CLIMATE MOONSHOT PORTFOLIO

Billions to save trillions

MCB Experimental Research Initiative

Proposed $1 Billion / Five-Year R&D Program

MARINE CLOUD BRIGHTENING (MCB)

FIELD EXPERIMENTS • LABORATORY EXPERIMENTS

By Glenn Weinreb

Developed with assistance from ChatGPT

OPEN SOURCE

Executive Summary

Purpose. The proposed $1 billion, five-year MCB Experimental Research Initiative is designed to determine whether marine cloud brightening can be predicted, measured, governed, and stopped well enough to justify any later research. It is a research program, not an authorization for regional or global climate control. The central scientific chain runs from seawater intake and aerosol generation, through near-source plume evolution and boundary-layer transport, to arrival at cloud base, cloud-droplet activation, cloud microphysical and dynamical response, and finally a measurable change in reflected sunlight. The program is built to test each link rather than assume that successful aerosol production implies successful cloud brightening.

Research architecture. The portfolio combines baseline marine-cloud and aerosol observations, sea-salt source engineering, shore-based and moving-vessel plume experiments, small cloud-response experiments, replicated multi-platform campaigns, natural ship-track studies, deposition and ecological monitoring, cloud-resolving and global modeling, and shared aircraft, vessel, drone, radar, lidar, and radiometric capabilities. Controlled field work is divided into two linked experiment families: source-and-plume studies establish whether a known, useful particle population can be produced, tracked, and delivered to cloud base; cloud-response studies test whether that delivered perturbation changes droplet number, liquid-water path, drizzle, cloud organization, and shortwave reflection as predicted. The proposed allocation puts slightly more controlled-field effort into the latter because causal cloud-response closure is more demanding and expensive.

Program sequence and safeguards. Early years emphasize governance, baseline measurements, generator characterization, modeling, and lower-risk plume studies. Later years increase replicated cloud-response campaigns only after source performance, instrumentation, forecasting, environmental review, and independent readiness criteria are satisfied. Releases remain bounded and are not intended to cause a detectable regional climate or ocean-temperature change. An independent release and safety function is separated from the teams conducting experiments, while the Managing Organization controls procurement, finance, data delivery, and contractor performance.

Success criterion. At the end of five years, success would mean reliable public knowledge rather than a predetermined conclusion that MCB should proceed. The initiative should know which particle sizes and source designs work, what fraction of emitted particles reaches cloud base, under which cloud regimes treatment produces a repeatable response, whether measured radiation changes close against aerosol and cloud observations, how well models reproduce the experiments, what deposition or ecological signals require attention, and where uncertainty remains too large for scale-up. Data, code, generator settings, calibration records, negative results, and technical documentation are open by default for independent reproduction and review.

Climate Moonshot Portfolio. We define "Climate Moonshot" as conducting R&D to the extent required to solve the climate problem. This would require a portfolio of R&D initiatives, an example of which is at www.APlanToSaveThePlanet.org. The document you are reading is one initiative within that portfolio. It uses a Common Framework that establishes shared rules for governance, procurement, data rights, independent review, and oversight. All documents within this portfolio are open-source and may be freely viewed, used, and modified.

Program at a Glance

The program is designed to answer a bounded research question: can MCB be produced, measured, predicted, independently verified, governed, and stopped well enough to justify any later research? It is not an authorization for regional or global climate control.

