᐃᐃᐃ Ukiuq	ᐃᐃᐃᐃᐃᐃ Upirngasaaq	ᐃᐃᐃᐃᐃᐃ Upirngaaq	ᐃᐃᐃᐃ Aujaq	ᐃᐃᐃᐃᐃᐃ Ukiassaaq	ᐃᐃᐃᐃ Ukiaq
January to mid-March	Mid-March through third week of May	End of May to mid-July	Mid-End of July to mid-September	End of September to October / November	End of November and December
Not present. In deep water		Moving northward past Qikiqtarjuaq in mid-June	Seldom seen. Maybe be seen in Merchants Bay and Padle Fiord.		Not present

Figure 11 Beluga seasonal distribution near Qikiqtarjuaq (Qikiqtani Inuit Association, 2018, p. 48)

ᐃᑭᐅᓄ Ukluq	ᐃᓕᓴᓴᓴᓴ Upirngasaaq	ᐃᓕᓴᓴ Upirngaaq	ᐱᑭᓂᓄ Aujaq	ᐃᑭᐅᓴᓴᓴ Ukiassaaq	ᐃᑭᐅᓴᓴ Ukiaq
January to mid-March	Mid-March through third week of May	End of May to mid-July	Mid-End of July to mid-September	End of September to October / November	End of November and December
Not present. In deep water at floe edge in Baffin Bay	Migrating north in April	At floe edge; near Qikiqtarjuaq mid-June migrating northward	Migrating south along with other whales	Migrating south along with other whales; Gone by November	Not present; Offshore northern Davis Strait and southern Baffin Bay

Figure 10 Narwhal seasonal distribution near Oikigtarjuag (Oikigtani Inuit Association, 2018, p. 54)

		ᠳᠦᠫᠤᠭ Ukiuq	ᠳᠠᠭᠦᠰᠠᠭ Upirngasaaq	ᠳᠠᠭᠦᠰᠠᠭ Upirngaaq	ᠠᠵᠠᠭ Aujaq	ᠳᠦᠭᠦᠰᠠᠭ Uklassaaq	ᠳᠦᠭᠦᠰᠠᠭ Ukilaq
		winter	early spring	late spring	summer	early fall	fall, early winter
	Qikiqtarjuaq	Not present	Not present	Arriving in July	Present	Leave the area in September	Not present

Figure 9 Seasonal location of killer whale based on IQ (Qikiqtani Inuit Association, 2018, p. 58)

	ᐅᓯᑏᕐ Ukiuq winter	ᐅᓱᑎᑭᓂᓴᑦ Upirngasaaq early spring	ᐅᓱᑎᑭᓴᑦ Upirngaaq late spring	ᐅᓴᑭᓴᑦ Aujaq summer	ᐅᓯᐅᑭᑦ Ukiassaaq early fall	ᐅᓯᐅᑦ Ukiaq fall, early winter
Qikiqtarjuaq	Not present	Not present	Arrive in the area	Abundant in near shore waters, and fiords and inlets	Whales from the north passing by Qikiqtarjuaq. Leave before ice forms	Not present

Figure 12 Seasonal location of bowhead whales based on IQ (Qikiqtani Inuit Association, 2018, p. 60)

Potential Impacts on Birds around Qikiqtarjuaq (February–March)

The majority of marine related birds arrive on Baffin Island during Upirngasaaq (mid-March – beginning of May) and depart towards the end of Aujaq (mid-September).

The exceptions are the Black guillemot and thick-billed murre. They remain in Baffin Bay and Davis Strait year-round, keeping to open

waters during the winter (Qikiqtani Inuit Association, 2018, p. 84).

Our operations in February and beginning of March (Ukiuq) will be on sea ice therefore no birds expected to be present.

	Upirngasaaq	Upirngaaq	Aujaq
Arctic Loon			
Arctic Tern		X	X
Black Guillemot*	X	X	X
Brant Goose		X	X
Canada Geese		X	X
Common Loon			
Red breasted Merganser		X	X
Dovekie		X	X
Eider duck*	X	X	X
Greater Snow Geese		X	X
Gulls		X	X
Harlequin duck		X	X
King Eider		X	X
Black-legged Kittiwake		X	X
Long-tailed Jaeger		X	X
Northern Fulmar		X	X
Long-tailed duck (Oldsquaw)		X	X
Red-necked Phalarope		X	X
Plovers		X	X
Razor Bill		X	X
Red knot		X	X
Ruddy Turnstone		X	X
Sandhill Crane		X	X
Sandpiper		X	X
Shorebirds		X	X
Thick-billed murre*	X	X	X
Tundra Swan		X	X
White-fronted goose		X	X
Yellow-billed Loon		X	X

*These birds remain year round wintering in open water areas

Figure 13 Common birds of Baffin Bay and Davis strait (Qikiqtani Inuit Association, 2018, p. 85)

Potential Impacts on Phytoplankton and Zooplankton

Sea ice is a crucial habitat for microorganisms such as phytoplankton and other microbes that form the base of the Arctic food chain. The spring and summer algae bloom, particularly from April to June, marks a vital period for Arctic marine life, with ice algae starting to bloom as early as April, followed by phytoplankton as the ice melts. These organisms support a wide range of species, from fish to marine mammals and birds. The timing of our operations in February and beginning of March avoids disrupting this critical bloom period, which starts when the sea ice starts thinning.

Artificial light may disturb the natural cycle of zooplankton and krill and invertedly start their diel vertical migration (M. Teunis, 2023, p. 34). Minimizing artificial light will reduce this risk.

Potential Impacts on harvesting

As noted by the Nattivak Hunters & Trappers Organization, field test operations may mainly impact seal harvesting activities. Noise and human activity could potentially disturb seals, causing them to leave the area.

To minimize these impacts, mitigation measures will be implemented, including noise level reduction, avoiding key habitats, and the utilization of low-impact lighting to limit disturbances to seal populations.

To further mitigate risks, local wildlife monitors will be engaged during the flooding phase of the operations. The field test will avoid areas with known wildlife concentrations and key habitats, including seal dens. Additionally, the advice and expertise of wildlife monitors will guide the selection of the exact location for the Arctic Ice Thickening (AIT) field test.

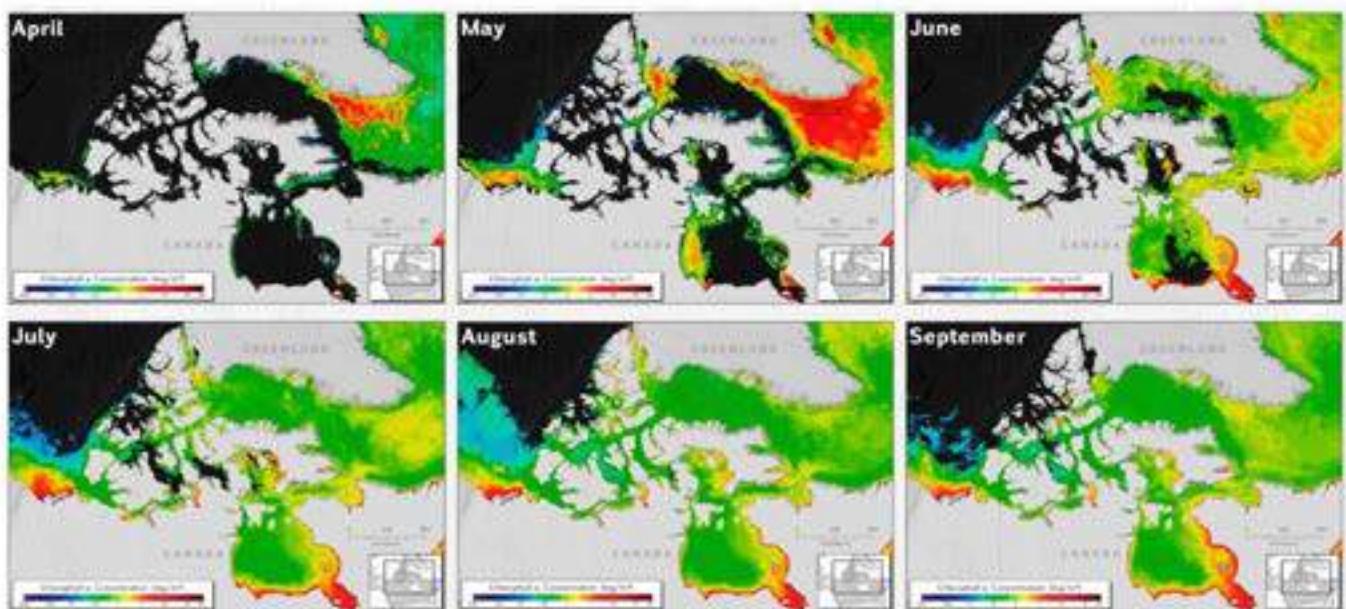


Figure 3.2 Monthly average chlorophyll-a concentration in the Canadian Arctic based on satellite imagery (pelagic phytoplankton). Chlorophyll is the green pigment in phytoplankton, so areas with high chlorophyll concentrations are places where phytoplankton are growing (Oceans North Conservation Society et al. 2018).

Exploring Options for Actively Cooling the Earth

Programme thesis

v2.0

Mark Symes, Programme Director

CONTEXT

This document presents the core thesis underpinning a programme that has now launched.

See the programme page [here](#), provide feedback on this programme thesis [here](#) or sign up for all updates about this opportunity space [here](#).

An ARIA programme seeks to unlock a scientific or technical capability that

- + changes the perception of what's possible or valuable
- + has the potential to catalyse massive social and economic returns
- + is unlikely to be achieved without ARIA's intervention

UPDATE: OUR THINKING, EVOLVED

A summary capturing the evolution of our thinking since first publication.

This programme thesis is derived from the ARIA opportunity space: [Future Proofing our Climate and Weather](#). The original version of the thesis was published in May 2024 and has been updated following community feedback. Read the original version of the thesis [here](#). The main changes to the thesis are:

- + More detail has been provided on the governance of outdoor experiments, including an outdoor experiment funding approval decision tree. An outline of the roles and responsibilities of the independent programme oversight committee is also provided in a separate [programme oversight and governance document](#).
- + A section on why ARIA is leading this research effort has been added, together with some thoughts around how international collaboration and cooperation in this space could be catalysed.
- + Some of the language has been clarified to better reflect the intended purpose and scale of the research that ARIA will support.

PROGRAMME THESIS, SIMPLY STATED

This programme thesis is derived from the ARIA opportunity space: [Future Proofing Our Climate and Weather](#).

Climate change, largely caused by anthropogenic greenhouse gas emissions, could cause the global temperature to increase by several degrees by the end of the century, precipitating climate tipping points with serious consequences. The solution to this problem is to cease the burning of fossil fuels and to eliminate excess greenhouse gases from the atmosphere. However, lowering atmospheric greenhouse gas levels – even under the most aggressive scenarios – may not happen fast enough to prevent the onset of tipping points.

Such reasoning has led to proposals for methods to actively cool the Earth in order to “buy time” to decarbonise, and there has been considerable debate around the risks and benefits of these various methods. However, in the absence of substantial physical (as opposed to simulated) data on the mechanisms behind how these concepts might work (and what their effects might be), there is no prospect of being able to make proper judgements on what are or are not feasible, scalable, and controllable approaches for cooling the Earth.

This programme aims to answer fundamental questions as to the practicality, measurability, controllability and possible (side-)effects of such approaches through indoor and (where necessary) small, controlled, outdoor experiments. In answering these questions, we plan to fund not only the experiments themselves, but also the necessary modelling, simulation, observation and monitoring required to support the experiments, as well as research into the ethical, governance, law, and geopolitical dimensions of the approaches under investigation. Our objective is that the information gathered by this programme will allow for more definitive assessments on whether one or more of the approaches examined may one day be used responsibly and ethically to delay or avert the onset of temperature-induced climate tipping points.

PROGRAMME THESIS, EXPLAINED

A detailed description of the programme thesis, presented for constructive feedback.

Why this programme

Risk vs. risk

The Intergovernmental Panel on Climate Change (IPCC) has noted that global warming in excess of 1.5 °C above pre-industrial levels is now likely, even if increased action allows the world to achieve net zero emissions by 2040 ^[1]. Furthermore, it has stated that “the pace and scale of what has been done so far, and current plans, are insufficient to tackle climate change” ^[2]. In this context, there is increasing debate as to whether society should (and whether it can) buy time to decarbonise by manipulating certain variables to reduce global temperatures on a short-to-medium term basis.

This comes against a background of concern around the potential for climate tipping points (abrupt alterations in the Earth’s climate system), which may lead to essentially irreversible disruptive changes on a regional or global scale if the global temperature exceeds certain thresholds for any length of time ^[3,4]. Examples of such tipping points include the melting of the Arctic winter sea ice (leading to accelerated warming via ice-albedo feedback ^[5]), dieback of the Amazon rainforest and consequent ecosystem loss, and collapse of the major land-based ice sheets, leading to significant global sea level rises.

The thresholds for many such tipping points remain far from clear, but it seems likely that a certain amount of continued global warming is already locked in, even with rapid decarbonisation, on account of the amount of carbon dioxide already in the atmosphere ^[6,7]. The practical difficulties of rapid decarbonisation also imply that further warming will occur ^[8]. In this context, approaches such as stratospheric aerosol injection ^[9], marine cloud brightening ^[10], increasing the reflectivity of the Earth's surface (e.g. by re-growing ice sheets) ^[11], and constructing space-based reflectors to shade the Earth from a proportion of incoming sunlight ^[12] have been proposed as potential methods by which to cool the Earth whilst sufficient carbon dioxide is removed from the atmosphere to bring global temperatures down.

However, many poorly-constrained risks associated with the approaches above currently exist, especially regarding the scope and scale of their side-effects — which may affect different parts of the world unevenly ^[13]. Concerns also exist related to moral hazard ^[14], and the extent to which developing the capability to lower global temperatures without lowering atmospheric greenhouse gas levels (i.e. “treating the symptoms, but not the disease”) reduces the incentive to reach net zero and/or remove carbon dioxide from the atmosphere in a timely manner.

How (or whether) research into methods that could be used to reduce global temperatures should be conducted throws up a number of open questions ^[15-17]. For example, do the risks of unintended consequences and moral hazard associated with learning more about Earth-cooling approaches outweigh the risks of continued global warming without researching any intervention strategies? How should we weigh the risks associated with researching approaches for reducing global temperatures against the risk that the world discovers in 2040 or 2050 that efforts to achieve net zero and to remove carbon dioxide from the atmosphere have been insufficient to prevent very detrimental tipping points ^[18]? In such a scenario, what might be the risks of hurried deployment* of under-researched climate engineering approaches where we have little understanding of the consequences? And if these approaches were deployed, what might be the risks associated with a later, more sudden deployment relative to a slower ramp-up? Or the risks of termination shocks if deployment were suddenly stopped ^[19]?

Questions like these have fuelled a debate that has been ongoing for years ^[20], but which remains unresolvable with our current level of understanding. After considerable deliberation on the balance of risks, ARIA has come to the view that the risks of not being able to answer such questions are greater than the risks of researching approaches for actively cooling the Earth through a well-governed research programme. Others have come to similar conclusions regarding the need for research in this area to be undertaken transparently and in the public interest ^[21, 22]. It is in this context that ARIA has chosen to pursue a research programme into approaches for actively cooling the Earth.

* Following the example of the [European Commission's 2023 scoping paper on Solar Radiation Modification](#), we define “deployment” in this context to mean “a deliberate and large-scale intervention in the Earth's climatic system, with the aim of reducing global warming”.

Our discovery process has suggested to us that a key barrier to advancing our understanding of this field and being able to reach more definitive conclusions on particular approaches is a comparative dearth of real and relevant physical data from outdoor experiments ^[23-25].

Hence, we see a need for a programme that will accommodate small, controlled, geographically-confined outdoor experiments on approaches that may one day scale to help reduce global temperatures. These outdoor experiments are intended to answer critical scientific questions as to the practicality, measurability, controllability and likely (side-)effects of the proposed approaches that cannot be answered by other means. They may not be necessary or possible for all the projects we fund, and they are not meant to be stepping stones to deployment. To support the outdoor experiments, we plan to fund activities ranging from modelling and simulation, through to in-field observation and monitoring, and research on the legal, ethical, governance and geopolitical dimensions of the approaches under study.

The research conducted in this programme should allow us to provide critical (and currently missing) real-world data to scientists and society on what the options are for actively cooling the Earth, how such approaches might work, and what the consequences of their use might be, allowing better-informed assessments of their risks and benefits. Successful outcomes from this programme include ruling particular options out from further study as technically infeasible, ruling them out as infeasible due to risks that cannot be adequately constrained, or highlighting which approaches show promise and would benefit from further research and development.

Our approach

Our approach will be to develop a scientific framework to underpin strong predict → test → monitor → validate loops for a range of approaches (Figure 1). The “predict”, “monitor” and “societal aspects” nodes in Figure 1 have received some (although arguably insufficient) interest in recent years. However, research into how approaches for cooling the Earth might work in practice, how their effects would be demonstrated with statistical confidence, and how any resulting technology might be scaled effectively has received much less attention. Therefore, whilst further research across all of the areas shown in Figure 1 is vital, we see that the “test” and “validate” nodes are particularly underserved.

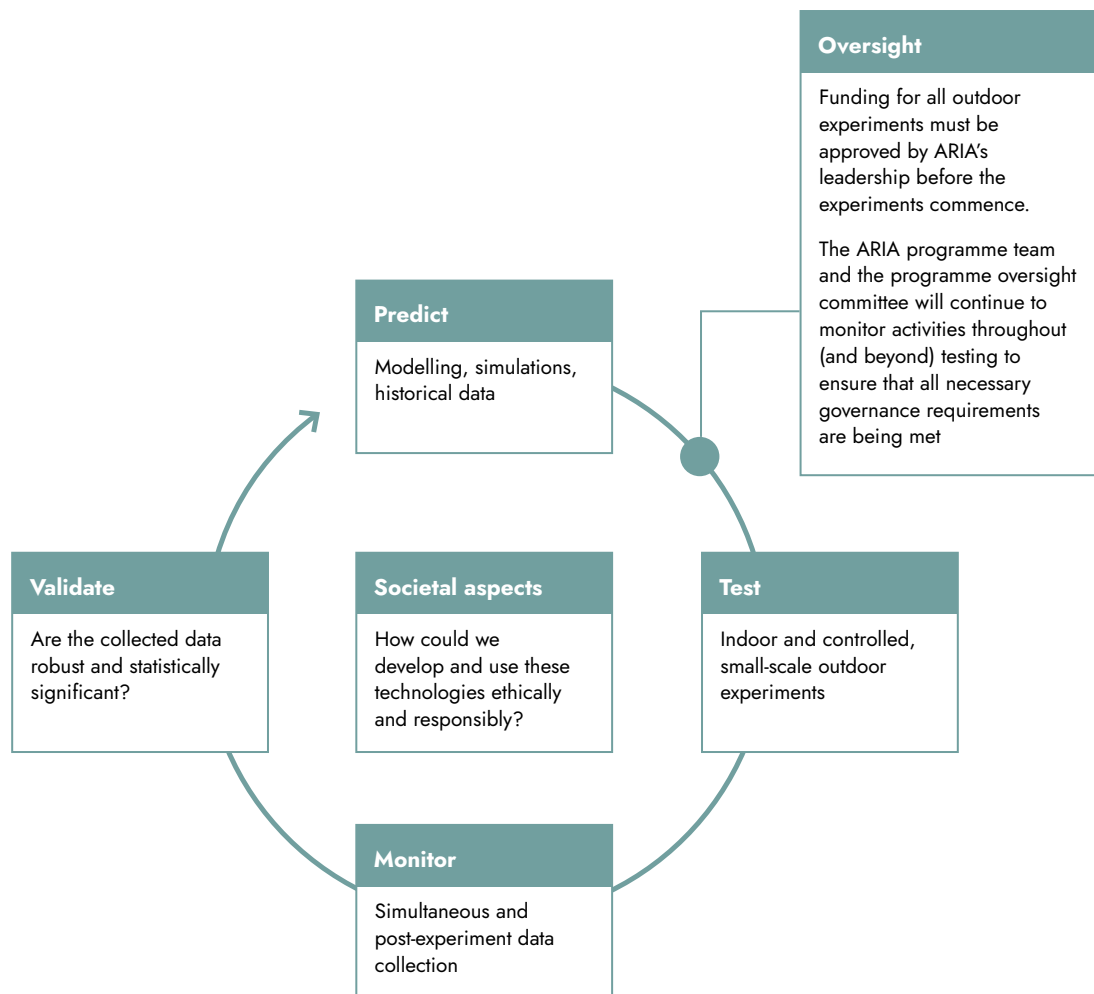


Figure 1: A technology research loop showing the "predict", "test", "monitor", "Validate" and "Societal aspects" nodes. Details on the oversight mechanisms are described herein and in the separate programme oversight and governance document.

Computer modelling and the indoor testing of approaches are essential and necessary first steps in establishing the basic science behind how (or whether) a particular approach might work. However, modelling and indoor testing alone cannot provide all the data necessary to predict the effects of a given approach in the real world with a suitable level of confidence. Controlled outdoor experiments are therefore likely to be required to truly advance our understanding of the phenomena underlying potential approaches. Initial thoughts on how outdoor experiments in this programme could be conducted openly and responsibly are presented throughout this thesis for constructive feedback, with the aim that these form the basis for decisions on whether any given outdoor test could proceed and how such experiments could be conducted responsibly.

A suggested framework for outdoor experiments

There is the potential for unintended negative consequences in any outdoor experiment. Therefore, it will be important to define transparently and at the outset a set of principles that can guide the programme's consideration of whether and how outdoor testing can proceed. ARIA has incorporated lessons from previous projects where outdoor experiments have been cancelled before commencing ^[26-29] and those where outdoor experiments have gone ahead ^[30,11] in developing these principles, with the aim of supporting the development of best practices for safe and transparent outdoor experiments.