Item	Program design
Total funding and duration	$1.0 billion over five years.
Scientific chain	Source output -> plume evolution -> cloud-base delivery -> droplet activation -> cloud microphysics/dynamics -> reflected sunlight.
Controlled field program	About 10 full source-and-plume campaigns and about 6 full cloud-response campaigns, plus lower-cost repetitions, test days, and sub-campaigns.
Controlled field funding	$220M source-and-plume; $300M cloud-response.
Other program funding	$480M for baseline observations, campaign-source qualification and laboratory aerosol science, natural analogues, ecology/environmental measurement, modeling, shared observing capability, governance/international participation, and the central replication/rapid-response reserve.
Stage gates	G0 observability/value of information -> G1 source readiness -> G2 plume delivery -> G3 cloud response -> G4 radiative closure -> G5 independent replication -> G6 model performance -> G7 five-year decision readiness. A separate Release Authorization (RA) overlay applies before every outdoor release and every scale increase.
Evidence standard	Preregistered hypotheses; treated/control comparisons; uncertainty budgets; independent review; publication of null and negative results.
Open science	Data, code, generator settings, calibration records, technical documentation, and funded foreground designs are open by default.
End product	Reliable public evidence for proceed / redirect / pause / stop decisions by workstream, plus a clear statement of remaining uncertainty. Completion does not authorize deployment.

Scientific Causal Chain and Measurement Architecture

The program should be managed around one quantitative causal chain. Each link must have a prospectively defined measurement, uncertainty budget, control design, and decision consequence. A successful aerosol source is not sufficient unless the program can trace the perturbation through cloud-base delivery, activation, cloud response, and reflected sunlight.

Chain element	What must be known	Primary evidence	Experiment / gate
Source	Particle number, dry size distribution, composition, output stability and uncertainty.	Independent source metrology and calibration.	E2 / G1
Near-source plume	Evaporation, crystallization, coagulation, dilution, lofting and deposition.	Aerosol transects, turbulence, lidar and trajectory reconstruction.	E3 / G2
Cloud-base delivery	Fraction of emitted useful particles that survives and reaches cloud-base height.	Aircraft/UAS aerosol and CCN profiles with source inversion.	E4 / G2
Activation	Fraction of delivered particles activating as cloud droplets under measured updrafts.	CCN spectra plus below-cloud and in-cloud droplet measurements.	E6-E8 / G3
Cloud response	Changes in droplet number/size, liquid water, drizzle, entrainment and cloud organization.	Treated/control in-cloud sampling, radar and lidar.	E6-E8 / G3
Radiative response	Shortwave reflection attributable to the known perturbation.	Above-cloud, aircraft-level, surface and satellite radiometry with uncertainty closure.	E9 / G4
Replication and models	Whether the causal response repeats and whether models predict withheld observations.	Independent repeats, blinded/withheld-data model challenges.	E8-E12 / G5-G6

Table of Contents

What is Marine Cloud Brightening (MCB)?

Marine Cloud Brightening (MCB) is a proposed form of solar radiation modification intended to cool the climate by making selected low marine clouds reflect more sunlight back to space. The leading concept would use seawater as the feedstock. Shore-based systems, ships, or autonomous vessels would generate very large numbers of carefully sized sea-salt aerosol particles and release them into the marine boundary layer beneath or near susceptible clouds.

Some emitted particles could act as cloud-condensation nuclei. If the same amount of cloud water is divided among a larger number of smaller droplets, the cloud can become brighter—the first aerosol indirect effect often associated with Twomey. Changes in drizzle, evaporation, mixing, cloud thickness, and cloud lifetime can either strengthen or weaken the initial brightening. The response therefore depends on particle size and number, background aerosol, cloud type, updraft speed, humidity, atmospheric stability, precipitation, and the organization of the cloud field.

MCB differs from stratospheric aerosol injection in several important respects. The material remains in the lower atmosphere for only days rather than a year or more; the forcing is geographically concentrated; and the immediate scientific problem is an aerosol–cloud–meteorology interaction rather than long-lived stratospheric aerosol chemistry. These features may make MCB more controllable, but they also make performance highly weather-dependent and difficult to scale from a plume to a regional or global climate effect.

MCB would not remove carbon dioxide, stop ocean acidification, or eliminate the need to reduce greenhouse-gas emissions. Potential side effects include changes in regional precipitation, circulation, storm tracks, marine-cloud cover, air quality, visibility, salt deposition, ecosystems, and distant climate patterns such as ENSO. Benefits and harms could be unevenly distributed.

MCB has been studied in models, natural analogues such as ship tracks, laboratory work, and a limited number of outdoor aerosol-generation campaigns. It has not been demonstrated as a global climate intervention. A credible research program should therefore focus on whether sea-salt particles can be generated, transported, measured, modeled, and shown to produce repeatable cloud and radiative responses under defined conditions—without assuming that technical feasibility implies permission to deploy.

Program Architecture and $1 Billion Budget

Prompt to AI: If a Funding Source wants to spend $1B on Marine Cloud Brightening research, especially field experiments, over 5 years, what experiments should it consider?

Response From AI:

A $1 billion, five-year program should not attempt to demonstrate regional or global climate control. It should determine whether MCB can be predicted, measured, governed, and stopped well enough to justify any later research. The most important scientific chain is:

> Seawater intake and aerosol generation → near-source plume evolution → boundary-layer transport and dilution → arrival at cloud base → cloud-droplet activation → cloud optical and dynamical response → regional radiative and weather effects

Major uncertainty remains at every link. The program should therefore combine laboratory work, source engineering, natural experiments, carefully bounded outdoor releases, aircraft and ship observations, cloud-resolving models, regional and global models, ecological monitoring, and independent governance.

Illustrative $1 billion portfolio

Program	Five-year budget	Main purpose
Area 1. Baseline marine-cloud and aerosol observatory network	$90M	Measure untreated clouds, aerosol, meteorology, radiation and precipitation across candidate regions.
Area 2. Campaign source qualification and aerosol microphysics	$100M	Develop controllable particle generators; map size, number, energy, salinity and impurities.
Area 3. Shore-based source-and-plume experiments	$100M	Measure near-field evaporation, crystallization, coagulation, lofting, deposition and detectability.
Area 4. Ship and autonomous-platform plume campaigns	$120M	Track sea-salt plumes from moving marine sources to cloud-base height under varied conditions.
Area 5. Small cloud-response experiments	$180M	Conduct tightly bounded releases beneath susceptible clouds and measure microphysical and radiative response.
Area 6. Replicated multi-platform cloud campaigns	$120M	Repeat cloud-response experiments across seasons, regions and cloud regimes with aircraft and remote sensing.
Area 7. Natural experiments and ship-track program	$60M	Use shipping-emission changes and other perturbations to constrain aerosol–cloud causal effects.
Area 8. Deposition, ecology, air quality and	$55M	Measure salt deposition, visibility, coastal exposure and

Program	Five-year budget	Main purpose
marine effects		ecological consequences.
Area 9. Cloud-resolving, regional and global modeling	$70M	Assimilate observations; test scale-up, regional teleconnections and control strategies.
Area 10. Shared aircraft, ships, drones, lidar, radar and instruments	$55M	Build reusable observing and mission-control capability.
Area 11. Governance, permitting, engagement and international participation	$30M	Independent review, public process, Indigenous and climate-vulnerable participation.
Area 12. Independent replication and rapid-response reserve	$20M	Repeat key results and respond to natural analogues, instrument failures or unexpected findings.

Budget accounting rule. The $22M source-and-plume and $48M cloud-response campaign models later in this proposal are bottom-up planning views that draw from the Area budgets above. They are not additional budget lines and should not be multiplied by nominal campaign counts and added again to the $1 billion portfolio.

The dedicated controlled-field Areas total $520 million: $220 million for source-and-plume work (Areas 3-4) and $300 million for cloud-response work (Areas 5-6). The remaining $480 million supports baseline observations, campaign-source qualification and laboratory aerosol science, natural analogues, ecology/environmental measurement, modeling, shared observing capability, governance/international participation, and the central replication/rapid-response reserve.