Our guiding principle for outdoor experiments is that these should be conducted on the smallest possible length and timescales required to validate, with statistical confidence, that the approaches being tested can affect the parameters under investigation. These scales will be approach-specific; however, **Appendix A** posits what the upper bounds for the scale and duration of an outdoor experiment could be. In all cases, we expect initial outdoor tests to occur at much smaller scales than these upper bounds (for example, an appropriate scale for an initial outdoor cloud brightening experiment might be on the order of a few hundred metres).

The magnitude of the intended perturbation should be limited so that it is within the bounds of known and benign natural phenomena (or anthropogenic phenomena that are considered harmless), so that there is precedent for the size of the effect that will be produced. The experiments should be designed so that as far as possible the effects either dissipate through natural mechanisms within hours, or can be localised with very high certainty, or else that there should be an obvious and reliable mechanism for switching off the effect at any time, on demand. These features should minimise the risks of negative unintended consequences by confining the effects in space and/or time. A combination of considerations on the size, duration and reversibility of outdoor experiments leads to the following suggested decision tree for assessing whether a particular outdoor experiment might be supported through this programme (Figure 2).

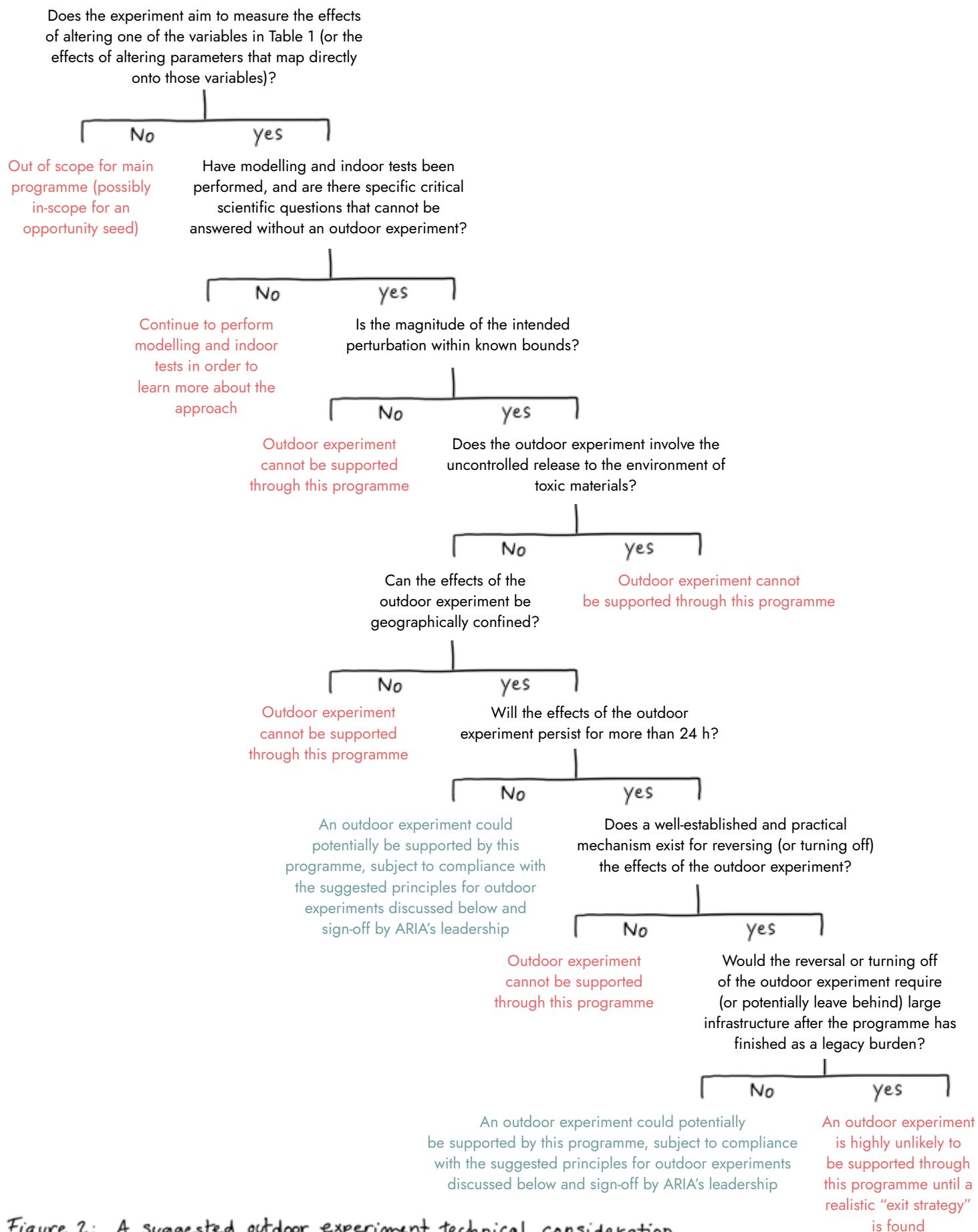


Figure 2: A suggested outdoor experiment technical consideration decision tree, to be used in conjunction with the principles for outdoor experiment oversight described in the main text. Please refer to Table 1 under What will projects need to demonstrate? for a description of the relevant variables.

The suggestion is that applicants proposing outdoor experiments use this decision tree at the application stage in order to see if their intended experiment could in theory be supported by this programme or not.

In addition to this basic technical information, the following suggested principles for oversight of any subsequent outdoor experiments are presented here for feedback:

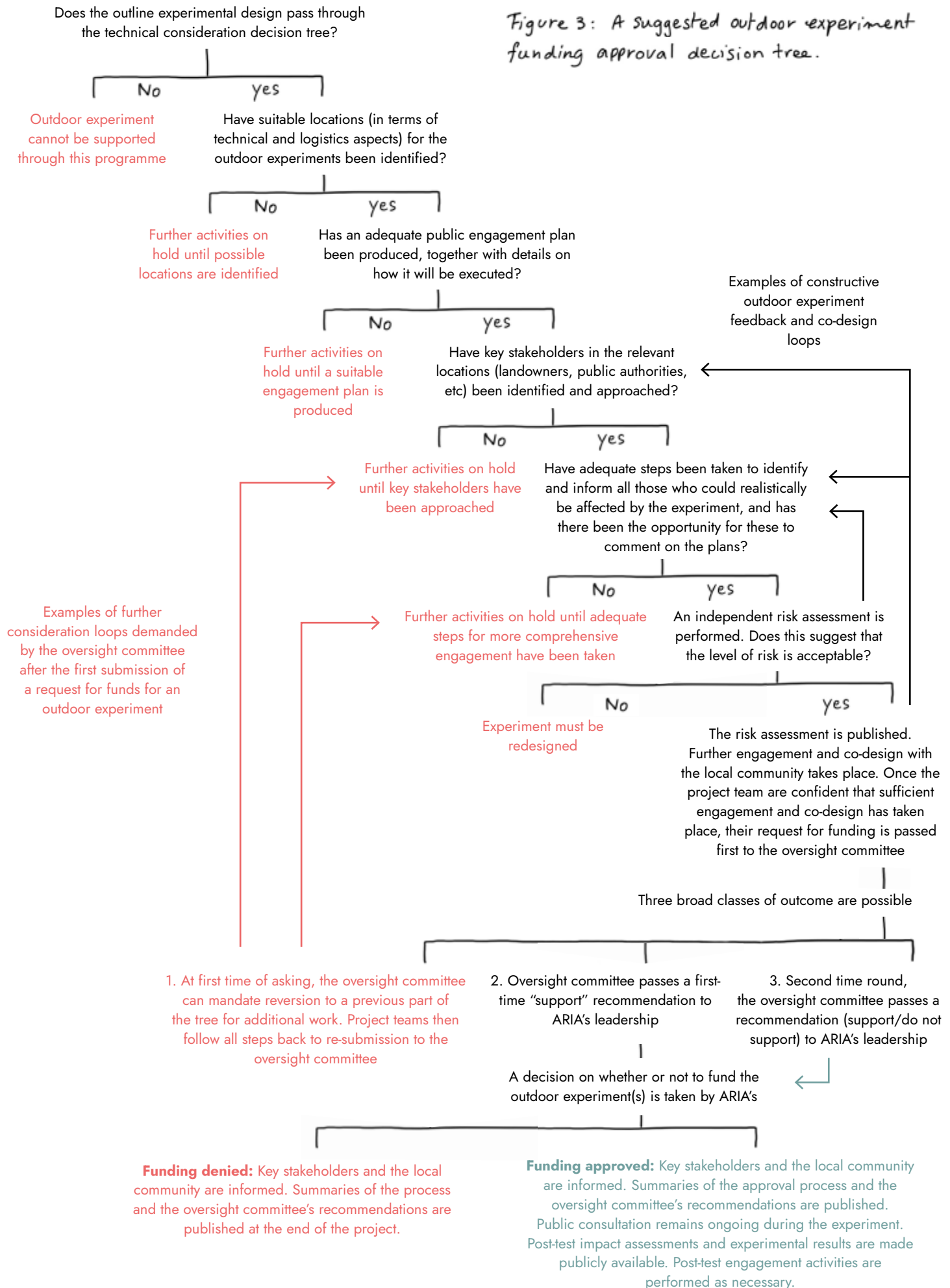
- 1. ARIA will not fund experiments where the activities proposed are prohibited by domestic or international law.** Project teams will be required to show how their tests comply with all applicable laws.
- 2. A risk assessment will be performed and the findings made publicly available before any outdoor experiment.** This will be conducted by experts who are independent of the team performing the experiment, and will include relevant potential technological, environmental and socio-economic risks.
- 3. Minimising risk by design.** Outdoor experiments should be designed at the minimum viable scale required for the generation of robust data, and where the magnitude of any perturbation has a natural analogue or commonly accepted anthropogenic precedent (and therefore where the effect of the perturbation is within the range of known and benign phenomena). Such considerations are summarised in Figure 2.
- 4. Transparency, public participation and consultation.** Wherever possible, those conducting outdoor experiments will be required to notify and consult those who could reasonably be considered as likely to be affected by the experiments. ARIA sees consultation and engagement with the public as processes that will be sustained for the lifetime of projects. To facilitate informed decision making, detailed plans for the outdoor experiments, and the key decisions taken in developing these plans, will be consulted upon as transparently as possible well in advance of any experiment. The specific protocols for transparency will be developed in consultation with the Oversight Committee, and will include provisions for transparency regarding what the experiments involve, why the experiments are necessary, who is conducting the experiments, and who might be impacted by the experiments. The results of the experiments (including negative results) will also be made publicly available in an accessible form.
- 5. Independent impact assessment.** Post-experiment, the environmental and any socio-economic impacts will be assessed by experts who are independent of the team performing the outdoor experiments, and the results of these assessments will be made publicly available. ARIA may also commission assessments of the broader implications of the experiments as appropriate.
- 6. Limited scope.** Activities in this programme will be limited to research scale – ARIA will not fund deployment or any demonstration beyond the approved experiments.

These principles then underpin the following outdoor experiment funding approval decision tree (Figure 3), which describes our current thinking on the steps that project teams will need to take in order for funding for a particular outdoor experiment (or series of linked experiments) to be approved. We expect that ARIA will provide specialist support to assist project teams in undertaking these activities.

ARIA's leadership will be ultimately responsible for governance, oversight and the release of funding for outdoor experiments, leveraging input from an independent programme oversight committee. ARIA also has a Committee of the Board for ethics and social responsibility, which has visibility across all of ARIA's programmes.

Find out more about the independent programme oversight committee and its relationship to other actors in the programme [here](#).

Figure 3: A suggested outdoor experiment funding approval decision tree.



A key aim is to earn and maintain trust in the research that is being undertaken. This will be underpinned by a culture of transparency. Our aim is to establish a culture of complete openness for outdoor experiments in terms of what activities are undertaken and their outcomes, similar to that which the International Civil Aviation Organization champions for the sharing of best practices in the aviation industry ^[31]. The principles above are designed to embed this mindset from the beginning of the R&D pathway for the approaches supported by this programme.

International partnerships with other funding organisations

The impacts of climate tipping points (and the effects of actively cooling the Earth to delay or avoid the onset of these) are likely to be felt globally. Therefore, we contend that it is vital that public institutions lead research into approaches for actively cooling the Earth, acting in a spirit of open international collaboration and cooperation, with full transparency, for the benefit of the global community ^[32].

By funding research into both the technical and non-technical aspects of approaches for actively cooling the Earth, this programme aims to drive forward both fundamental understanding of these approaches and their risks, and the development of structures for just and informed deliberation on their benefits and risks in lockstep.

Responsible and transparent research into actively cooling the Earth - including what the impacts of these approaches might be, and how their use might be governed - will require an international effort, led by public institutions. To aid international cooperation, ARIA intends to:

1. Fund projects and researchers globally as part of this programme
2. Bring an open mindset to co-funding projects with other government funding agencies
3. Make ourselves and our expert networks available to other government and (potentially other public benefit) funding agencies which are considering establishing their own research programmes in this space, including support with validation and verification of experiments
4. Create opportunities for sharing best practice and learning with representatives of international and public benefit funding agencies, including annual workshops and invitations to observe the outdoor experiments that we fund
5. Upon invitation, send expert teams from ARIA, or within its network, to observe and feed back on experiments being funded by other government funding agencies
6. Consider requests from other government funding agencies (both UK and non-UK) to observe the workings of the ARIA programme's oversight committee.

Through these routes for promoting international participation in the programme, sharing best practice, and building a culture of transparent cooperation for governing small-scale research experiments, we aim to start building up the expertise, ways of working, and critical mass and diversity of practitioners that a future international governance body would find immensely useful. To further these aims, ARIA commits to being fully transparent across our programme design, management, and disclosure of the results of the research that is funded, by:

1. Requiring that the results from the work that we fund (including negative results) are available in a publicly available, open-access form, unless such publication would be likely to lead to public harm.
2. Making supporting documentation related to our outdoor experiments publicly available on the ARIA website (including pre-experiment risk assessments, post-experiment impact assessments, recommendations from our oversight committee, and results from our public engagement and co-design activities)
3. Continuing to update and iterate our (publicly available) governance and oversight procedures, explaining why any changes are being made.

What we expect to fund

Funding across silos

We anticipate supporting research into approaches for reducing global temperatures across the entire range of science and engineering disciplines. We also expect to support projects across the social sciences, arts, humanities, and law/policy research that are of direct relevance to those approaches (including, but by no means limited to, consideration of public perception; design of potential legal, ethical, regulatory and governance frameworks; and the economic or broader social impacts of those approaches). We have also set aside funding to support project teams in working through specific aspects of ethics and community engagement, as well as documenting lessons that may be more broadly applicable for other research programmes.

ARIA is aware of previous and ongoing initiatives that have considered some of the ethical and societal issues around governance, stakeholder engagement and perceptions related to approaches for actively cooling the Earth over the last few years (see, for example: ^[33-36]).

ARIA aims to provide as much flexibility as possible in terms of how the social sciences and humanities are represented in this programme. For example, ARIA may fund social scientists, ethicists, legal scholars, or humanities researchers to work specifically on certain technical research teams. In addition, ARIA may also fund a dedicated social science, law, and governance strand that works across the full range of approaches under investigation, in a manner that complements the efforts of social scientists that are embedded in specific research teams.

What will projects need to demonstrate?

The overarching goal of this programme is to answer fundamental questions on the practicality, measurability and controllability of technologies that might one day be used to actively cool the Earth. Projects will therefore need to demonstrate how they align with this goal.

A very simplified estimate of the equilibrium temperature at the Earth's surface (T_{surf}) is provided by the equation below ^[37]:

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

Where S is the solar constant (the power per unit area impinging on the Earth from solar irradiation), α is the planetary albedo (a measure of how much short-wave radiation is reflected from the Earth without being absorbed), σ is the Stefan-Boltzmann constant, and ε is the effective emissivity of the atmosphere (σ and ε together give a measure of how much long-wave radiation is emitted by the Earth back out to space).

In order to be in-scope for this programme, projects will need to demonstrate how the research they are proposing meets at least one of the following criteria:

1. The approaches being researched have the potential to alter T_{surf} (at any scale) by affecting at least one of the variables α , ε or S (see Table 1) in a manner that is statistically distinguishable from the background
2. The approaches being researched have the potential to alter parameters that map directly onto the variables α , ε or S (applicants will be required to justify explicitly how the parameters being perturbed map onto α , ε or S) in a manner that is statistically distinguishable from the background
3. The research proposed has direct bearing on the prediction, modelling, measurement, monitoring, validation, governance, education, public perception, ethics or other research questions related to approaches or experiments that could alter at least one of the variables α , ε or S (or parameters that map directly onto those variables)
4. The research proposed has direct bearing on open questions or uncertainties about the ecological or other environmental impacts, risks or side-effects related to approaches or experiments that could alter at least one of the variables α , ε or S (or parameters that map directly onto those variables).

ARIA encourages research plans that build in careful attention to measuring possible unintended side-effects and understanding possible risks. Where physical experiments are being proposed, applicants will need to consider testability and statistical significance in their proposals (for example, can any parallels or lessons be drawn from some of the ways in which statistical methods have been employed to evaluate field trials of cloud seeding ^[38-40]?).

For physical experiments, project teams will need to convince the reviewers as to why the measurements/perturbations that they intend to make are the right things to measure/perturb, and how the results would substantially advance the validation or invalidation of the approach on the grounds of practicality, scalability, safety or impacts. ARIA will require publication of the results of the work that we fund (including negative results) in an accessible form, except if their publication would be likely to lead to public harm.

Table 1: Variables for study in this programme. The examples of activities that could address these variables are not exhaustive, and neither should they be construed as use cases that ARIA considers to be more or less valuable than any others that can be imagined.

Variable	Examples of activities that could address this variable (non exhaustive)
Planetary albedo (α)	Marine cloud brightening ^[10] ; ice sheet thickening ^[41]
Effective solar constant (S)	Space-based reflectors ^[12]
Effective emissivity of the atmosphere (ϵ)	Cirrus cloud thinning ^[42, 43]

Programme differentiation

To date, there have been very few actual (or even attempted) outdoor experiments into approaches whose ultimate goal would be to reduce global or regional temperatures on a short-to-medium term basis. We are not aware of any other programmes that have funded outdoor experiments with multiple different approaches in a coordinated way. Indeed, to date, all outdoor experiments that have been attempted or conducted in this space have been undertaken as individual stand-alone projects. This means that these projects have therefore also struggled to cover all of the nodes represented in Figure 1 comprehensively.

This programme has a strong emphasis on statistical significance and on understanding the physical principles that underlie the effects that the various approaches may produce. In this context, even if the only outcome of the programme is to prove that all the approaches that are investigated are either infeasible at scale or produce effects that are indistinguishable from natural background processes, then we will consider this a success. Such an outcome would directly support our objective to allow better-informed assessments as to whether any of the approaches examined might one day be used responsibly and ethically to reduce global temperatures on a short-to-medium term basis. This technology and outcome agnosticism strongly differentiates this programme.

Programme scope

Table 2 gives a breakdown of areas that we expect to be **out of scope** for this programme, along with the reasoning we have taken in coming to these decisions. Approaches that are not explicitly listed as out of scope will be considered (provided that their specific intent relates to the controlled perturbation of one of the variables given in Table 1, or altering parameters that map directly onto those variables). **Opportunity seed funding** may subsequently be available to support individuals or teams pursuing ambitious research that is out of scope for the programme, but which falls within the scope of the wider opportunity space **Future Proofing Our Climate and Weather**.

Table 2: Out of scope areas for this programme

Topic or activity	Reasoning and comments
Removal, sequestration and/or utilisation of carbon dioxide	Multiple other public and private funders are already funding carbon dioxide removal and utilisation
General weather/climate simulation or monitoring activities that do not provide insights into the effects of altering one of the variables in Table 1 (or parameters that map directly onto those variables)	Only simulation or monitoring activities that could be relevant to the temperature-reducing approaches being researched in this programme will be in scope. This programme is distinct from the work of the Natural Environment Research Council and their Research programme to model the impact of solar radiation management ^[44] , and has been developed independently. ARIA will continue to engage with NERC as development of both programmes progresses
Outdoor experiments where analysis via Figure 2 indicates that such experiments cannot be supported by this programme	Outdoor experiments that Figure 2 indicates cannot be supported will not be funded through this programme
Large-scale trials of climate engineering technologies continuously or over extended durations	This programme will only fund activities at research scale

Our approach to results and IP for this programme

We are pursuing a very open approach to intellectual property (IP). Work under this programme should be undertaken with the intention of making project outcomes open-source and freely available. This means that the results from the work that we fund (including negative results) should be made available in a publicly available, open-access form, unless such publication would be likely to lead to public harm. As part of this, project teams will be required to give as much detail as possible on methodology and experimental data to ensure openness and transparency.

Intellectual property created by projects funded as part of this programme shall be published under creative commons or open source licences as appropriate. Our default position will be that project teams will not be permitted to file for patents in respect of inventions resulting from work that has been funded as part of this programme. We'll be asking all successful applicants and their team members to sign a public pledge not to seek patents on any work that is funded by this programme. This approach is designed to enhance the public good by maximising the accessibility, usability, and collaborative potential of the funded projects, ensuring that the benefits extend to a wider community and fostering a culture of open innovation.

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APPENDIX A: Initial analysis on outdoor experiment scale

Rossby waves ^[45] caused by the Earth's rotation define characteristic length scales for weather systems in the UK that are on the order of 1000 km. Work examining the impact that perturbations in weather models have on the predictability of atmospheric conditions suggests that very large perturbations (by up to 100%) can be made on a length scale of 10 km without any significant effect on the behaviour of the overall system (at 1000 km scale) ^[46]. Therefore, a maximum outdoor experiment grid parameter on the order of 10 km should be small enough that any perturbation caused in that space for short periods (e.g. 24 hours or less) will subsequently be dwarfed by natural chaotic processes operating at larger scales once the experiment has ended. However, proposers will be required to start with outdoor experiments smaller than this (especially for initial tests) in order to demonstrate safety and controllability. Likewise, ARIA strongly prefers outdoor experiments in areas remote from population centres. Such scales place these outdoor experiments and their effects in the range of "microscale meteorology", as distinct from both the larger weather systems that we are familiar with from weather forecasts and the climate at large (see Figure 4).