The most valuable experiments

Experiment E1. Baseline mapping of susceptible cloud regimes

Before deliberate releases, conduct repeated campaigns in eastern-boundary stratocumulus regions, trade-wind cumulus regions, mid-latitude marine clouds, and one coral-reef region. Measure aerosol number and size, cloud-condensation nuclei, cloud-droplet number, liquid-water path, cloud fraction, drizzle, precipitation, updrafts, turbulence, inversion strength, humidity, winds, radiation and sea-surface temperature. Baselines must capture seasonal cycles and day-to-day meteorological variability because cloud changes caused by weather can easily exceed the expected signal from a small experiment.

Experiment E2. Campaign-source characterization

Test multiple methods for producing submicron sea-salt particles from seawater. Characterize dry-particle size distribution, production rate, energy use, droplet evaporation, salt composition, organic impurities, nozzle fouling, corrosion, wind sensitivity and reliability. The acceptance metric should not be liters of seawater sprayed; it should be the number of useful cloud-active particles delivered per unit of energy and per hour of operation, with tight control of the coarse-particle tail.

Experiment E3. Shore-based source-and-plume experiments

Operate a generator from a coastal or offshore research facility without attempting to brighten clouds. Use towers, drones, tethered balloons, lidar, aerosol counters and downwind boats to measure the first seconds through several hours of plume evolution. This is the least expensive way to resolve evaporation, crystallization, coagulation, salt deposition, plume rise, entrainment and the effect of ambient humidity and turbulence.

Experiment E4. Moving-vessel plume transport experiments

Mount a modular generator on a research ship or autonomous surface vessel and follow the plume with a second vessel, drones, aircraft and remote sensing. Vary vessel speed, release height, wind direction, source rate and particle distribution. Determine what fraction of emitted particles survives and reaches cloud base, and whether source-inversion models can reconstruct the known release.

Experiment E5. Natural ship-track and shipping-regulation studies

Use satellite imagery, aircraft measurements and changes in shipping emissions to quantify how aerosol perturbations affect real marine clouds. Ship tracks are imperfect analogues because combustion particles differ from sea salt, yet they provide a much larger observational sample than deliberate experiments. The program should maintain an open global ship-track database linked to meteorology, ship activity, fuel rules and cloud state.

Experiment E6. Small cloud-response experiments

Conduct short releases beneath or upwind of a single cloud element or a small cloud field. Compare treated and untreated air using a crossing or randomized release design. Measure aerosol at cloud base, cloud-droplet number, droplet radius, liquid-water content, optical depth, reflected shortwave radiation, cloud-top height, drizzle and entrainment. The success criterion is a closed causal chain from known emission to measured radiative response—not a surface-temperature change.

Experiment E7. Paired particle-size experiments

Under closely matched conditions, compare a narrow distribution centered in the expected useful submicron range with distributions containing more ultrafine or coarse particles. This directly tests a central result of models: too-small particles may not activate, while a small coarse-particle tail can accelerate collision–coalescence and drizzle, potentially reducing cloud water and offsetting brightening.

Experiment E8. Cloud-regime comparison

Repeat the same source and measurement design in closed-cell stratocumulus, open-cell stratocumulus, precipitating and nonprecipitating clouds, and shallow cumulus. MCB may work only in a subset of conditions. A program should learn when not to spray as clearly as when spraying produces an effect.

Experiment E9. Radiative and dynamical closure campaigns

For selected releases, combine in-situ aerosol and cloud probes, airborne and ground-based radar and lidar, microwave radiometers, broadband and spectral radiometers, satellite retrievals, and large-eddy simulations. Require agreement among released particle number, observed activation, cloud optical response and top-of-atmosphere shortwave change within a stated uncertainty budget.

Experiment E10. Downwind, deposition and ecological monitoring

Track sea-salt aerosol and altered clouds after the primary sampling period. Measure salt deposition on the ocean and coast, aerosol exposure, visibility, chemistry, impacts on solar generation, marine-surface microlayer properties, and any detectable ecological response. Small experiments are unlikely to produce measurable ecosystem effects, but methods and baseline data must be established before larger research.