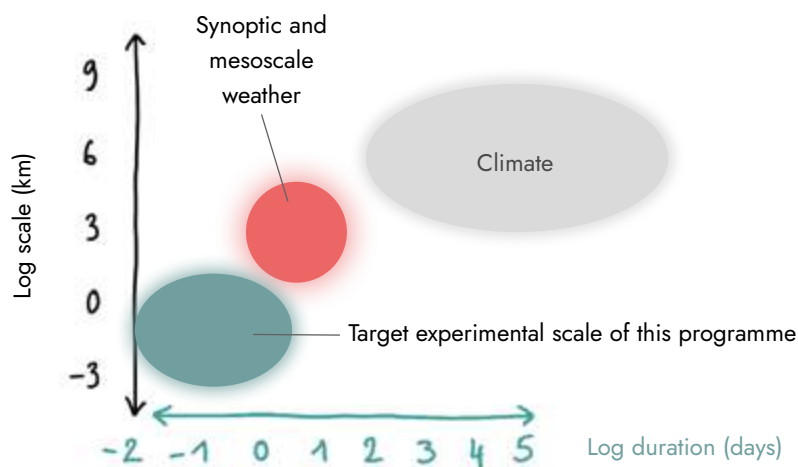


Figure 4: Context on the suggested scale and duration of outdoor experiments that could be accommodated in this programme.

These suggested length and timescale upper bounds are commensurate with (or indeed smaller than) those previously employed in anthropogenic climate perturbation experiments. Two examples are provided. Firstly, the marine cloud brightening project operating on the Great Barrier Reef ^[30] generates a plume behind the vessel that can grow in extent to 10-20 km, with effects that dissipate within hours. Secondly, as an example of an "unintentional" climate perturbation experiment, the "average" ship track (clouds that form after ships pass through an area due to nucleation of water droplets on emissions released from the ships' funnels) is on the order of 10 km wide and anything from a few km to several hundred km long ^[47]. Lifetimes for such artificially-generated clouds are generally a few hours, with formation starting around half an hour after emission of the exhaust ^[47]. The number of droplets in the track (corresponding to a peak brightness of the cloud) tends to peak roughly 3-5 hours after emission, with the track then fading such that the droplet count is indistinguishable from the background within 20 hours or so ^[48]. When the International Maritime Organization introduced tighter emissions limits for ships in an area off the coast of California in 2010, ships were obliged to navigate further from the coast. This in turn led to a dramatic shift (sustained over the timescale of years) in the location of ship tracks over an area of around 60,000 square kilometres ^[49].

Exploring Climate Cooling

Call for proposals

Date: 13 September 2024

V1

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SECTION 1: Programme Thesis and Overview

This solicitation is derived from the programme thesis [Exploring Options for Actively Cooling the Earth](#), in turn derived from the ARIA Opportunity Space: [Future Proofing Our Climate and Weather](#).

Climate change, largely caused by anthropogenic greenhouse gas emissions, could cause the global temperature to increase by several degrees by the end of the century, precipitating climate tipping points with serious consequences [1,2]. The only sustainable solution to this problem is to cease the burning of fossil fuels and to eliminate excess greenhouse gases from the atmosphere. However, on account of the amount of carbon dioxide already in the atmosphere, a certain amount of continued global warming is almost certainly locked in [3,4]. In this context, there is a risk that the essential work of lowering atmospheric greenhouse gas levels – even under the most aggressive scenarios – does not happen fast enough to prevent the onset of temperature-induced tipping points.

Were such a temperature-induced climate tipping point to become apparent, our current level of understanding provides us with no options for how we might actively intervene to cool the relevant regions on the timescales required to avert or delay that tipping point. Approaches such as stratospheric aerosol injection [5], marine cloud brightening [6], increasing the reflectivity of the Earth's surface (e.g. by re-growing ice sheets), [7] and constructing space-based reflectors to shade the Earth from a proportion of incoming sunlight [8] have been proposed as potential methods by which to cool the Earth on a global or regional basis. However, an enormous amount of research is required on all these approaches: even basic questions as to whether they could work, what their immediate effects and side-effects might be, and whether they could ever be used safely and predictably remain unanswered. Informed debate as to the risks and impacts of such approaches requires resolution of these uncertainties.

Accordingly, following a 12-month discovery and engagement process, ARIA is now launching a programme aimed at answering fundamental questions as to the practicality, measurability, controllability and possible (side-)effects of approaches for actively cooling the Earth through indoor and (where necessary) small, controlled, outdoor experiments. In answering these questions, ARIA will fund not only the experiments themselves, but also the necessary modelling, simulation, observation and monitoring required to support the experiments, as well as research into the ethical, governance, law, and geopolitical dimensions of the approaches under investigation. Successful outcomes from this programme could include ruling particular options out from further study as technically infeasible, ruling them out as infeasible due to risks that cannot be adequately constrained, or highlighting which approaches show promise and would benefit from further research and development.

Acknowledging that this is a complex and ethically-challenging area of research, ARIA will be applying a particular set of governance and management principles in this programme, which are described in detail in the [programme thesis](#) and the [programme oversight and governance document](#).

SECTION 2: Programme Objectives

The programme aims to develop a scientific framework to underpin strong predict → test → monitor → validate loops for a range of approaches (Figure 1). The “predict”, “monitor” and “societal aspects” nodes in Figure 1 have received some (although arguably insufficient) interest in recent years. However, research into how approaches for cooling the Earth might work in practice, how their effects would be demonstrated with statistical confidence, and how any resulting technology might be scaled effectively has received much less attention. Therefore, whilst further research across all of the areas shown in Figure 1 is vital, we see that the “test” and “validate” nodes are particularly underserved.

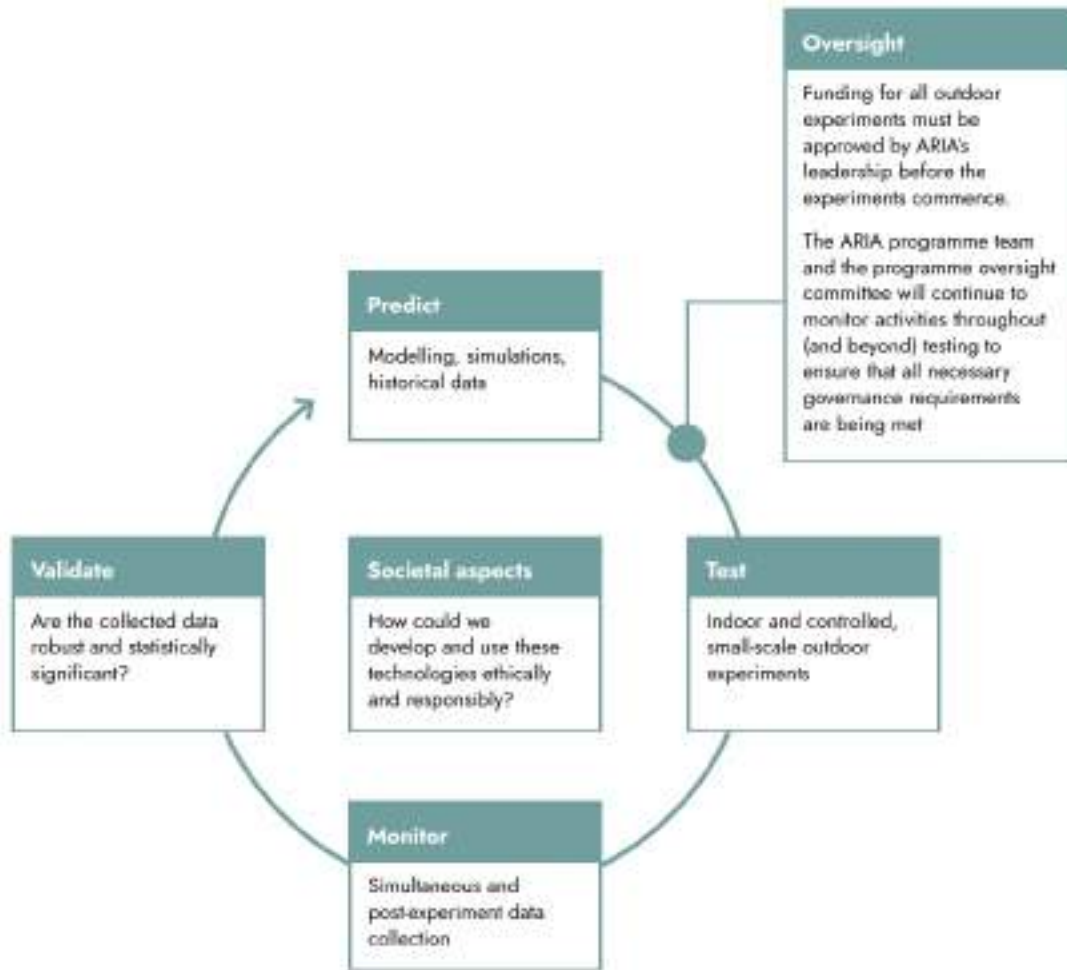


Figure 1: A technology research loop showing the “predict”, “test”, “monitor”, “validate” and “societal aspects” nodes. Details on the oversight mechanisms are described in the programme thesis and in the programme oversight and governance document.

Computer modelling and indoor testing are essential and necessary first steps in establishing the basic science behind how (or whether) a particular approach might work. However, modelling and indoor testing alone cannot provide all the data necessary to predict the effects of a given approach on the real world with a suitable level of confidence. Controlled outdoor experiments are therefore likely to be required to truly advance our understanding of the phenomena underlying potential approaches.

The overarching goal of this programme is to answer the most critical technical and fundamental questions on the practicality, measurability, controllability, and likely (side-)effects of approaches that might one day be used to actively cool the Earth. Projects will therefore need to demonstrate how they align with this goal.

SECTION 3: Technical Metrics

A very simplified estimate of the equilibrium temperature at the Earth's surface (T_{surf}) is provided by the equation below [9]:

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

Where S is the solar constant (the power per unit area impinging on the Earth from solar irradiation), α is the planetary albedo (a measure of how much short-wave radiation is reflected from the Earth without being absorbed), σ is the Stefan-Boltzmann constant, and ε is the effective emissivity of the atmosphere (σ and ε together give a measure of how much long-wave radiation is emitted by the Earth back out to space).

In order to be in-scope for this programme, projects will need to demonstrate how the research they are proposing meets at least one of the following criteria:

1. The approaches being researched have the potential to alter T_{surf} (at any scale) by affecting at least one of the variables α , ε or S (see Table 1) in a manner that is statistically distinguishable from the background
2. The approaches being researched have the potential to alter parameters that map directly onto the variables α , ε or S (applicants will be required to justify explicitly how the parameters being perturbed map onto α , ε or S) in a manner that is statistically distinguishable from the background
3. The research proposed has direct bearing on the prediction, modelling, measurement, monitoring, validation, governance, education, public perception, ethics or other research questions related to approaches or experiments that could alter at least one of the variables α , ε or S (or parameters that map directly onto those variables)
4. The research proposed has direct bearing on open questions or uncertainties about the ecological or other environmental impacts, risks or side-effects related to approaches or experiments that could alter at least one of the variables α , ε or S (or parameters that map directly onto those variables).

ARIA encourages research plans that build in careful attention to measuring possible unintended side-effects and understanding possible risks. Where physical experiments are being proposed, applicants will need to consider testability and statistical significance in

their proposals (for example, can any parallels or lessons be drawn from some of the ways in which statistical methods have been employed to evaluate field trials of cloud seeding [10-12]?). **For physical experiments, project teams will need to convince the reviewers as to why the measurements/perturbations that they intend to make are the right things to measure/perturb, and how the results would substantially advance the validation or invalidation of the approach on the grounds of practicality, scalability, safety or impacts.**

ARIA will require publication of the results of the work that we fund (including negative results) in an accessible form, except if their publication would be likely to lead to public harm.

Table 1: Variables for study in this programme. The examples of approaches that could address these variables are not exhaustive, and neither should they be construed as use cases that ARIA considers to be more or less valuable than any others that can be imagined.

Variable	Examples of approaches that could address this variable (non-exhaustive)
Planetary albedo (α)	Marine cloud brightening [6]; ice sheet thickening [13]
Effective solar constant (S)	Space-based reflectors [8]
Effective emissivity of the atmosphere (ε)	Cirrus cloud thinning [14,15]

SECTION 4: What are we looking for/what are we not looking for

Funding across silos

We anticipate funding research into approaches for reducing global temperatures across the full range of science and engineering disciplines, in accordance with the framework presented in Figure 1.

Therefore, we expect to support projects across the social sciences that are of direct relevance to those approaches (including, but by no means limited to, consideration of public perception, potential legal, ethical, regulatory and governance frameworks, ethics, community engagement, and the economic impact of those approaches). ARIA is aware of previous and ongoing initiatives that have considered some of the ethical and societal issues around governance, stakeholder engagement and perceptions related to approaches for actively cooling the Earth over the last few years (see, for example: [16-19]). It will be

incumbent on proposers to demonstrate how any proposed research avoids duplication of effort with previous studies, be this in regards to technical or social research.

ARIA aims to provide as much flexibility as possible in terms of how the social sciences and humanities are represented in this programme. For example, ARIA may fund social scientists, ethicists, legal scholars, or humanities researchers to work specifically on certain technical research teams. In addition, ARIA may also fund a dedicated social science, law, and governance strand that works across the full range of approaches under investigation, in a manner that complements the efforts of social scientists that are embedded in specific research teams.

ARIA's ultimate aim is to integrate aspects of all the nodes in Figure 1 (including relevant societal aspects) into each project, but we appreciate that different projects will have different requirements and that such integration may take time. Therefore, ARIA is open to receiving proposals for (and indeed funding) projects that focus solely on one node of Figure 1 in the first instance, with a view to encouraging greater cohesion between the different nodes as projects progress. Encouraging cohesion might also include suggesting that various teams combine their efforts at full proposal submission or award negotiation stage. If ARIA identifies areas that are especially poorly represented in submissions to the initial call, then we may issue a further call for relevant expertise in those areas.

Programme scope

Table 2 gives a breakdown of areas that are **out of scope** for this programme, along with the reasoning we have taken in coming to these decisions. **Approaches that are not explicitly listed as out of scope will be considered** (provided that their specific intent relates to the controlled perturbation of one of the variables given in Table 1, or altering parameters that map directly onto those variables).

Table 2: *Out of scope areas for this programme*

Topic or activity	Reasoning and comments
Removal, sequestration and/or utilisation of carbon dioxide	Multiple other public and private funders are already funding carbon dioxide removal and utilisation
General weather/climate simulation or monitoring activities that do not provide insights into the effects of altering one	Only simulation or monitoring activities that could be relevant to the temperature-reducing approaches being researched in this

of the variables in Table 1 (or parameters that map directly onto those variables).	programme will be in scope. This programme is distinct from the work of the Natural Environment Research Council and their Research programme to model the impact of solar radiation management [20], and has been developed independently. ARIA will continue to engage with NERC as development of both programmes progresses.
Outdoor experiments where analysis via Figure 2 indicates that such experiments cannot be supported by this programme	Outdoor experiments that Figure 2 indicates cannot be supported will not be funded through this programme
Large-scale trials of climate engineering technologies continuously or over extended durations	This programme will only fund activities at research scale

A framework for outdoor experiments

There is the potential for unintended negative consequences in any outdoor experiment. Therefore, it will be important to define a transparent set of principles from the outset that can guide the programme's consideration of whether and how outdoor testing can proceed. ARIA has incorporated lessons from previous projects where outdoor experiments have been cancelled before commencing [21-24] and those where outdoor experiments have gone ahead [25,7] in developing these principles, with the aim of supporting the development of best practices for safe and transparent outdoor experiments.

Our guiding principle for outdoor experiments is that these should be conducted on the smallest possible length and timescales required to validate with statistical confidence that the approaches under test can affect the parameters under investigation. These scales will be approach-specific. A discussion on scale and duration of outdoor experiments is provided in the [programme thesis](#), and applicants are strongly encouraged to refer to this document when proposing outdoor experiments.

The magnitude of the intended perturbation should be limited so that it is within the bounds of known and benign natural phenomena (or anthropogenic phenomena that are considered harmless), so that there is precedent for the size of the effect that will be produced. The experiments should be designed so that as far as possible the effects either dissipate

through natural mechanisms within hours, or can be localised with very high certainty, or else that there should be an obvious and reliable mechanism for switching off the effect at any time, on demand. These features should minimise the risks of negative unintended consequences by confining the effects in space and/or time.

A combination of considerations on the size, duration and reversibility of outdoor experiments leads to the following suggested decision tree for assessing whether a particular outdoor experiment might be supported through this programme (Figure 2). Applicants proposing outdoor experiments are strongly advised to refer to this decision tree in their proposals, and to state explicitly how the experiments that they are proposing comply with the considerations listed.

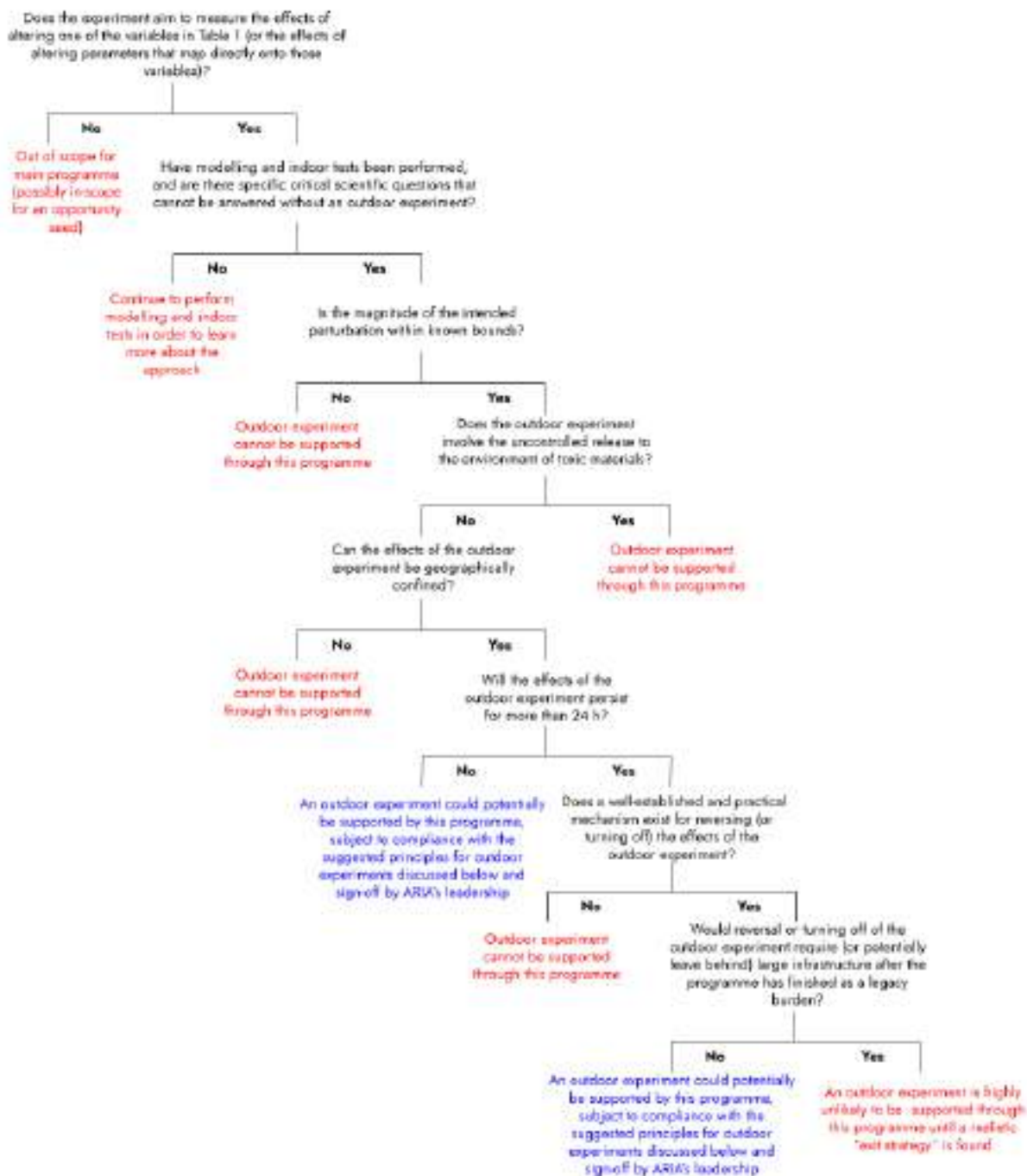


Figure 2: The outdoor experiment technical consideration decision tree for guiding applicants towards outdoor experiments that could be funded through this programme. Please refer to Table 1 for a description of the relevant variables.

In addition to this basic technical information, all outdoor experiments will need to comply with the following oversight and governance principles, which are given here so that project teams can see what will be required for any outdoor experiments:

1. **ARIA will not fund experiments where the activities proposed are prohibited by domestic or international law.** Project teams will be required to show how their tests comply with all applicable laws.
2. **A risk assessment will be performed and the findings made publicly available before any outdoor experiment.** This will be conducted by experts who are independent of the team performing the experiment, and will include relevant potential technological, environmental and socio-economic risks.
3. **Minimising risk by design.** Outdoor experiments should be designed at the minimum viable scale required for the generation of robust data, and where the magnitude of any perturbation has a natural analogue or commonly accepted anthropogenic precedent (and therefore where the effect of the perturbation is within the range of known and benign phenomena). Such considerations are summarised in Figure 2.
4. **Transparency, public participation and consultation.** Wherever possible, those conducting outdoor experiments will be required to notify and consult those who could reasonably be considered as likely to be affected by the experiments. ARIA sees consultation and engagement with the public as processes that will be sustained for the lifetime of projects. To facilitate informed decision making, detailed plans for the outdoor experiments, and the key decisions taken in developing these plans, will be consulted upon as transparently as possible well in advance of any experiment. The specific protocols for transparency will be developed in consultation with the Oversight Committee, and will include provisions for transparency regarding what the experiments involve, why the experiments are necessary, who is conducting the experiments, and who might be impacted by the experiments. The results of the experiments (including negative results) will also be made publicly available in an accessible form.
5. **Independent impact assessment.** Post-experiment, the environmental and any socio-economic impacts will be assessed by experts who are independent of the team performing the outdoor experiments, and the results of these assessments will be made publicly available. ARIA may also commission assessments of the broader implications of the experiments as appropriate.

6. **Limited scope.** Activities in this programme will be limited to research scale – ARIA will not fund deployment or any demonstration beyond the approved experiments.

ARIA intends to apply stage-gates to projects based around compliance with these principles, including undertaking sufficient engagement and experiment co-design with local communities and key stakeholders prior to funding being released for any outdoor experiment (or series of outdoor experiments). Details on the steps that project teams will be required to take for approval of funding for an outdoor experiment (or a series of linked outdoor experiments) is provided in the section 'A suggested framework for outdoor experiments' in the [programme thesis](#), and ARIA will provide specialist support to assist project teams with these steps. Information on ARIA's processes for approving funding for outdoor experiments can also be found in the programme thesis and the [programme oversight and governance document](#).

ARIA's leadership will be ultimately responsible for governance oversight and the release of funding for outdoor experiments, leveraging input from an independent programme oversight committee (see Figure 1 of the [programme oversight and governance document](#) for information on the role of this committee and its relationship to other actors in the programme). ARIA has also established a Committee of the Board for ethical and social responsibility, which will have visibility across all of ARIA's programmes.

A key aim is to earn and maintain trust in the research that is being undertaken. This will be underpinned by a culture of transparency. Our aim is to establish a culture of complete openness for outdoor experiments in terms of what activities are undertaken and their outcomes, similar to that which the International Civil Aviation Organization champions for the sharing of best practices in the aviation industry [26]. The principles above are designed to embed this mindset from the beginning of the projects supported by this programme.

SECTION 5: Programme Duration and Project Management

Programme & Project Management

We will fund early-stage and conceptual ideas through to more developed capabilities, across a portfolio of different approaches. Applications may therefore be initially highly speculative and may constitute one or more individuals or teams working together at the point of application. As projects develop, we would expect additional partners to join project teams to add their expertise; in some cases, ARIA may make the continuation of funding contingent on adding additional expertise to the project team. We also expect that some projects may fail to meet their agreed assessment criteria, which could result in a

managed phase-down of funding or a pivot in a new direction. Project teams will be able to bid for additional funding during the course of ongoing projects in order to bring in new members, explore new avenues, or undertake scale up or other activities which were not anticipated at application stage, but for which a strong case can be made. A schematic illustrating how this could work in practice is shown in Figure 3.

There will be a single call for proposals, with applicants able to request funding for durations ranging from a few weeks to five years. We aim to be as flexible as possible with our funding and to make additional funds available to successful projects. Projects opting to specify durations towards the longer end of the five-year maximum and requesting larger sums at initial application stage will be required to supply stronger justification for their requests. Conversely, more speculative projects may wish to request a shorter duration at application stage, with the possibility that ARIA will follow up with more substantial funding in the event that the project meets its objectives. The aim is to allow projects to “fail fast”, to reward success, and to help ARIA manage risk across the portfolio of funded projects. In cases where project teams ask for large awards of long duration at initial application stage, but ARIA considers the overall project to be too high risk, ARIA reserves the right to fund only the first stages of the proposed scheme of work, with the possibility of releasing further funding later on if progress de-risks the later stages of the project sufficiently.

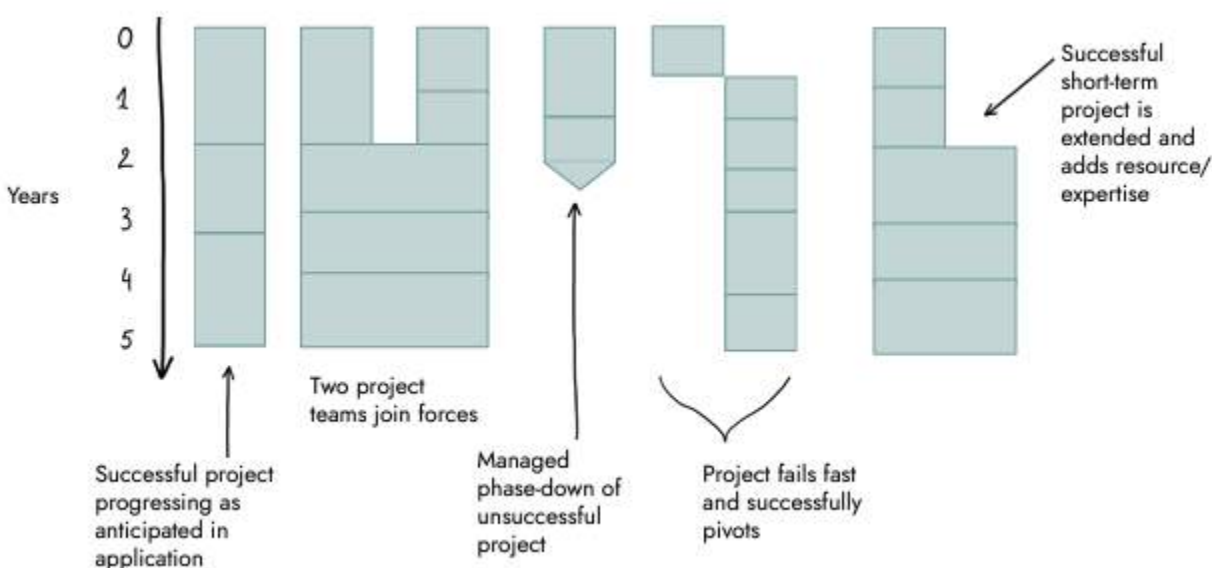


Figure 3: Illustration of the adaptive funding structure. Horizontal bars indicate project review points.

Project Milestones

ARIA will engage in negotiations with shortlisted applicants and will work together with those teams to develop their suggested success criteria into a rigorous set of staged performance metrics by which to gauge project progress. ARIA expects that each funded project will therefore have its own unique set of testable hypotheses, with a number of associated predefined and quantifiable key performance targets. For each project that is funded, ARIA will require the project teams to make public their hypotheses and key performance targets, together with a short discussion on how these are expected to lead to a step-change in understanding of the approach under consideration, as soon as realistically possible after project kick-off (most likely as part of the project's Q1 milestones). ARIA may then make use of third-party independent validation and verification at project review points in order to ensure rigour in the assessment of project performance.

Timelines for outdoor experiments and the steps that would need to be taken before these could take place will be discussed on a case-by-case basis during the project negotiation phase. For each outdoor experiment (or series of linked experiments), we will work with the project teams to provide a public statement on what the tests are attempting to achieve, and why those specific activities are critical, for publication during the outdoor experiment engagement/co-design phase. This document will then continue to be updated and iterated as a result of the engagement and co-design process.

There will be a programme-wide kick-off workshop for the projects selected for funding in the first half of 2025. Details will be provided to successful applicants.

Approach to Results and Intellectual Property

We are pursuing a very open approach to intellectual property (IP). Work under this programme should be undertaken with the intention of making project outcomes open-source and freely available. This means that the results from the work that we fund (including negative results) should be made available in a publicly available, open-access form, unless such publication would be likely to lead to public harm. As part of this, project teams will be required to give as much detail as possible on methodology and experimental data to ensure openness and transparency.

Intellectual property created by projects funded as part of this programme shall be published under creative commons or open source licences as appropriate. Our default position will be that project teams will not be permitted to file for patents in respect of inventions resulting from work that has been funded as part of this programme. We'll be asking all successful applicants and their team members to sign a public pledge not to seek patents on any work that is funded by this programme. This approach is designed to

enhance the public good by maximising the accessibility, usability, and collaborative potential of the funded projects, ensuring that the benefits extend to a wider community and fostering a culture of open innovation.

International partnerships

The impacts of climate tipping points (and the effects of actively cooling the Earth to delay or avoid the onset of these) are likely to be felt globally. Therefore, ARIA sees the need for a coordinated international effort led by public institutions to research approaches for actively cooling the Earth, what the effects and impacts of these approaches might be, and how their use might be governed.

To aid international collaboration and cooperation in this space, ARIA intends to:

1. Fund projects and researchers globally as part of this programme
2. Create opportunities for sharing best practice and learning with representatives of international and public benefit funding agencies, including annual workshops and invitations to observe the outdoor experiments that we fund.

For more detailed information on our approach to international partnerships with other funding organisations please see ‘International partnerships with other funding organisations’ in [the thesis](#). To further these aims, ARIA commits to being fully transparent across our programme design, management, and disclosure of the results of the research that is funded, by:

1. Requiring that the results from the work that we fund (including negative results) are available in a publicly available, open-access form, unless such publication would be likely to lead to public harm.
2. Making supporting documentation related to our outdoor experiments publicly available on the ARIA website (including pre-experiment risk assessments, post-experiment impact assessments, recommendations from our oversight committee, and results from our public engagement and co-design activities).
3. Continuing to update and iterate our (publicly available) governance and oversight procedures, calling out why any changes are being made and why we have made them.

Community events

In addition to programme workshops and in an effort to foster a collaborative research environment, ARIA will host regular community events to allow all programme teams to exchange updates, ideas, and feedback on the best paths forward. ARIA will also host annual in-person workshops where teams can showcase their work to a wider research community.

SECTION 6: Eligibility & Application process

Eligibility

We welcome applications from across the R&D ecosystem, including individuals, universities, research institutions, small, medium and large companies, charities and public sector research organisations.

ARIA can award funding to applicants who are based outside of the UK and/or whose projects will primarily take place outside of the UK for this Programme, provided these projects boost the net impact of the programme. Collaborations between UK and non-UK researchers are encouraged.

Finding potential collaborators and teaming

For those seeking specific expertise to support their proposal, we have created a teaming platform to facilitate finding potential team members who have registered their interest in this programme. By following the link to the [sign up form here](#) you will be able to register, submit your details, and gain access to a list of other individuals seeking to find/share their expertise. All requests are screened via ARIA's internal team prior to access, after which connections will be made by individual users based on aligned expertise.

Application Process

The application process consists of two stages:

Stage 1 - Concept paper

Concept Papers are designed to make the solicitation process as efficient as possible for applicants. By soliciting short concept papers (no more than three pages) ARIA reviewers are able to gauge the feasibility and relevance of the proposed project and give an initial indication of whether we think a full proposal would be competitive. Based on this feedback

you can then decide whether you want to submit a full proposal. If you miss the deadline for submission of concept papers you can still submit a full proposal. You can find out more about ARIA's review process [here](#).

To ensure the process is quick and open we do not require your organisation's consent prior to submission of a concept paper.

You can find guidance on what to include in a concept paper [here](#).

Following review of concept papers, applicants will either be encouraged or discouraged from submitting a full proposal. For more details on the evaluation criteria we'll use, click [here](#).

Stage 2 - Full proposals

This step requires you to submit a detailed proposal including:

- **Project & Technical information** to help us gain a detailed understanding of your proposal
- **Information about the team** to help us learn more about who will be doing the research, their expertise, and why you/the team are motivated to solve the problem
- **Administrative questions** to help ensure we are funding R&D responsibly. Questions relate to budgets, IP, potential conflicts of interest, etc.

You can find more detailed guidance on what to include in a full proposal [here](#). You can submit a full proposal even if you did not submit a concept paper.

More information on the evaluation criteria we will use to assess your answers can be found later in the document, or [here](#).

If you are a non-UK applicant we have provided some additional guidance in our [FAQs](#), including available visa options.

Use of Natural Environment Research Council (NERC) Facilities

We're working with the NERC to establish how their facilities may support the programme.

If your proposed research requires the support and use of a [NERC facility](#), you should do the following at each stage of the application process:

Stage 1 - Concept Papers

You should contact the [NERC facility](#), service and/or High Performance Computing (HPC) consortia lead to notify them of a potential dependency before submitting your concept paper. If applicable you should also notify Marine Planning via marineplanning@nerc.ukri.org directly if your proposal requires use of NERC's marine [facilities](#). For facilities relating to arctic services please contact arctic@bas.ac.uk

In submitting your concept paper, you must note potential use of the facility by detailing the relevant facility(ies) in the concept paper application portal. Details and facility costs do not have to be included at concept paper stage. You can find guidance on what to include in a concept paper [here](#).

Stage 2 - Full proposals

If encouraged to submit a full application, you should contact the NERC facility, service or HPC consortia lead as soon as possible to discuss your research proposal, and where applicable to complete any necessary HPC or facility form/application process as requested by the facility/marine planning, following the facility's normal access request procedures. As part of this process, NERC will provide a costed quotation for the services. The costing methods for this activity are currently being established with NERC and may not be finalised in time for the deadline for submission of proposals. As such, in submitting your full proposal, you should:

- Note the potential use of the NERC facilities in your proposal by completing the specific question included in the full proposal application portal. You can find guidance on what to include in a full proposal [here](#).
- For proposals that are assessed as compliant and in scope (in accordance with our project [review process](#)) you will be asked to submit a quotation from the HPC Consortia lead or facility, and evidence of prior agreement from the facility that your request is feasible and deliverable in the timeline indicated in your proposal. This should be submitted to ARIA no later than 16th January 2025. You will be notified by email that this information is required to be submitted via the application portal.

In any case you must ensure that you have discussed your proposal with the facility in good time prior to full application submission. Further discussion may be needed with any

successful projects in order to determine the most effective usage for delivery of the fieldwork aspects of the programme.

SECTION 7: Timelines

This call for project funding will be open for applications as follows (we may update timelines based on the volume of responses we receive):

Applications open	13 September
Concept paper submission deadline	07 October (12:00 Midday BST)
Concept paper review & notification of encouraged/not encouraged to submit full proposal sent	07 October - 08 November
At this stage and based on your concept paper, you will either be encouraged/discouraged to submit a full proposal. If you receive feedback indicating that you are not encouraged to submit a full proposal you can still choose to submit a full proposal. You should note that this preliminary assessment/encouragement provides no guarantee of any full proposal being selected for award of funding.	
Full proposal submission deadline	09 December (12:00 Midday GMT)
Full proposal review	09 December - 13 February
If you are shortlisted following full proposal review, you will be invited to meet with the Programme Directors to discuss any critical questions/concerns prior to final selection. This discussion can happen virtually.	
Successful/Unsuccessful applicants notified	13 February
At this stage you will be notified if you have or have not been selected for an award subject to due diligence and negotiation. If you have been selected for an award (subject to negotiations) we expect a 1 hour initial call to take place between ARIA's programme director and your lead researcher within 10 working days of being notified. We expect contract/grant signature to be no later than 8 weeks from successful/	

unsuccessful notifications. During this period the following activities will take place:

- Due diligence will be carried out
 - The programme director and the applicant will discuss, negotiate and agree the project activities, milestones and budget details
 - Agreement to the set Terms and Conditions of the Grant/Contract. You can find a copy of our funding agreements [here](#)
-

SECTION 8: Evaluation Criteria

Concept Paper and Proposal Evaluation Principles

To build a programme at ARIA, each Programme Director directs the review, selection, and funding of a portfolio of projects, whose collective aim is to unlock breakthroughs that could impact society. As such, we empower Programme Directors to make robust selection decisions in service of their programme's objectives ensuring they justify their selection recommendations internally for consistency of process and fairness prior to final selection.

We take a criteria-led approach to evaluation. As such, all proposals are evaluated against the criteria outlined below. We expect proposals to spike against our criteria and have different strengths and weaknesses. Expert technical reviewers (both internal and external to ARIA) evaluate proposals to provide independent views, stimulate discussion and inform decision-making. Final selection will be based on an assessment of the programme portfolio as a whole, its alignment with the overall programme goals and objectives and the diversity of applicants across the programme.

Further information on ARIA's proposal review process can be found [here](#).

Proposal evaluation process and criteria

Proposals will pass through an initial screening and compliance review to ensure proposals conform to the format guidance and they are within the scope of the solicitation. At this stage we will also carry out some checks to verify your identity, review any national security risks and check for any conflicts of interest. Prior to review of applications, Programme Directors and all other reviewers are required to recuse themselves from decision making related to any party that represents a real or perceived conflict of interest.

Where it is clear that a proposal is not compliant and/or outside the scope, these proposals will be rejected prior to a full review on the basis they are not compliant or non-eligible.

Proposals that pass through the initial screening and compliance review will then proceed to full review by the Programme Director and expert technical reviewers.

In conducting a full review of the proposal we'll consider the following criteria:

- 1) **Worth Shooting For** – The proposed project uniquely contributes to the overall portfolio of approaches needed to advance the programme goals and objectives. It has the potential to be transformative and/or address critical challenges within and/or meaningfully contribute to the programme thesis, metrics or measures.
- 2) **Differentiated** – The proposed approach is innovative and differentiated from commercial or emerging technologies being funded or developed elsewhere.
- 3) **Well defined** – The proposed project clearly identifies what R&D will be done to advance the programme thesis, metrics or measures, is feasible and supported by data and/or strong scientific rationale. The composition and planned coordination and management of the team is clearly defined and reasonable. Task descriptions and associated technical elements provided are complete and in a logical sequence with all proposed stage-gates and deliverables clearly defined.
- 4) **Responsible** – The proposal identifies major ethical, legal or regulatory risks and planned mitigation efforts are clearly defined and feasible.
- 5) **Intrinsic motivation** – The individual or team proposed demonstrates deep problem knowledge, have advanced skills in the proposed area and shows intrinsic motivation to work on the project. The proposal brings together disciplines from diverse backgrounds.

- 6) **Benefit to the UK and the wider world** – In order for this programme to succeed and provide benefit to the UK and globally it must be an international endeavour. Therefore, ARIA's criteria around proposals from non-UK applicants being considered with regard to the next best alternative proposal from a UK organisation/individual have been adjusted for this call. Strong applications will therefore be those that benefit the UK and the wider world, and that will promote scientific innovation and invention with the ultimate aim of improving the quality of life in the UK and elsewhere.

ARIA may share a summary of the proposals encouraged to submit full proposals and information on proposals shortlisted following stage 2 full proposal review with NERC to prevent overlap with their [research programme to model impact of solar radiation management](#). Any information will be shared on a confidential basis.

SECTION 9: How to apply

Before submitting an application we strongly encourage you to read this call in full, as well as the [programme thesis](#) and [general ARIA funding FAQs](#).

If you have any questions relating to the call, please submit your question to clarifications@aria.org.uk.

Clarification questions should be submitted no later than 4 days prior to the relevant deadline date. Clarification questions received after this date will not be reviewed. Any questions or responses containing information relevant to all applicants will be provided to everyone that has started a submission within the application portal. We'll also periodically publish questions and answers on our website: to keep up to date click [here](#).

Please read the portal instructions below and create your account before the application deadline. In case of any technical issues with the portal please contact clarifications@aria.org.uk.

Application [Portal instructions](#)

APPLY [HERE](#)

SECTION 10: References

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Annex 3 – 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.

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2.	<i>'Planetary Sunshade Baseline Survey'</i> Planetary Sunshade Foundation	12-19
3.	<i>'Investigating the Impacts of Solar Geoengineering on the Variability and Wet-Dry Spell Dynamics of the West African Monsoon'</i> Institut Polytechnique Rural de Formation	20-29
4.	<i>'Ice-Nucleating Particles in the Upper Troposphere: Advancing Cirrus Control and Experimental Science Strength'</i> University of Leeds	30-37
5.	<i>'Monitoring Aerosol Climate Engineering (MACE)'</i> University of Bristol	38-45
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18.	<i>'Eco-Gap: Ecological assessment of Geoengineering at the Poles'</i> British Antarctic Survey	153-170
19.	<i>'A Responsible innovation Framework for assessing NOvel Spray Technology Research to examine local AlbeDo changes from Marine brightening and its mUlti-Scale impacts. (NOSTRADAMUS)'</i> University of Manchester	171-180
20.	<i>'Marine Cloud Brightening in a complex world – moving beyond the Twomey effect'</i> Southern Cross University	181-190
21.	<i>'Exploring Geoengineering's Effects on the Dynamics and Thermodynamics of Monsoon and Precipitation extremes'</i> The Energy and Resources Institute	191-198

This project will evaluate whether it is possible to intentionally modify the properties of cirrus clouds to achieve a useful ($>100 \text{ mW/m}^2$) 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 alone¹.

1 Cirrus clouds: a potential climate dial

Globally, cirrus clouds lead to a warming effect of $\sim 5 \text{ W/m}^2$. Inadvertent cirrus cloud modification by aircraft, where cirrus-forming regions are “overseeded” by ice nucleating particles (INPs) resulting in long-lived warming clouds, already causes² a radiative forcing of $\sim 100 \text{ mW/m}^2$. 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 benefit³ of $2\text{--}3 \text{ W/m}^2$. 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 deliberately⁵, as industrial emissions do inadvertently⁶. The true efficacy of CCM is however uncertain, with some models showing negligible benefit⁷ and a key uncertainty being the challenging-to-measure concentration of background ice nucleating particles (INPs) at altitude⁸. **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.**

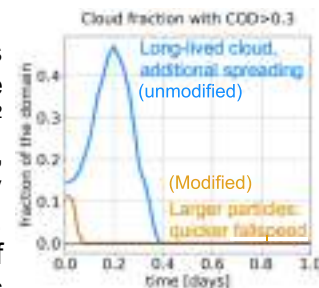


Figure 1. Homogeneous (blue) and heterogeneous (brown) cirrus lifecycles in an idealized LES model (Gasparini et al., in prep).

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 create 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 clouds¹¹.