Experiment E11. Blind detection and attribution exercise

An approved release team would disclose the experiment to regulators and independent oversight but withhold exact time and route from a second scientific team. The second team would use radar, lidar, satellites, aircraft, drones and trajectory models to determine whether a release occurred, where it went, and whether a cloud response can be attributed to it.

Experiment E12. Regional-model falsification tests

Before each field campaign, modeling teams should preregister predictions of plume location, cloud-droplet response, optical depth, drizzle and reflected sunlight. After the campaign, compare predictions against withheld data. Models that cannot reproduce small, observed perturbations should not be trusted to project regional or global MCB impacts.

Five-year sequence

- **Year 1:** governance, baseline observations, aerosol-generator laboratory work, instrument development, natural-experiment analysis and preregistered modeling.

- **Year 2:** shore-based plume experiments, moving-vessel plume experiments, drone and lidar validation, and first very small cloud-interaction trials if approved.
- **Year 3:** replicated cloud-response campaigns, paired particle-size tests, radiative closure and expanded ecological and deposition monitoring.
- **Year 4:** additional regions, seasons and cloud regimes; independent replication; multi-platform campaigns; regional-model evaluation.
- **Year 5:** repeat the most informative experiments, conduct blinded prediction challenges, complete international assessment and identify explicit stop or proceed criteria. Completion of Year 5 would not authorize deployment.

Boundaries I would impose

- No experiment designed to produce a detectable regional climate or ocean-temperature change.
- No multi-week regional treatment during the first five-year program unless separately authorized after an independent assessment.
- No use of additives other than seawater-derived material without toxicology, chemistry and ecological review.
- No proprietary atmospheric data, undisclosed releases or secret operating routes.
- No claim of efficacy based only on aerosol production; useful delivery to cloud base and a measured cloud/radiative response are required.
- No scale increase unless the preceding stage meets preregistered scientific, environmental, engagement and monitoring criteria.
- No coupling of research authorization to a promise of later commercial deployment.

Program Crosswalk

This program crosswalk links the portfolio budget to the campaign and procurement architecture. PO references are illustrative mappings, not additional budget lines; the same work should not be counted both as an area budget and again as a campaign budget.

Program area	Experiment family	Principal deliverable	5-year budget	Relevant POs / agreements
Area 1. Baseline marine-cloud and aerosol observatory network	Program-wide baseline	Untreated aerosol, cloud, radiation, precipitation, and meteorological baselines across candidate regimes.	$90M	Baseline observing, aircraft/vessel, remote-sensing, and data task orders.
Area 2. Campaign source qualification and aerosol microphysics	Source engineering / shared capability	Validated particle generators, size distributions, energy use, composition, reliability, and operating envelope.	$100M	SP3; CR3; aerosol-source engineering master agreement.
Area 3. Shore-based source-and-plume experiments	Source-and-plume	Near-field evaporation, crystallization, coagulation, lofting, deposition, and detectability.	$100M	SP1-SP4; SP6-SP10.
Area 4. Ship and autonomous-platform plume campaigns	Source-and-plume	Measured survival, dilution, vertical transport, and fraction of emitted particles reaching cloud base.	$120M	SP5-SP10; ship, UAS, lidar, and mission-control task orders.
Area 5. Small cloud-response experiments	Cloud-response	Causal source-to-cloud response under tightly bounded treated/control conditions.	$180M	CR1-CR11.
Area 6. Replicated multi-platform cloud campaigns	Cloud-response / replication	Repeated microphysical and radiative response across seasons, sites, and cloud regimes.	$120M	CR6-CR11; aircraft, vessel, satellite, and remote-sensing task orders.
Area 7. Natural experiments and ship-track program	Natural analogue / attribution	Open ship-track database and causal constraints from real-world aerosol perturbations.	$60M	Science subawards; satellite, shipping-data, and analysis agreements.
Area 8. Deposition, ecology, air quality and marine effects	Cross-cutting safeguards	Salt deposition, exposure, visibility, chemistry, coastal/marine monitoring, and ecological methods.	$55M	SP2, SP8-SP9; CR2, CR9; ecological and analytical subawards.
Area 9. Cloud-resolving, regional and global modeling	Cross-cutting modeling	LES, data assimilation, attribution, model falsification, scale-up limits, and teleconnection analysis.	$70M	SP1, SP8-SP10; CR1, CR10-CR11; modeling master agreement.
Area 10. Shared aircraft, ships, drones, lidar, radar and instruments	Shared capability	Reusable observing platforms, calibrated payloads, mission control, and data synchronization.	$55M	Aircraft, marine operations, instrumentation, UAS, and remote-sensing master agreements.
Area 11. Governance,	Independent	Permits, public process,	$30M	SP2, SP10; CR2, CR11;

permitting, engagement and international participation	oversight	transboundary consultation, release approval, and engagement records.		governance and independent-review agreement.
Area 12. Independent replication and rapid-response reserve	Replication / reserve	Independent repeats, response to natural analogues, instrument failures, and unexpected findings.	$20M	Independent replication task orders; prepriced contingency and replacement options.

Acceptance and Decision Crosswalk

The following table adds the decision dimension to the budget crosswalk. It does not create new funding; it shows the principal quantity each Area must resolve and the gate or authorization decision that the evidence supports.

Program area	Primary acceptance quantity	Main gate	Decision consequence
Area 1. Baseline observations	Background variability and covariance needed for powered treated/control designs.	G0	Whether deliberate experiments are observable and where they should occur.
Area 2. Campaign source qualification	Known source output, size/composition, uncertainty and operating envelope.	G1	Whether a source is suitable for bounded plume/cloud experiments.
Area 3. Shore plume	Detectability, near-field evolution, deposition and source reconstruction.	G2	Whether moving-source/cloud-base work is justified.
Area 4. Ship/platform plume	Cloud-base delivery fraction and uncertainty.	G2	Whether very small cloud-response work is justified.
Area 5. Small cloud response	Preregistered causal microphysical response and attributable shortwave signal.	G3-G4	Whether replication and stronger closure campaigns are justified.
Area 6. Replicated campaigns	Independent reproducibility across days, regimes, sites or platforms.	G5	Whether broader regime comparison is justified.
Area 7. Natural experiments	Causal constraints from ship tracks and emissions changes.	G0/G6	Whether natural evidence supports or challenges field hypotheses/models.
Area 8. Environment/ecology	Deposition, exposure and ecological/air-quality bounds with monitored uncertainty.	RA	Whether a proposed release remains inside approved environmental limits.
Area 9. Modeling	Prediction of withheld plume/cloud/radiation observations.	G6	Whether models may be used for bounded next-stage design or scale-up sensitivity.
Area 10. Shared capability	Calibration, availability, synchronization and data completeness.	G0-G6	Whether campaigns can achieve their measurement

			requirements.
Area 11. Governance	Permits, engagement, transboundary review and independent release approval.	RA	Whether a specific outdoor release may occur.
Area 12. Reserve/replication	Independent repeat or approved recovery need.	G5/G7	Whether to repeat, redirect or preserve funds.

Relationship to the MCB Equipment Development Initiative

The MCB Equipment Development Initiative and the MCB Experimental Research Initiative should be complementary. The Experimental Research Initiative pays for the minimum equipment, integration, calibration, and operations needed to answer defined scientific questions. The Equipment Development Initiative pays for longer-horizon engineering to reduce cost, improve performance and reliability, scale manufacturing, and develop operational systems beyond the needs of a specific experiment.