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 onwards¹⁴ 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

number²⁰. 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 periods²¹. Past work²¹⁻²³ 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 dust¹⁷, 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 instrument²⁶, 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 feasible¹. 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 engines²⁴ 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 crystals³⁰. 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 topic²⁴ 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 droplets³¹, 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 conditions³²) 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.

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 interactions³⁶. This will allow us to evaluate the regional sensitivities and atmospheric feedbacks of CCM, and will



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.

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 relations³⁷. *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.

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.

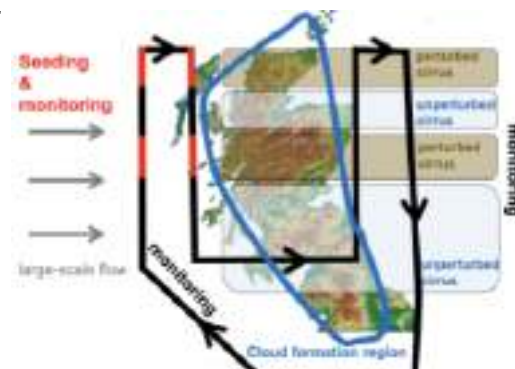


Figure 4. Schematic of the P3 seeding approach.

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.

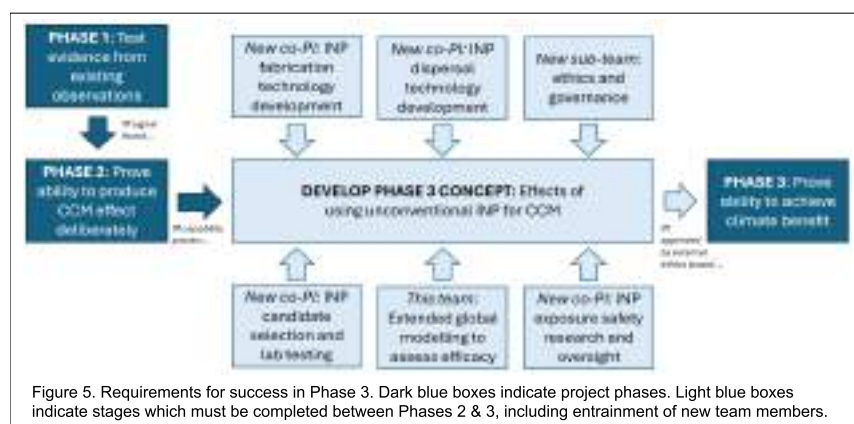


Figure 5. Requirements for success in Phase 3. Dark blue boxes indicate project phases. Light blue boxes indicate stages which must be completed between Phases 2 & 3, including entrainment of new team members.

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 used⁵ 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 seeding³⁸), 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 break¹. 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, P2 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.

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

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

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

B will commit 15% of 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.

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

will commit 5% of 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.

3 References

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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 km² 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.



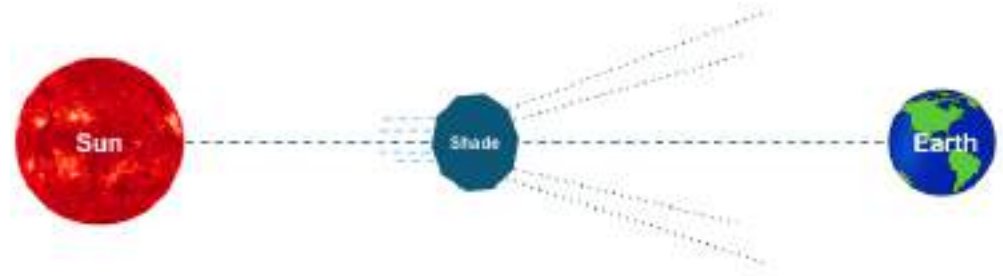
B: Reflective spacecraft at SEL1 in an orbit with preferential seasonal hemisphere shading

This intervention is a constellation of spacecraft, with a total area larger than the 2 M km² 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 Visoni 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 $\approx 4.52 \times 10^{23}$ particles of $1.6 \mu\text{m}$ -radius at SEL1. Since most of the Sun's energy is in wavelengths smaller than $2.5 \mu\text{m}$, 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 1600m² 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.

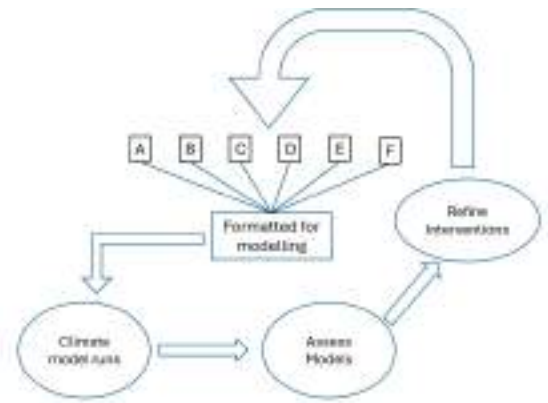
ARIA Sunshade Project Proposal

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:

Engineering Expertise from Ethos Space:

Climate Modeling Leadership:

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.

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 (Vioni et al., 2021). Some of the widely proposed approaches 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 Methodology

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

[illegible]

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

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

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

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

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

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.

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]

[REDACTED]

[REDACTED]

[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]

[REDACTED]

[REDACTED]

[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]

[REDACTED]

[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]

[REDACTED]

[REDACTED]

[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]
[REDACTED] **Role: Technical guidance and model refinement.**
- [REDACTED]
[REDACTED]
[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:

- 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.
- 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.
- 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.
- 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]: 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”**

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, B²SAP, 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 $0.5 \times 0.5 \text{ cm}$, corresponding to a sample volume of $25 \text{ cm}^3 \text{ s}^{-1}$, 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 B²SAP, 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)).												
Ballon 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, RH_i, 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]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

Balloon-borne observations: [REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

Ice nucleation measurements [REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

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

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

Proposal Facilities:

NOAA Chemical Sciences Laboratory: 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]

[REDACTED]

[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 B²SAP 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 climate¹. 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.

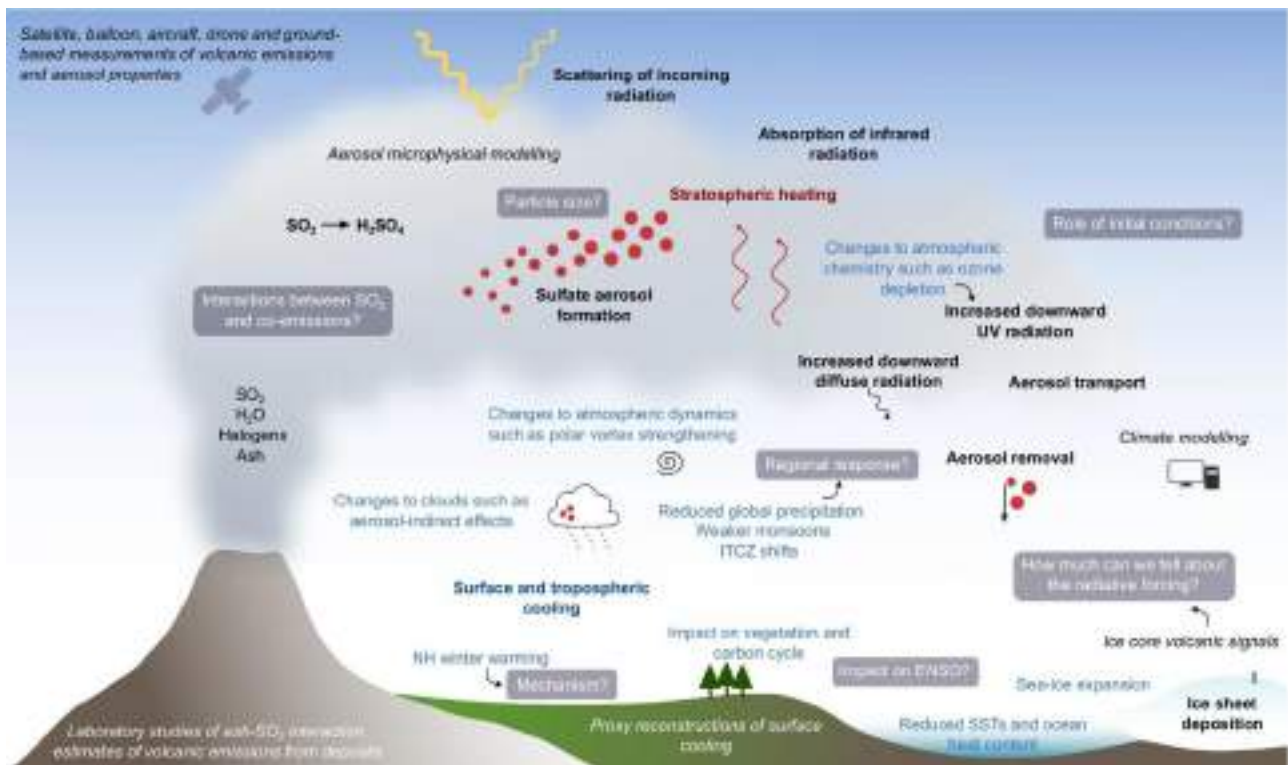


Figure 1. From Marshall et al., 2022¹. Figure showing volcanic influence on climate include aerosol and cloud albedo effects.

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 1991⁴, 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 eruption⁵. 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 events⁶.

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 SO₂ 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 SO₂ 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 quantify 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 The Risks

Technical Risks.

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 SO₂ 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 SPICE⁸ (Stratospheric Particle Injection for Climate Engineering), a more controversial project that included a deployment technology field test¹³. 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 emissions⁸ 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 distribution⁷. There are a wide variety of lightweight electrochemical gas sensors (e.g. H₂O, SO₂) 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. Pyrometers 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 SO₂. 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 learning¹⁰ to train the system to repeatedly intersect the same section of the plume at Fuego and investigate SO₂ 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 SO₂ is rapidly converted into sulphate aerosol¹¹, an effective source of cloud condensation nuclei observed at volcanoes during passive degassing¹². Lower plume altitudes mean potential heavier payloads and/or longer flight times and, given the rapid conversion of SO₂, allows us to investigate a series of physico-chemical reactions from heterogenous nucleation of aerosols through 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 SO₂ 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.

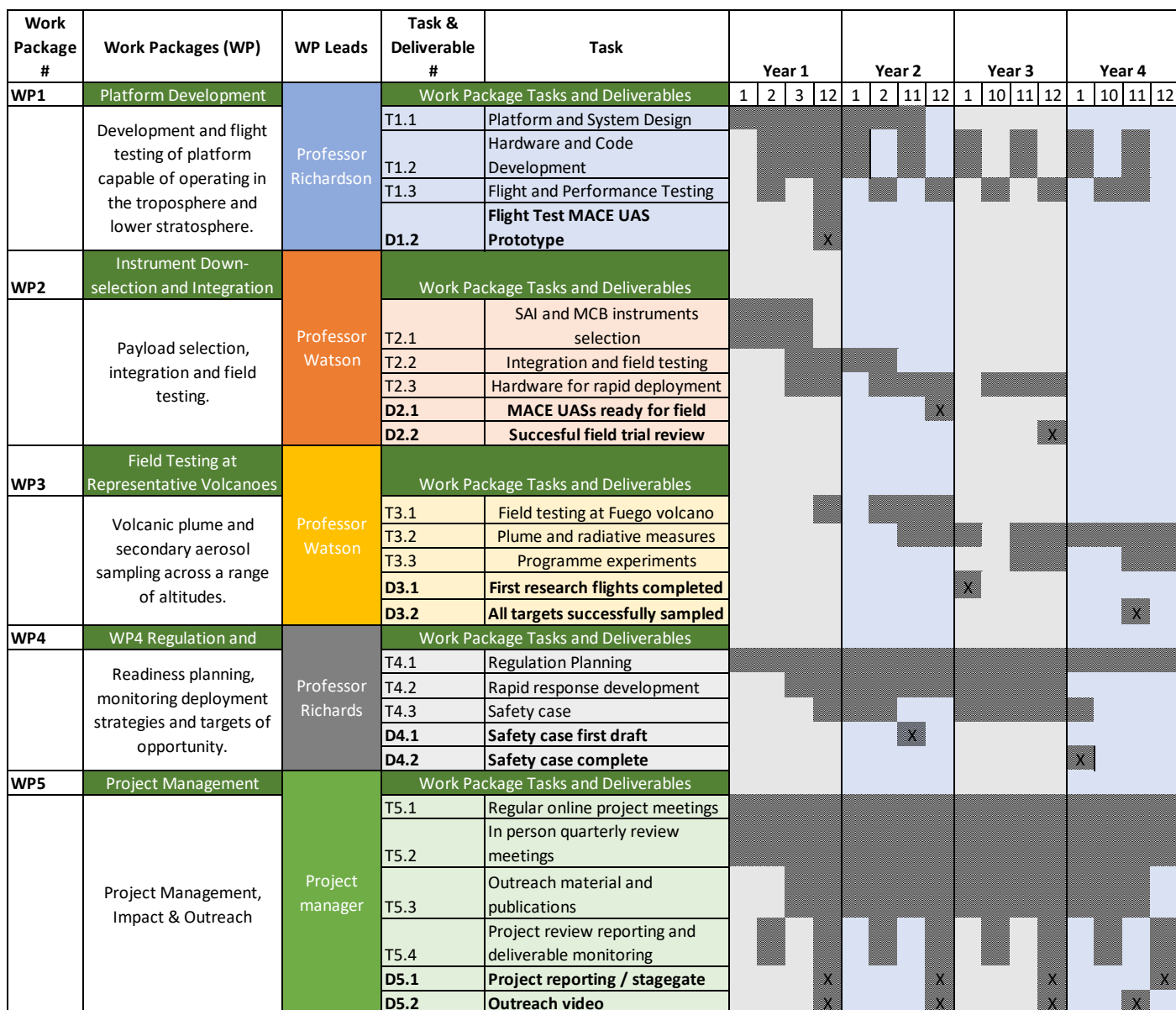


Figure 3. MACE Gantt Chart with Work Packages (WP), Tasks (Tx.x), Deliverables (Dx.x) and denoted by X on the timeline, shown over the four years of the project.

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.

[REDACTED]

[REDACTED]

[illegible]

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

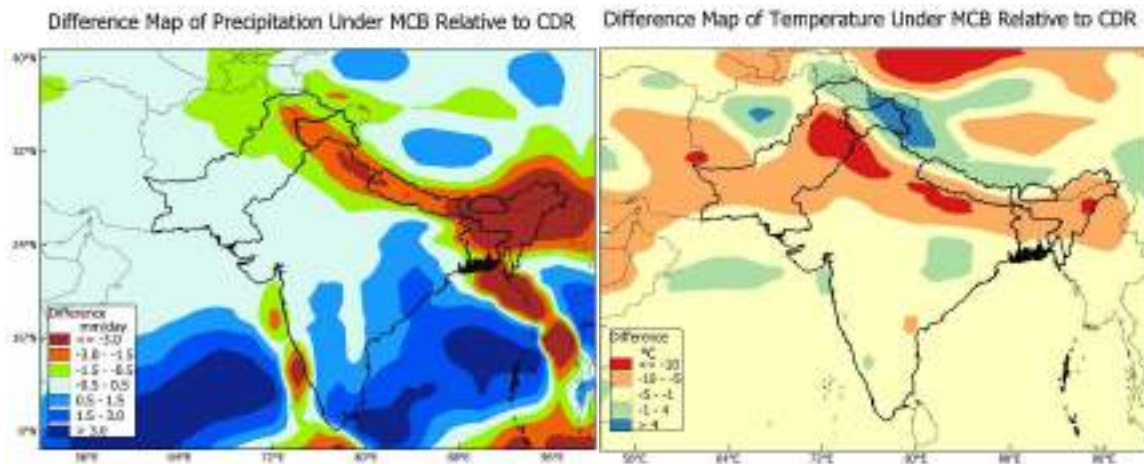


Figure 1: Mean difference of precipitation (left) and temperature (right) of MCB, relative to CDR, over South Asia (2021-2090)

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

- o **Comparative Analysis of MCB (GeoMIP) CDR (CDRMIP), mitigation (CMIP) Projections:**
 - Compare the efficacy of MCB and ocean alkalization (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.
- o **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.
- o **Policy Analysis:**
 - Analyze national and regional policies to identify gaps and opportunities for integrating MCB into climate strategies.
- o **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 alkalization, 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]

[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, particularly with respect to the scientific, governance and stakeholder engagement 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.

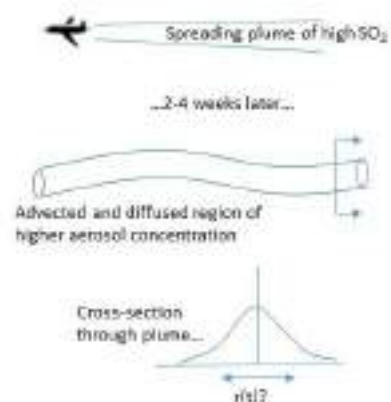
An outdoor experiment could be designed specifically aimed at reducing this uncertainty, but it is unclear what scale this experiment would need to be. This is the primary question we address here - not the detailed experiment design, but rather a robust scientific definition of the scale that such an 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 mission¹) to fly into the plume and sample the aerosols to determine size distribution. Designing modifications to existing aircraft to store and release SO₂ 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 experiment² or the somewhat arbitrarily-proposed 1000 kg limit suggested in the 2021 US National Academies report³. 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 mode⁴, 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 TROPOMI⁵ after volcanic eruptions, which have been demonstrated to be capable of tracking plumes of SO₂ 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 SO₂ 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 SO₂ 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 example⁶), 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

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 SO₂.** 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 SO₂ 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 SO₂-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]

[REDACTED]

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

[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 SO₂ 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)
██████████ ██████████	██████ ██████████ ██████	50%	12
██████████████ ██████████ ██████	██████████████ ██████	50%	12
██████████ ██████████	██████████████ ██████████ ██████e	50%	12
Hiring of Full-time Research Assistant		100%	24
██████████████ ██████	██████████████ ██████	10%	2.4
██████████	██████████ ██████████	20% (Policy workshop/dialogue and give critics on the research protocols)	4.8
██████████	██████████ ██████████	20% (Policy workshop/dialogue and give critics on the research protocols)	4.8
██████████ ██████████	██████████████ ██████████ ██████████	20% (Policy workshop/dialogue and give critics on the research protocols)	4.8
██████████	██████ ██████████ ██████	20% (Policy workshop/dialogue and give critics on the research protocols)	4.8
██████████████	██████ ██████████ ██████	20% (Policy workshop/dialogue and give critics on the research protocols)	4.8
██████████	██████████████	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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1. SAFE GEOGOV'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.

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.

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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 interlocutors 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.

SAFE GEOGOV 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

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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 SAFE GEOGOV 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 information 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.

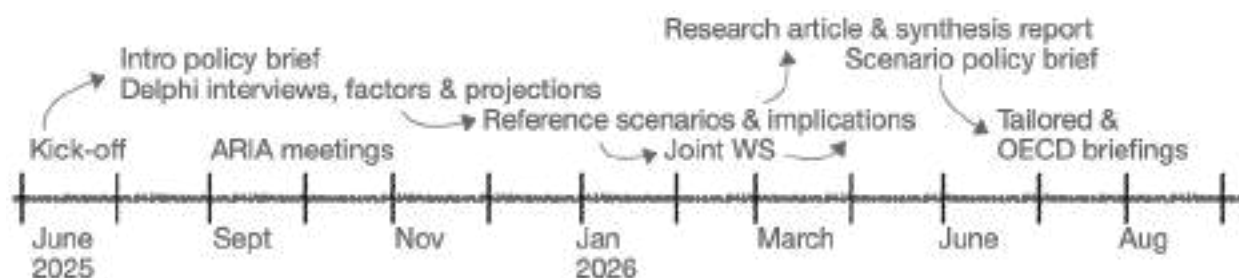


This substantive work is done in a staggered sequence, whereby the five scenario-development steps (Delphi interviews, impact factors short- and longlist, projections, reference scenarios, and implications analysis) are undertaken sequentially and in consultation with thematic experts and policymakers 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

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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 SAFE GEOGOV'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

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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]

[REDACTED]

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[REDACTED]

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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 SO₂ injections¹⁻⁶, 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 radiation²⁵ 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 studies³⁶⁻⁴³. To understand the efficacy, deliverability and risks of ASAIMs validated models are required. ASAIMs are instantaneously effective whereas SO₂ develops optical effectiveness over a period of weeks thus small-scale indoor experiments are relatively easy with ASAIMs.

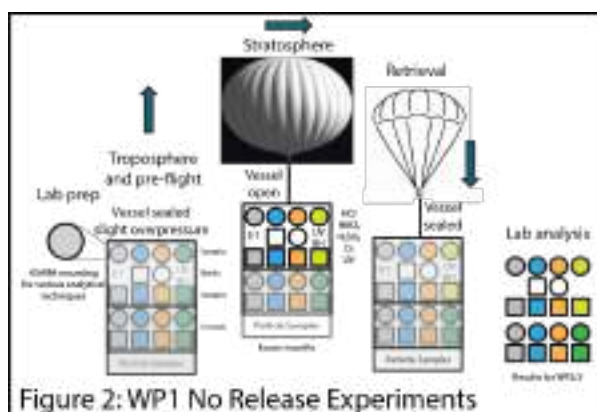
Central issues are the (i) scattering efficiency per injection mass, (ii) amount of radiation absorbed, primarily in the long-wave atmospheric window, and (iii) chemical impact on stratospheric composition. First-order questions are what is the ideal ASAIM with respect to radiative and chemical impacts 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 formation⁴² and surface particulate matter exposure⁴⁴ 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.

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



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

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 (*product is material mounting and vessel functional and for stratospheric conditions*).

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

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

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; *deliverable is publication of first scientific results on realistic ageing of ASAIMs providing input for WP1E, WP2 and WP3*.

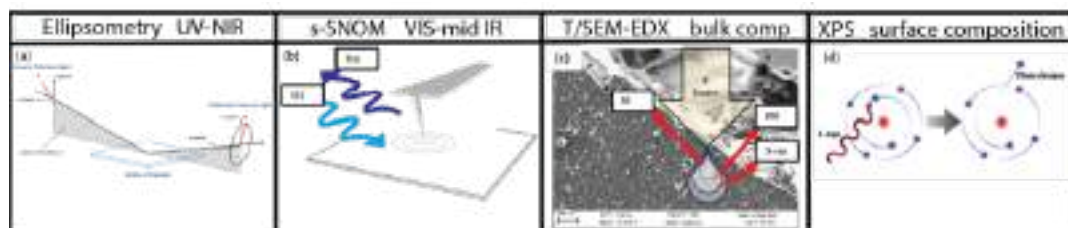


Figure 3. Some employed spectroscopic and imaging techniques. (a) Ellipsometry: UV-NIR refractive index (b) s-SNOM: nanoscale spatially resolved VIS-mid IR absorption and reflectivity; shape, size, morphology and surface roughness (c) T/SEM-EDS: high resolution imaging of topography/morphology and bulk 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 HNO₃, 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 project⁵⁷. 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

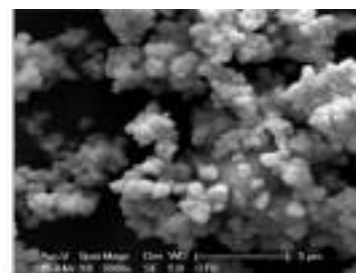


Figure 4. electron microscope image of a TiO₂ nanoparticle

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 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 aircraft⁵⁸ 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 SO₂ 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).

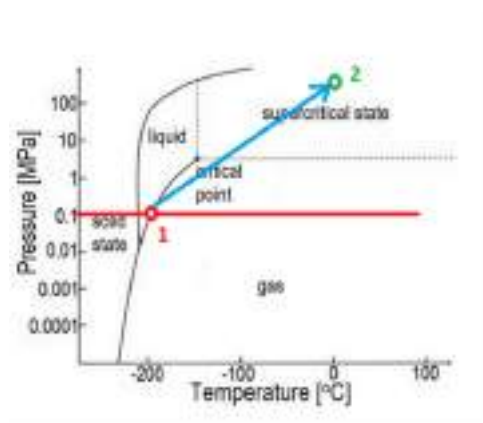


Figure 5. Phase diagram for nitrogen

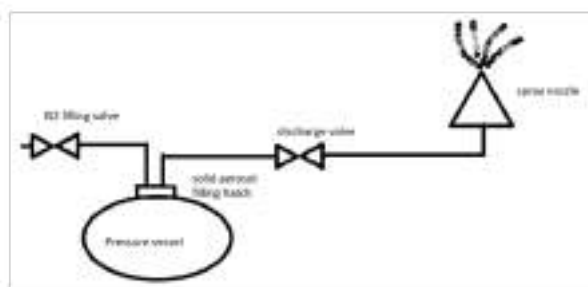


Figure 6. Example pressure vessel

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.

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.

1.3.3 Work Package 3 (WP3): Climate impact of non-sulphate aerosols

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

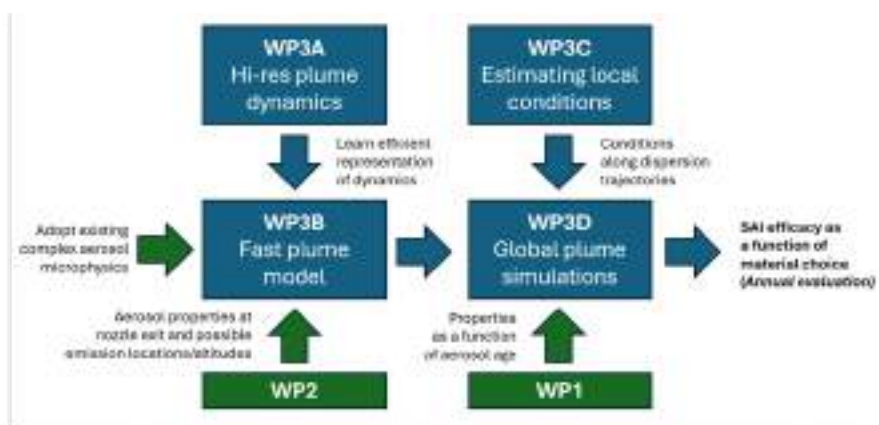


Figure 7. Schematic of the internal relationship between WP3 subpackages and external connections to other work packages.

shown in Figure 7.

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 flows⁵⁰ 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 m³ 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 model⁵⁴ 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

WP	Stage	Project Year & Quarter											
		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 SO₂.

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 Latham¹, 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 behaviour², including lengthening small droplet lifetimes by reducing their evaporation rate³, and through the disintegration of strongly charged drops into smaller droplets by the Rayleigh instability⁴. 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 aircraft⁵. (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 uncrewed⁶ 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 demonstrated¹. 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.

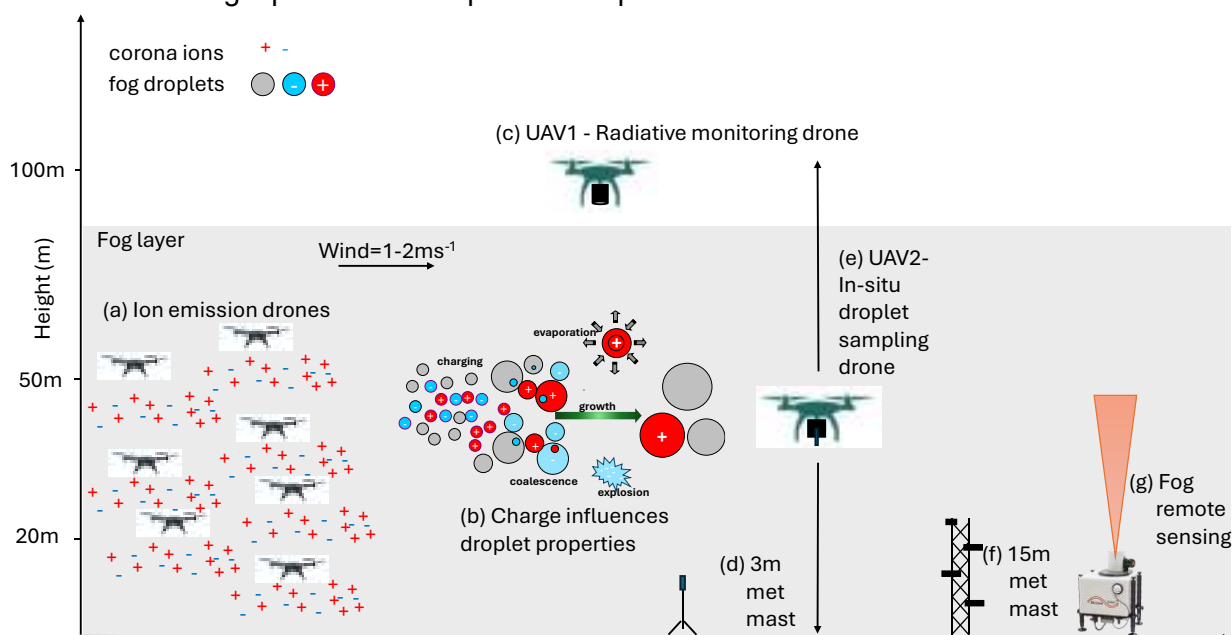


Figure 2. Schematic diagram of experimental campaign setup. (a) Up to 20 ion emission drones (Celestial) will emit bipolar ions into a fog layer, whose droplet properties are expected to change according to processes shown by (b). Changes in fog properties will be monitored by (c) an instrumented drone 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 clouds⁹. 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 measurement¹⁰ 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 by¹¹ 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 UCASS¹³. 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, ████████)

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 ████████ 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.

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:

Unknowns and risk mitigation

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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] 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]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[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.

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.

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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).

References (see Box 1 references).

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:

- ## Responsible participatory governance

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.

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).

[REDACTED] We will organise an in-person week of meetings in Buenos Aires with our UK advisors, [REDACTED]
[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.

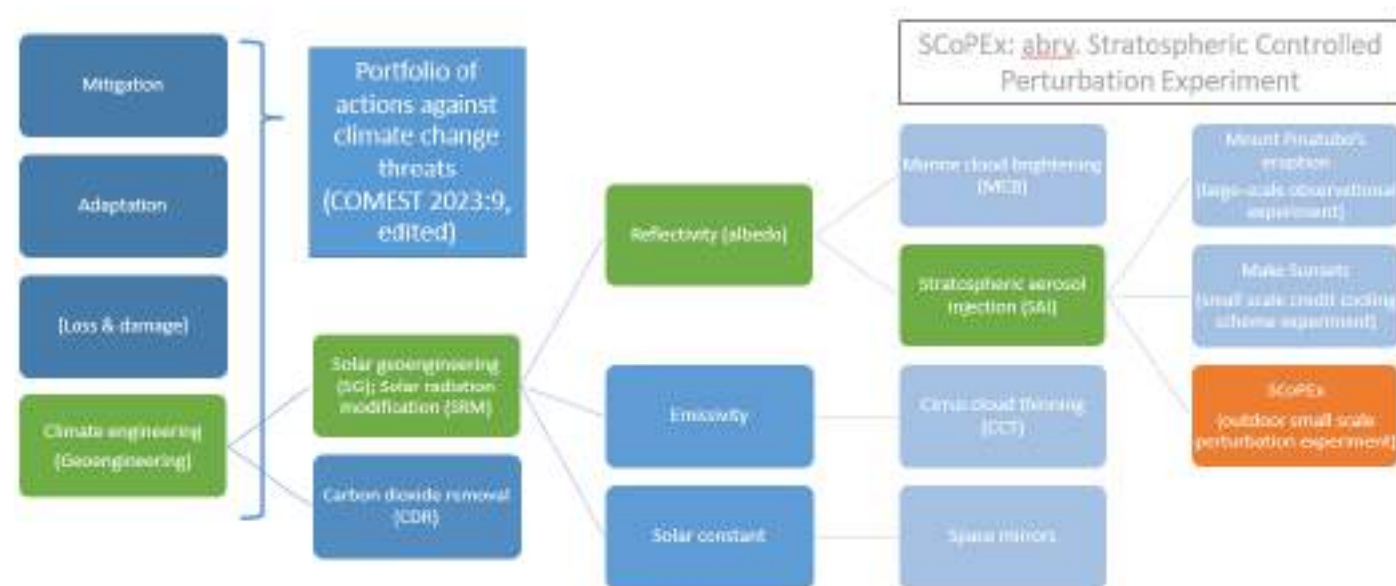


Figure 1. Analysis of SCoPEx experiment: SG SAI climate intervention of small scale outdoor research

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 be ethically 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 foresee 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 strengthen 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 scoping 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 text block]

- [Redacted text block]

- [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 SCoPEX² and the University of Washington’s experiments with Marine Cloud Brightening³ 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 Framework⁵ 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 deployment⁶. 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 citizens⁷.

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>.

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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 express⁸. 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 static⁹ – 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 Arctic¹⁰ 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 experimentation¹¹. There are several climate engineering research projects that conduct their own outreach¹² 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 Tromsø, Oulu, Manndalensjøen, 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 forums¹⁵ are focused on governance and decision making, not on the process of public engagement itself. Currently existing frameworks like post-normal science¹⁶ 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 Solutions¹⁷ 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-J](https://doi.org/10.1016/0016-3287(93)90022-J).

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 through 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.

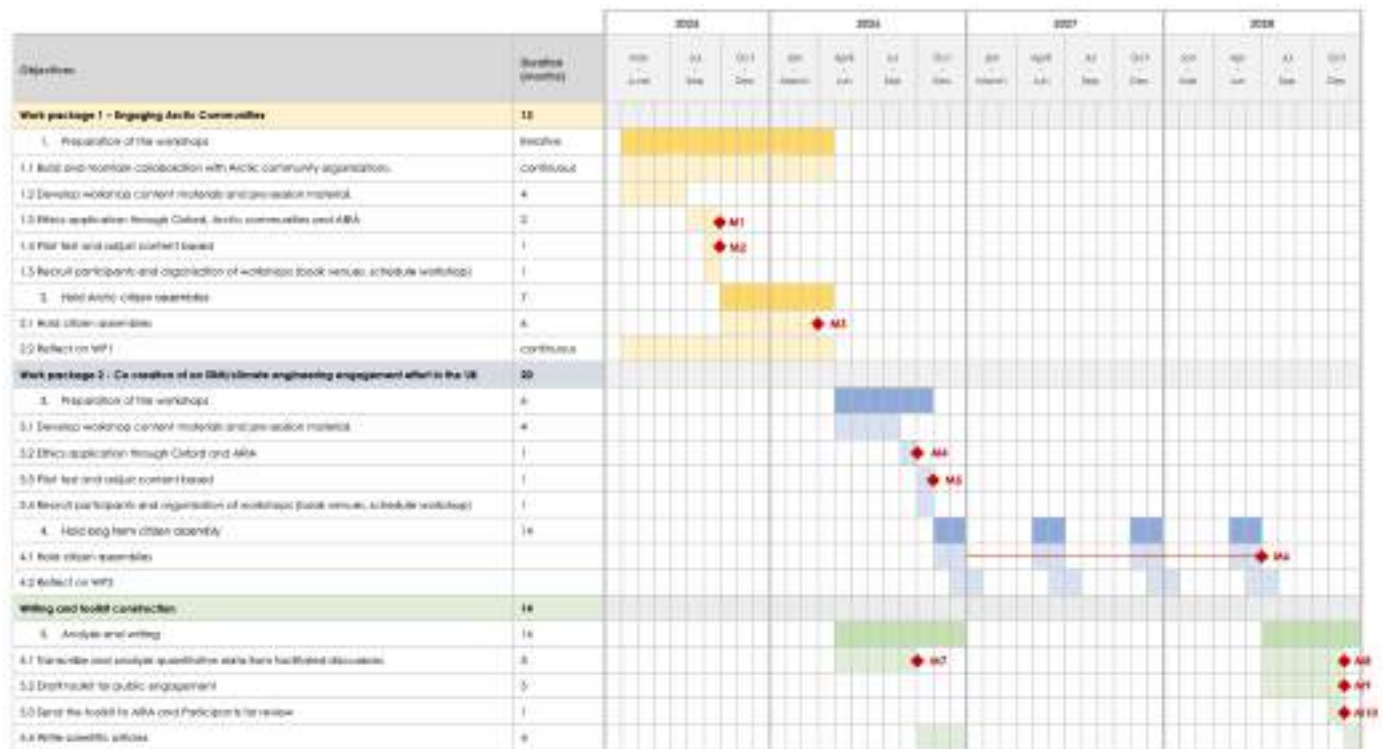
Timeline

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).



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 average¹. 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.

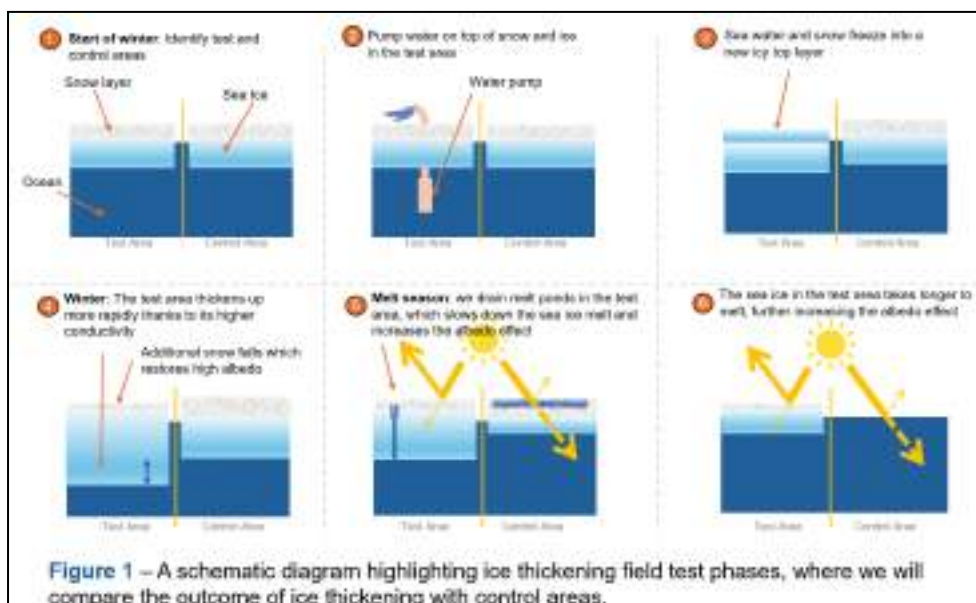
This proposal brings together a motivated, diverse and expert team uniquely positioned to address the aforementioned challenges. The project is both highly ambitious and novel, with the potential for significant climatic rewards and minimal risk. The project team is exceptionally suited to deliver this goal-focused proposal, having extensive experience in implementing high risk/reward science in extreme environments⁴, 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]

[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.

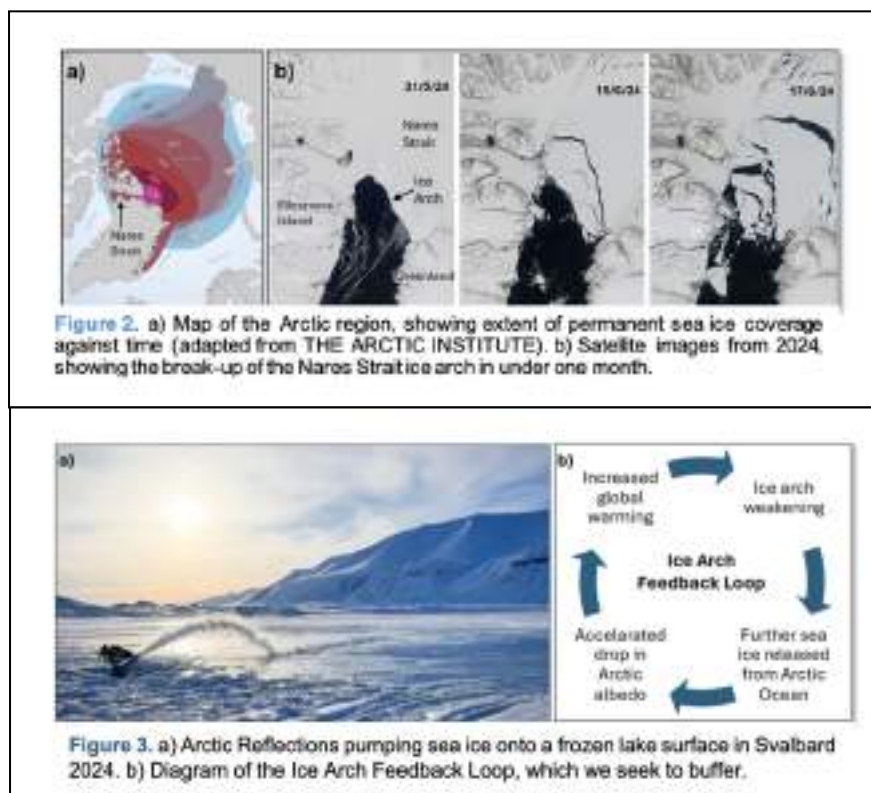
Throughout the project, results from our field tests will



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](#)

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 ice¹⁰.

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 months¹¹ before breaking apart, allowing the withheld sea ice to flush south. Approximately 95,000 km² 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 export¹². 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 arch¹³. However, the Nares Strait ice arch has been forming less frequently and lasting for shorter durations in recent decades¹⁴. Before 2007, the arch lasted an average 177 days per year, but since then the average duration has decreased to 128 days per year¹⁵. Thinner ice arch thicknesses, resulting from less favorable formation and maintenance conditions¹⁶, are less effective at holding back the surrounding glaciers¹⁷ and the Arctic Ocean's sea ice¹⁸.

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 ice¹⁹. In this study, it is anticipated that the maximum thickening required to stabilise an arch 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 companies²⁰. 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.

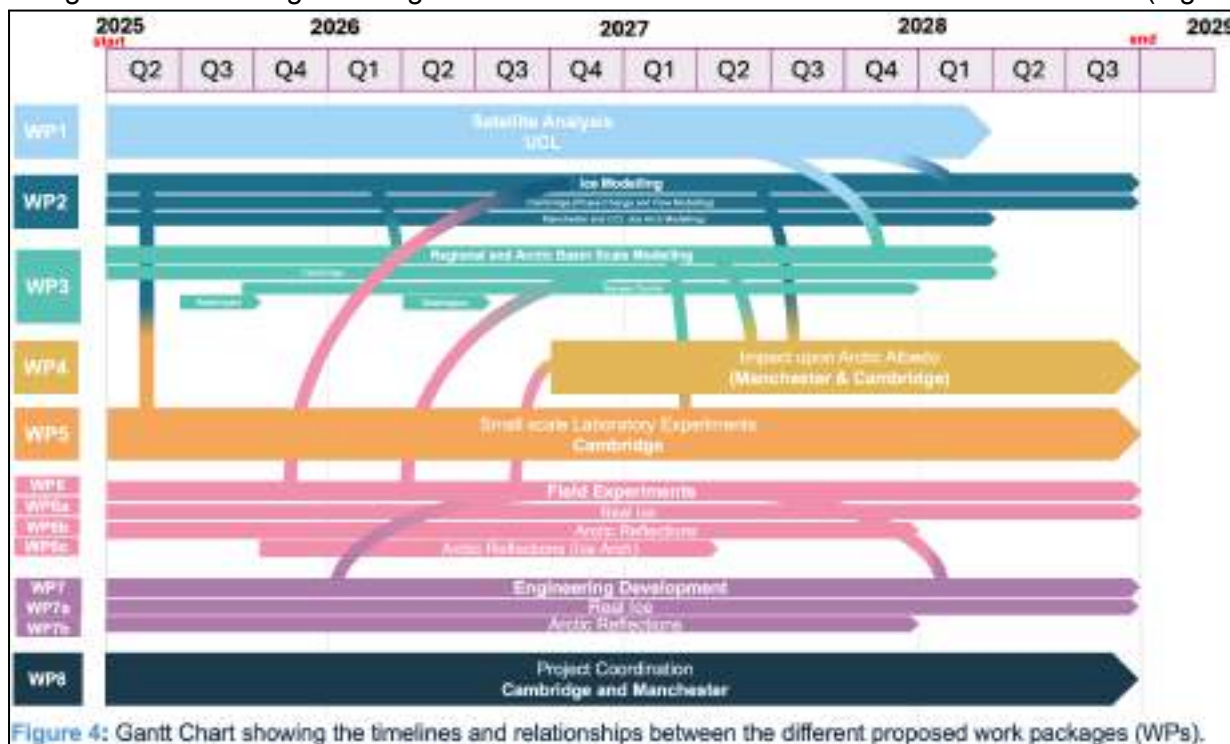
Scalability studies

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 (WPs). 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 **WPs** as shown in the Gantt Chart (Fig. 4).