Capability	Experimental Research Initiative	MCB Equipment Development Initiative
Sea-salt generators	Campaign-grade sources, calibration, source metrology, spares, and modifications required for approved experiments.	Next-generation high-throughput sources; energy reduction; tighter size control; durability; manufacturability; scalable production.
Vessels and source platforms	Temporary integration, release masts, ship time, safety review, and autonomous-platform use needed for campaigns.	Purpose-built or highly automated long-endurance source platforms, fleet automation, maintainability, and deployment-oriented marine systems.
Aircraft and airborne systems	Research-aircraft access, modular measurement payloads, characterized inlets, integration, calibration, and data links.	New specialized airborne hardware only if a persistent capability gap is demonstrated; cost/reliability improvements to reusable airborne systems.
Remote sensing and instruments	Calibrated aerosol, CCN, cloud, radar, lidar, radiometer, drone, and data-acquisition systems needed to close experiments.	Ruggedized, lower-cost, higher-autonomy, or scalable sensor networks not justified by one campaign.
Mission control and software	Real-time plume/cloud targeting, source records, forecasts, synchronization, and experiment safety functions.	Scalable autonomous control, fleet coordination, long-duration operations, and deployment-oriented optimization.

Boundary rules. Do not fund items twice: assign one lead initiative and track shared assets in a common registry. Experimental Research funds campaign-specific adaptations; Equipment Development hardens, scales, automates, and reduces the cost of validated prototypes.

Asset-Level Budget Boundary

Area 2 should be interpreted as campaign source qualification and aerosol microphysics, not as a second long-horizon equipment-development program. Every reusable shared asset should have one lead capital budget and a common registry; the other initiative pays only incremental adaptation, operating time, consumables, or intentionally independent capacity.

Shared capability	Lead capital budget	Experimental Research pays	Equipment Development pays
Sea-salt source	Equipment Development when reusable engineering is the primary purpose.	Campaign settings, science-specific modifications, calibration, consumables and campaign operation.	Competing source designs, scaling, durability, energy reduction, manufacturability and long-duration reliability.
Research aircraft	Experimental Research / shared asset registry.	Aircraft campaign hours, payload integration and experiment-specific calibration.	Only incremental reusable hardware improvements not justified by one campaign.
Radar/lidar/cloud instruments	Experimental Research / shared asset registry.	Scientific instrumentation, calibration and campaign operation.	Ruggedization or scalable sensor engineering only when a distinct equipment-development objective exists.
Vessels/platforms	Lead initiative designated per asset.	Campaign charter/use, temporary integration and scientific operations.	Purpose-built prototypes, autonomy, long-endurance reliability, maintenance and fleet engineering.
Data/software	Lead initiative designated per system.	Preregistration, science forecasts, causal analysis and scientific archive.	Engineering digital twins, scalable fleet control and lifecycle/maintenance systems.

Scientific Requirements, Traceability, and Acceptance

Prompt to AI: What scientific traceability system should connect each MCB experiment to a decision, a preregistered hypothesis, measurements, uncertainty, model predictions, and an explicit acceptance decision?

Response From AI:

Every major campaign should maintain a configuration-controlled Scientific Traceability Matrix. The matrix should make it possible for an independent reviewer to follow a proposed release from the decision question through the experimental design, raw evidence, uncertainty, model comparison, and final gate disposition.

Traceability level	Required content	Example
Decision question	The later decision that requires new evidence.	Does a defined cloud regime brighten predictably enough to justify replication?
Scientific hypothesis	Falsifiable process statement tied to the causal chain.	Delivered CCN increases droplet number under specified background aerosol and updraft conditions.
Controlled variable	Source setting or treatment assignment under configuration control.	Particle-size distribution, source rate, release/no-release pattern.
Primary endpoint	One decision-relevant outcome named before mobilization.	Attributable shortwave response, or cloud-base useful-particle delivery for plume work.
Controls / experimental unit	Treated/control structure and what counts as independent evidence.	Release period, cloud element, flight leg, day or campaign as prospectively defined.
Detectability	Expected effect, variance, minimum detectable effect and sample-size/weather-day logic.	Campaign proceeds only if the scientifically important effect is measurable.
Uncertainty	Traceable source, sampling, retrieval, calibration and meteorological uncertainty.	Source-to-plume-to-cloud-to-radiation uncertainty budget.
Model prediction	Prospective prediction locked before withheld observations are released.	Plume location, droplet response, drizzle and shortwave reflection.
Acceptance / decision	Prospectively defined pass, conditional pass, repeat, redesign or stop rule.	Gate disposition recorded with unresolved risks and negative results.