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 growth⁷ 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 observed²⁷. 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 km² 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.

(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>.

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 SO₂ in the stratosphere have a resolution of +/-2km and revisit time of 2 per day¹) to adequately measure the impact of any small-scale interventions in remote equatorial regions where interventions will likely be deployed². 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 risky⁴ before their effects could be detected using current sensing systems.

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 programmes⁵. 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 activity⁶ 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 clouds⁷ to a similar effect as would be instigated by marine cloud brightening⁸. 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 (B²SAP) project, which is NOAA's

'Earth's radiation budget initiative' project. The B²SAP 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 B²SAP short duration balloon systems. These include variants of the B²SAP 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 scenarios¹¹ from other countries – hence 'StratoGaurd'.

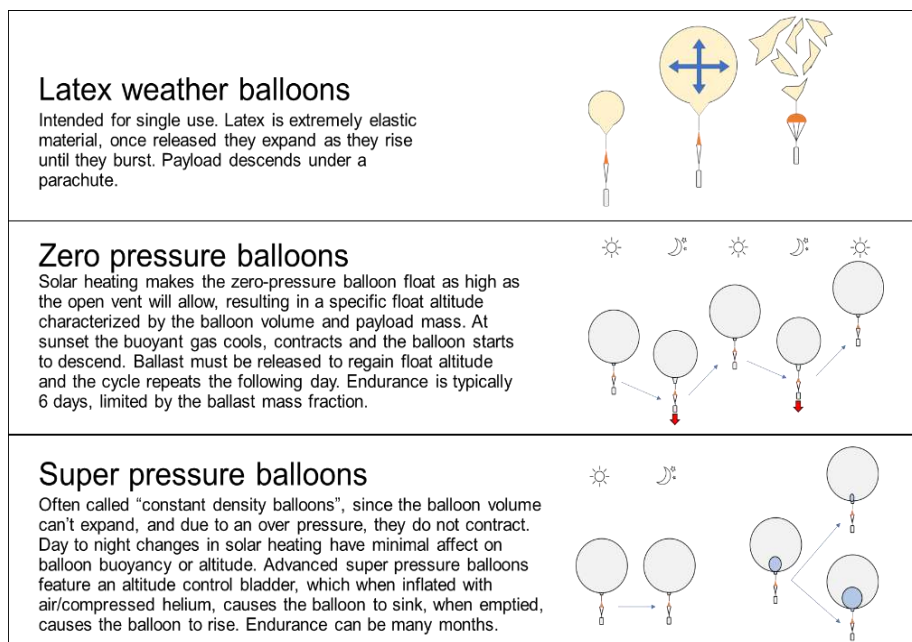
Why is it important? The world is striving towards net zero, however current forecasts by the IPCC¹², make grim reading. 1.1°C of global temperature rise has already occurred, with climate effects directly attributed to this change. Limiting global increases to 1.5°C is possible, however an overshoot 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 tropopause¹³. It is vitally important that were this scenario¹⁴ to play out an adequate method of monitoring the effects and measuring impacts relative to long term fiducial reference measurements¹⁵ 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 ballonnet, 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 $\pm$ 10kft. ZP balloons offer multi-day endurance – these systems have more coarse altitude control and navigation is not as accurate, but

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

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.

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

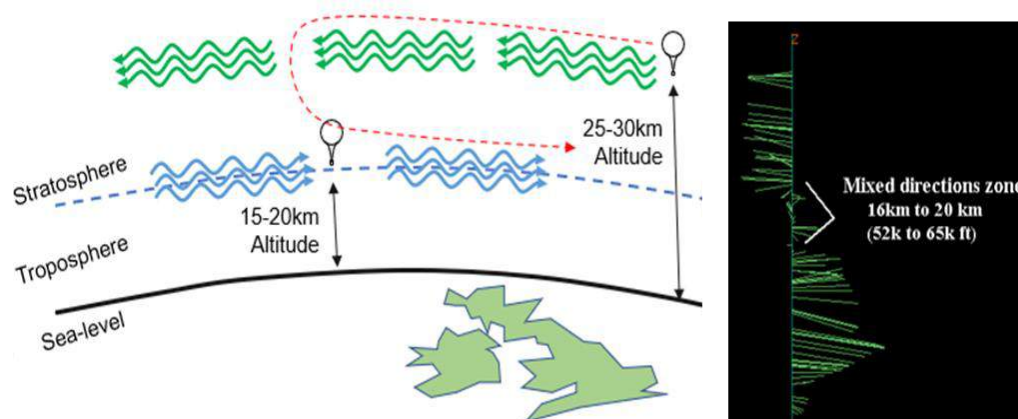


Figure 5: Navigation concept, in the light and variable winds of the lower stratosphere, just above the tropopause, a diversity of wind headings that rapidly change with small changes in altitude, can be selected by altitude controlling balloons to control drift direction and provide navigation.

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

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 Loon¹⁶ project (Figure 6) successfully deployed a fleet of these balloons in equatorial regions with endurances above 250 days, with payload capacities of 25kg. [REDACTED]



Figure 6: Google Loon (note the internal ballonet)

[REDACTED] Ultimately it was not commercially viable, and these systems now live on only in a military capacity¹⁷ as the Aerostar Thunderhead system.

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 polyethylene with shaped 'gores' where defects manifest as slow leaks rather than explosive failure.



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

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 boundaries¹⁸ 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]

[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 events¹⁹, 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.

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]

[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]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

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

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[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.

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])

Year 1: 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 in the stratosphere from Cabo Verde (CV), MS4. The Y1 flight tests, coordinated through 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.

Year 2: Aim to demonstrate a long duration navigable super pressure mHAB envelope, featuring balloonnet 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 balloonnet 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.

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]. 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 ARISE¹ and GLENS² 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).

[REDACTED]

[REDACTED]

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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

Technical Risks

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.

Non-Technical Risks

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.

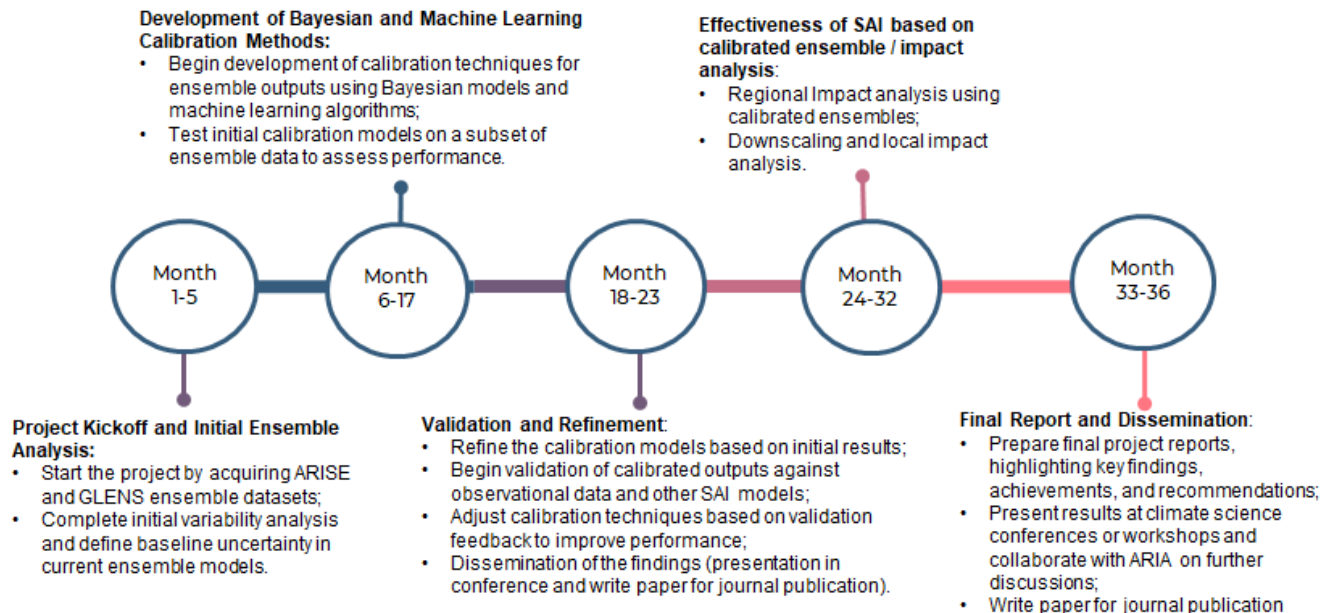


Figure 2. Estimated timelines and project milestone

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]
- [REDACTED]
- [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.

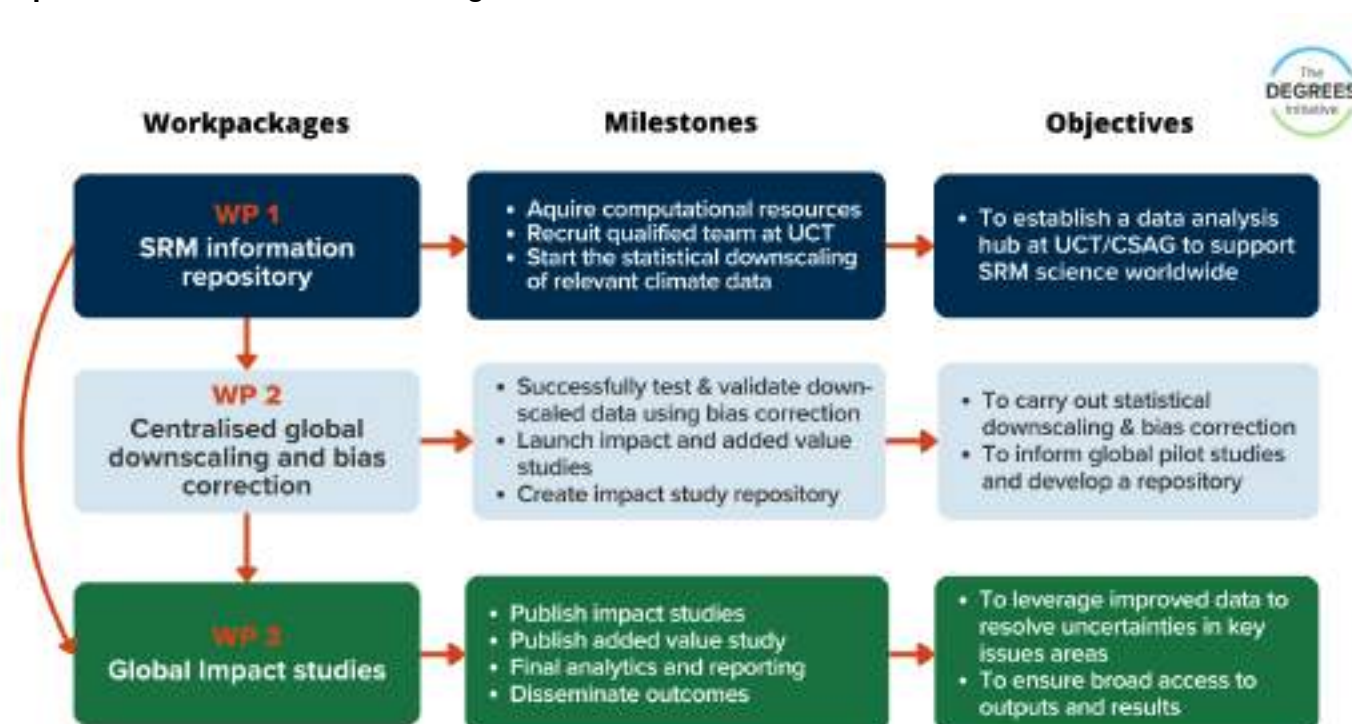
Year 3: Expansion, validation, and delivery

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]

[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] [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 Centerⁱ. 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^{iiiv}. 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}.

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

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} Visoni, 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>

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 interventions⁷⁻⁹. And, of course, concerns over the potential environmental impact on fragile polar ecosystems¹⁰. 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 programmes¹³⁻¹⁷ and are in a state of stress and flux due to global climate change¹⁸⁻²¹. 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

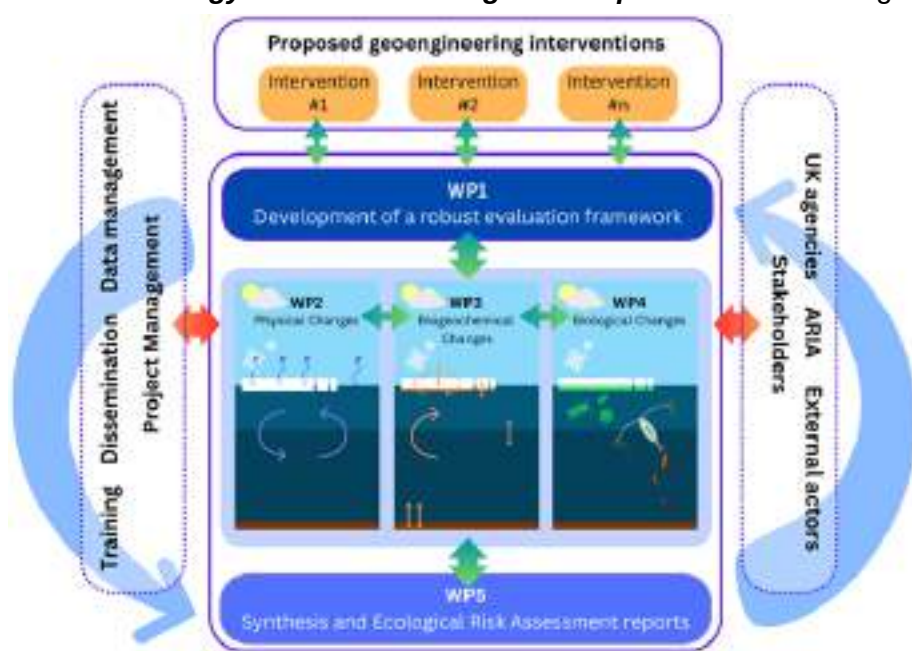


Figure 2: Schematic of WP Interconnectivity and links to inputs and outputs

been proposed as potential methods to mitigate climate change by cooling the Earth²². Polar regions have a disproportionate influence on the global climate¹⁸, 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

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: ██████████ (*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) Milestones 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: ██████████	
Participants/CO-I: ██████████ 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 framework³⁰ 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 CO₂^{e.g.31} to support WP5 reports. Additionally, an established high-resolution ocean model ACCESS-OM2-01³² 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 mechanisms³⁷.

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 regions¹⁰. 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 biogeochemical 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 model⁴⁴. 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 ice⁴⁵ 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 stressors⁵⁴ (**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 risk⁵⁵, 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, interpreted 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)**

Milestones: 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

	Month of Project																					
Work Package	0	3	6	9	12	15	18	21	24	27	30	33	36	39	42	45	48	Objectives				
WP 1.1		M1.1																1				
WP 1.2				M1.2														1				
WP 2.1				M2.1															2			
WP 2.2															M2.2					2		
WP 2.3																M2.3					2	
Scientific Synthesis WP2																		M2.4			2&5	
WP 3.1				M3.1																	3	
WP 3.2																M3.2					3	
Scientific Synthesis WP3																		M3.3			3&5	
WP 4.1															M4.1						4	
WP 4.2																			M4.2			4
Scientific Synthesis WP4																		M4.3			4&5	
WP 5.1	M5.1																	1				
WP 5.1					M5.2													5				
WP 5.2																		M5.3			5	
WP 5.3																				M5.4		5
Annual Project Meeting (APM)					APM1				APM2				APM3					All				
Ethics Board Meeting (EBM)					EBM				EBM				EBM					All				
Stakeholder Conference (SC)																	SC	All				
Outreach: ECR exchange				ECR																All		
Outreach: Summer school												SS						All				

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

[REDACTED]

[REDACTED]

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Grants

- 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 Skłodowska-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 Environmental 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)

- 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., Desjonquieres, 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

- 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=lvn4H3Lpr8A> **(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/zooplanktonplasticcup/> **(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-Russia 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 Krill 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 review¹, 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 Reef². It is necessary to also examine other cloud types important for MCB, such as stratocumulus clouds¹. 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 (WPs) to address widely recognised research questions (RQs)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

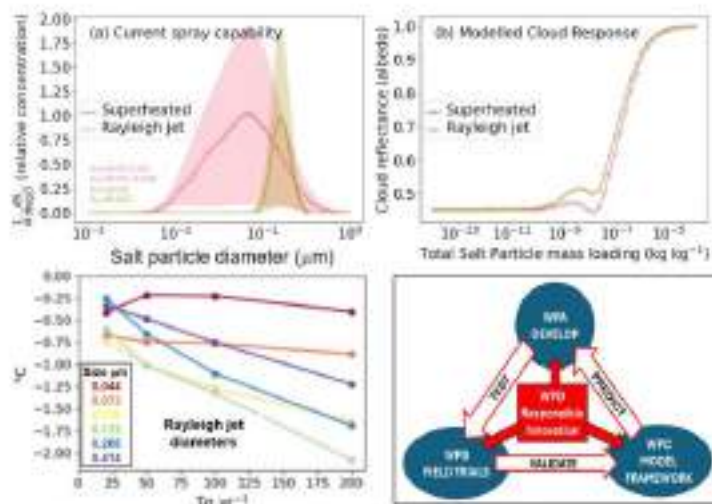


Figure 1. (a) spray number size distribution of two methods developed by UoC, the Rayleigh jet distribution is narrow and represents significant advance. (b) cloud albedo using the UoM parcel model: two spray distributions including representative background aerosol populations. The reduction of cloud 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.

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, ACPIM¹¹ and PARSEC¹², 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

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**.

Methods 1-4 will involve the use of engineering design consultants (UoC currently liaising with a potential

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 $(\text{NH}_4)_2\text{SO}_4$ 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, ACPIM¹¹, 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 ($(\text{NH}_4)_2\text{SO}_4$, 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 innovation¹³ (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 conditions¹⁴ where cloud albedo response is sensitive¹⁵ 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

BOX 1: TARGET SPRAY RATES FOR SAFE, CONTROLLED BUT MEASUREABLE

A spray rate of $1 \times 10^{15} \text{ s}^{-1}$ 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 $5 \times 10^{16} \text{ s}^{-1}$ would lead to 300-500 cm^{-3} at these distances, with plume widths of less than 3-4 km.

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 ($\sim 10^{14} \text{ s}^{-1}$) lasting only a few minutes, evaluating outcomes and risks at each stage as we scale in a stepwise manner to approach target rates of $\sim 5 \times 10^{16} \text{ s}^{-1}$ lasting up to one hour to examine cloud interactions. Our experiments involve real time monitoring so that they can be

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 aerosol¹⁶ and/or initiating drizzle¹⁷. Rapid evaporation of water from the spray may inhibit mixing¹⁸, and although initial experiments¹⁹ and modeling²⁰ 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 (ACPI)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/MSB²⁴.

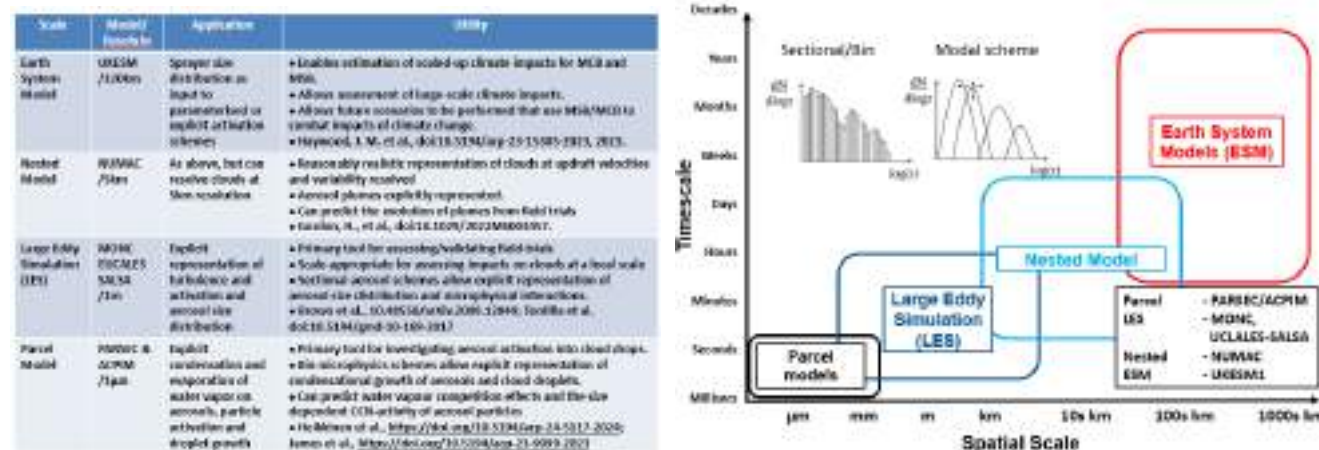


Figure 2. Left Panel): details of the specific models that are proposed. Right Panel): models and their spatial scales and schematic of sectional and modal aerosol size distributions.

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 scheme¹⁹ 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 PM_{2.5} 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 impacted²⁴. 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**) **KO20:** impacts of optimised sprayer deployment for MCB and MSB under various future climate scenarios (UKESM1-climate) (**M32; M48**)

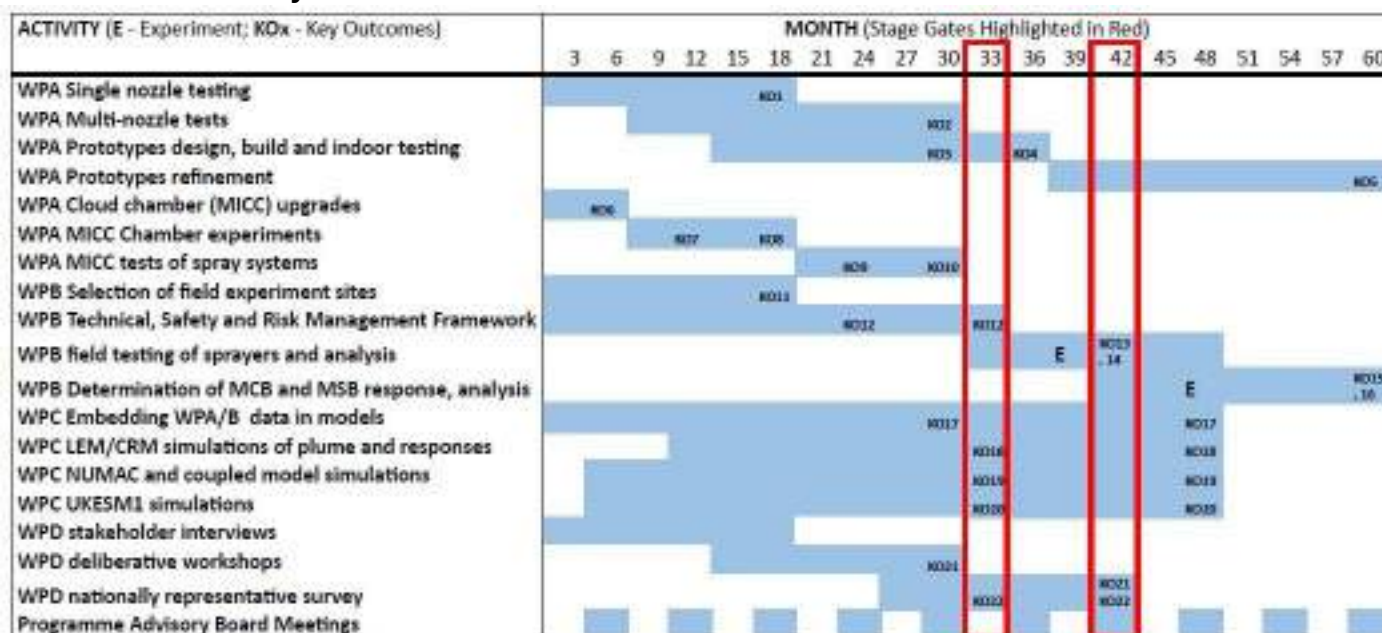
Work Package D (WPD): Responsible Innovation and Societal Engagement (UoM) (O6)

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 public²⁷ (**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 engagement¹³. 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

[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/optimize 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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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 balance¹. 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 forcings¹ highlights the need to better constrain the numerous atmospheric processes which are impacted by a change in composition and quantity of aerosol loading². 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 constrain³.

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 experiments⁴ measuring *in-situ* with aircraft the cloud microphysical response to perturbation (Fig. 1 B&E). In our nozzle laboratory we refined the effervescent atomisation technique⁵ 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 Twomey⁷ (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 calculated⁸, 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.

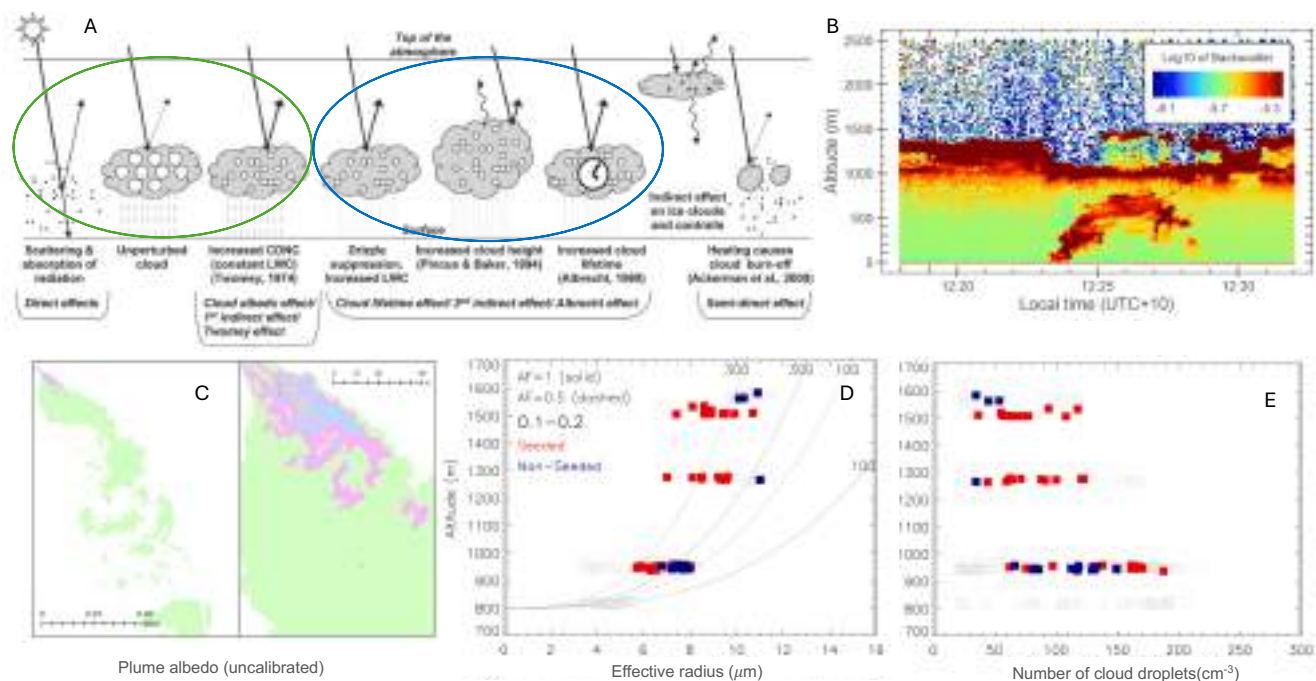


Figure 1: (A) Aerosol-cloud-radiative processes⁹, green circle represents MCB effects measured in past campaigns (C-E), blue indicates effects targeted in this proposal. (B) LiDAR measurement from a sampling vessel of the ARIEL produced MCB plume lifting into a cloud layer at ~ 1000m cloud base altitude. (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 summertime¹⁰. 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 stress¹³⁻¹⁵. Modelling¹⁶, field observations⁶, 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 reductions¹⁷. 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 decades¹⁸ 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 survey²¹.

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 model²⁴ 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

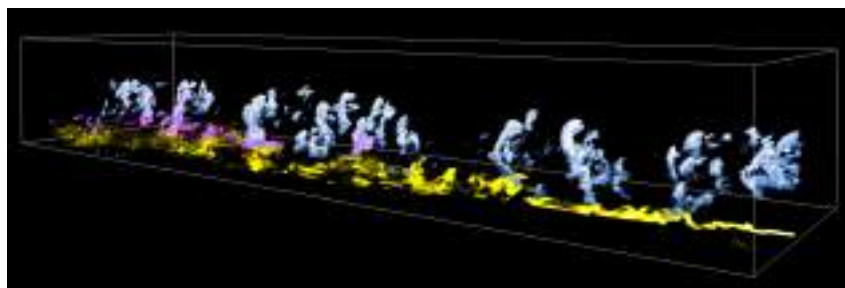


Figure 2: LES-LCM model results of a single MCB spraying vessel (at far right) in a shallow cumulus cloud field with wind right to left. White = cloud, Yellow = MCB aerosol, Magenta = aerosol impacted cloud.

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.

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 water²⁵⁻²⁷, electrospray²⁸, Rayleigh jet breakup^{29, 30}, bubble formation from pressurised air³¹, 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.

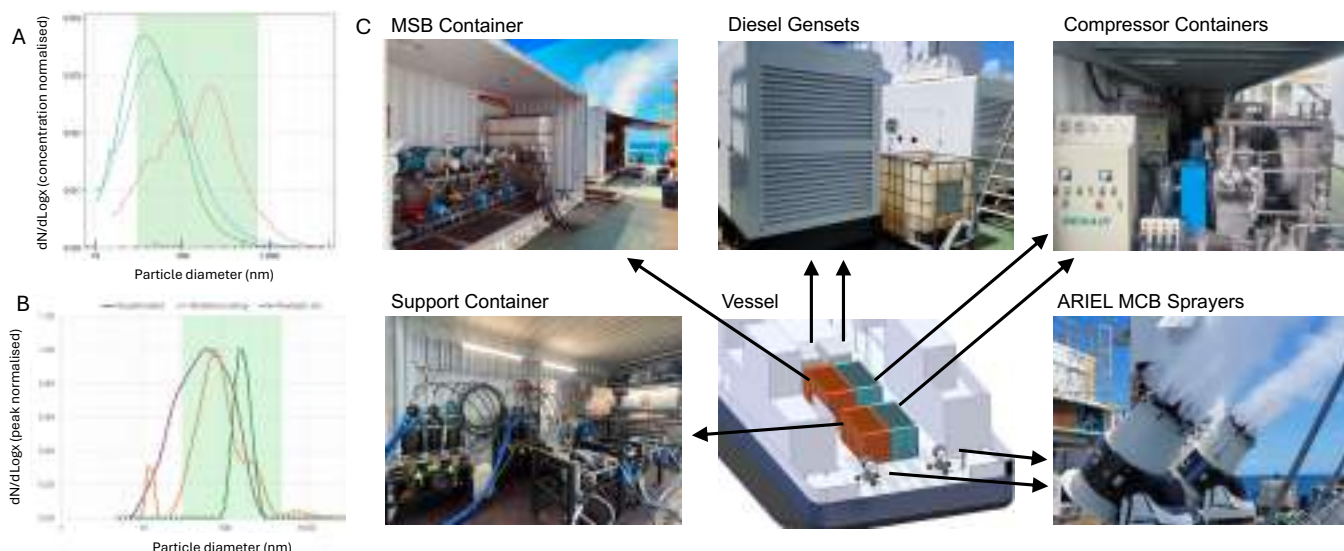


Figure 3: (A) Field measured size distributions for the 3 sprays currently produced by ARIEL. (B) Alternate spray technologies showing improved fraction in the target range (green shading). (C) ARIEL components.

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 $0.5\text{--}1 \times 10^{16}$ CCN s^{-1} , targeting $\sim 10\times$ 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 operations⁶, ground based remote sensing³⁴, 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.

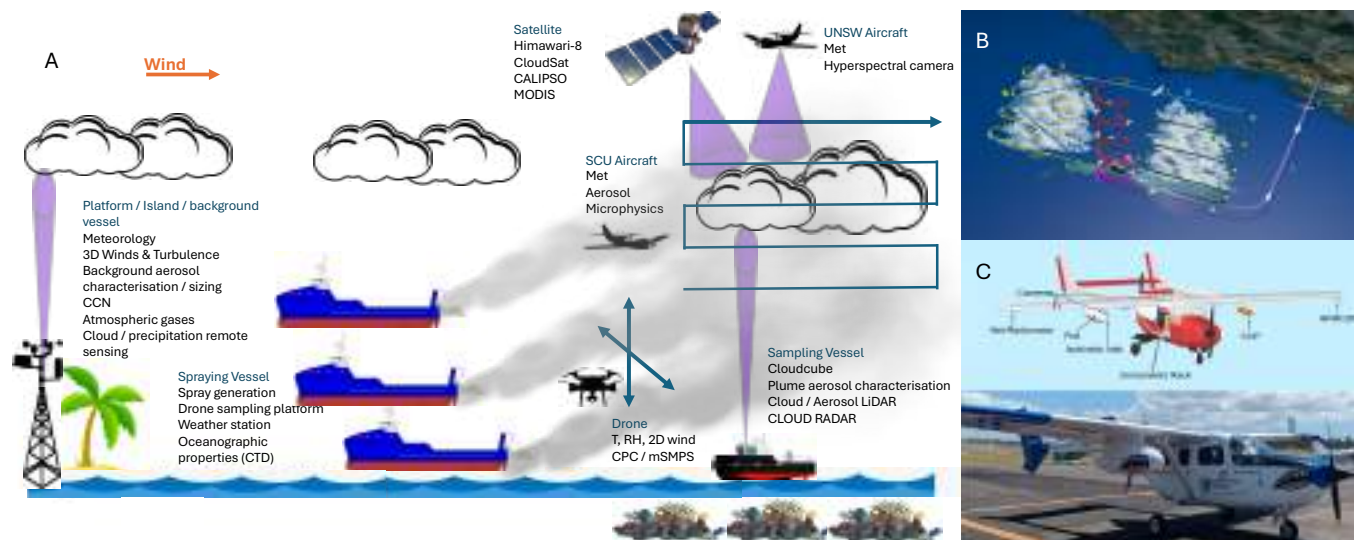


Figure 4: (A) The proposed major field campaign strategy. (B) Flight sampling strategy for aerosol and cloud physics sampling of upwind (background) and downwind (perturbed) cloud. (C) The SCU aircraft⁶.

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 layer³⁵.

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, spraying 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 microphysics³⁸ 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 consultation²⁰. 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 GBR⁴¹ (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.

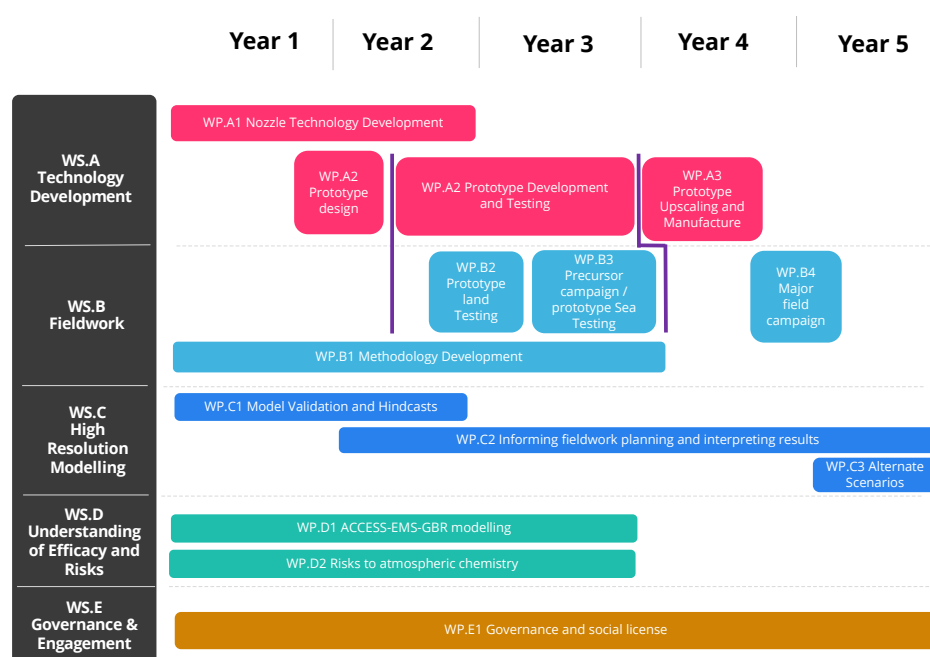


Figure 5: Project timeline. Purple lines indicate suggested stage gates.

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

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 research⁶ 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

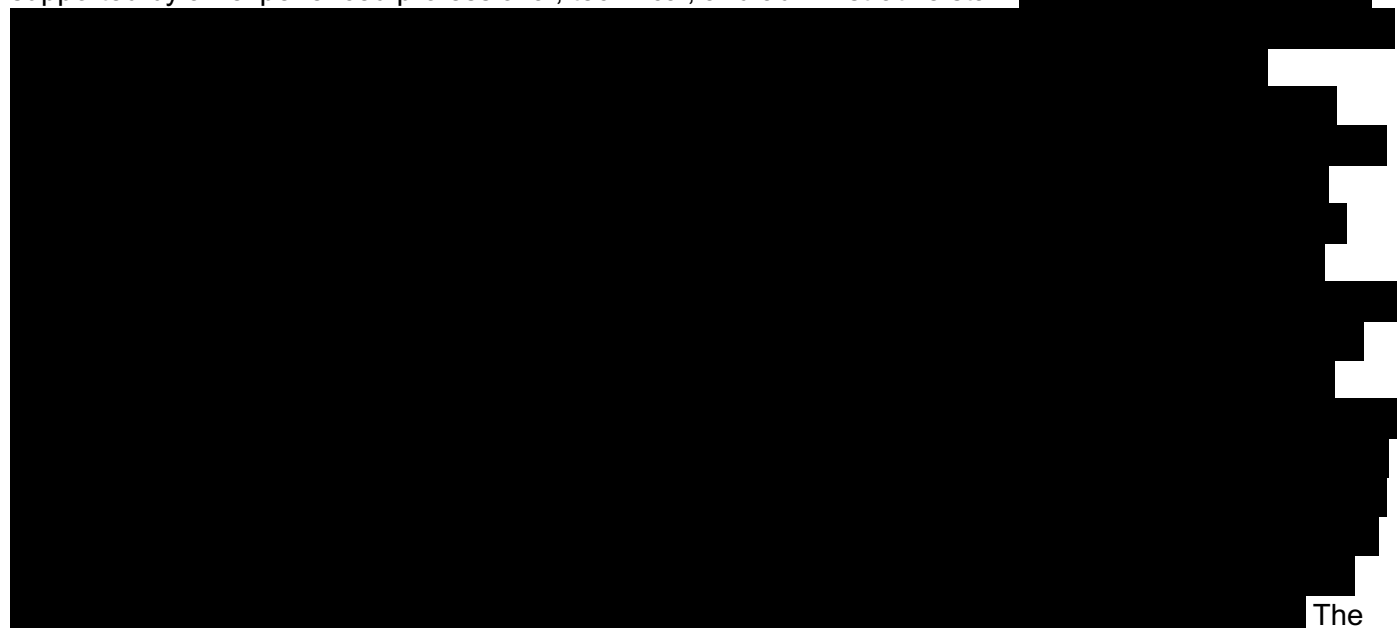
benefit from access to existing and future real-world datasets and transfer of critical knowledge and experience developed during the previous Australian RRAP project. SCU has agreed to support outdoor experiments in the UK under the UoM led proposal by providing ARIEL (or its upgrade), technical staff 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 Act⁴²), 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.



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 $^{\circ}\text{C}$) (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.

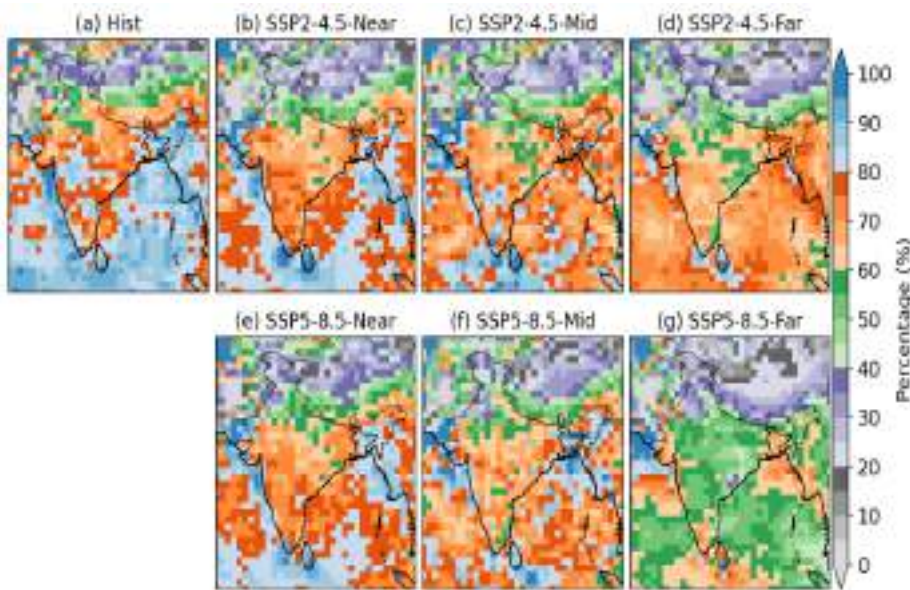


Figure 1: Spatial map showing ensemble mean percentage contribution of Vertical Dynamic component to extreme precipitation (a) for the historical time period 1995-2014 (Hist) (b-d) for SSP2-4.5 scenario near (2021- 2040), mid (2041-2060) and far (2081-2100) time period (e-g) for SSP5-8.5 scenario. Vertical 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 (SO₂) 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: -

$$P' = E' - \langle \bar{\omega} \cdot \partial_p q' \rangle - \langle \omega' \cdot \partial_p \bar{q} \rangle - \langle \omega' \cdot \partial_p q' \rangle - \langle \bar{V} \cdot \nabla q' \rangle - \langle V' \cdot \nabla \bar{q} \rangle - \langle V' \cdot \nabla q' \rangle + Res \quad \text{--- Eq (1)}$$

where the angle brackets ($\langle \rangle$) 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).

$$\bar{D} = \sum_{m=1}^{12} \bar{p}_m \log_2 (\bar{p}_m / q_m)$$

At each grid point, relative entropy ($\bar{D}$), 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 $S = \bar{D} \cdot R / R_{\max}$ 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' ($C = \frac{1}{R} \sum_{m=1}^{12} m \bar{p}_m$), represents peak precipitation timing during the peak precipitation period) and 'duration' ($Z = \sqrt{\frac{1}{R} \sum_{m=1}^{12} |m - C|^2 \bar{p}_m}$), 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?

██████████ 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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