Source-and-Plume vs Cloud-Response Experiments

Prompt to AI: MCB field research can be divided into (a) source-and-plume experiments and (b) cloud-response experiments. How much effort and funding would you put into each experiment family, and why?

Response From AI:

I would treat the two families as sequentially linked. Source-and-plume experiments establish whether the program can produce and deliver a known aerosol perturbation. Cloud-response experiments determine whether that perturbation produces a measurable, repeatable and beneficial change in cloud reflectivity.

Recommended division of effort

Experiment family	Share of controlled field budget	Illustrative campaigns	Primary question
Source-and-plume	About 42%	About 10 full campaigns	Can a known, useful particle population be produced, tracked and delivered to cloud base?
Cloud-response	About 58%	About 6 full campaigns	Does the delivered perturbation change cloud droplets, cloud amount, drizzle and reflected sunlight as predicted?

Within the $1 billion Area budget, $220 million is dedicated to source-and-plume field work (Areas 3-4) and $300 million to cloud-response field work (Areas 5-6). The remaining $480 million supports baseline observations, campaign-source qualification and laboratory aerosol science, natural analogues, ecology/environmental measurement, modeling, shared observing capability, governance/international participation, and the central replication/rapid-response reserve.

At the central repeat-campaign planning values used later in this document ($22M for source-and-plume and $48M for cloud-response), the dedicated field budgets are consistent with roughly 10 full source-and-plume campaigns and about 6 full cloud-response campaigns, with remaining field funds used for lower-cost repetitions, test days, shared infrastructure, or targeted sub-campaigns. These campaign models are planning views of the Area budgets, not additional appropriations.

1. Source-and-plume experiments: about 42%

These experiments answer the engineering and atmospheric-delivery question. The generator must create a sufficiently narrow distribution of sea-salt particles, avoid an excessive coarse tail, and emit enough useful particles that a measurable fraction survives evaporation, coagulation, dilution and deposition.

The plume will not remain a clean line. Wind shear, turbulence, convective mixing and changes in boundary-layer depth will create a widening three-dimensional filament. Particle measurements should be made from metres behind the source through tens of kilometres downwind and from the ocean surface to cloud-base height.

Key outputs should include useful cloud-condensation-nuclei delivered to cloud base per second, per kilowatt-hour, and per kilogram of seawater; plume width and vertical distribution versus time; salt deposition; and uncertainty in source reconstruction.

Experimental matrix

- Particle median diameter and width of the size distribution.
- Coarse-particle fraction and ultrafine-particle fraction.
- Seawater salinity, temperature, organics and filtration method.
- Nozzle or generator type, pressure, air-to-water ratio and release rate.
- Release height, vessel speed and orientation relative to wind.
- Stable, neutral and convective boundary layers.
- Dry and humid conditions, weak and strong turbulence, and different cloud-base heights.
- Single source versus multiple coordinated sources.

Measurements

- Particle number and size from a few nanometers through several micrometers.
- Cloud-condensation-nuclei spectra and hygroscopicity.
- Salt composition, water content and contamination.
- Wind, turbulence, temperature, humidity and boundary-layer depth.
- Plume geometry from lidar, radar, imaging and tracer measurements.
- Vertical transport and fraction reaching cloud-base height.
- Deposition to ocean, vessel and coastal surfaces.
- Generator power, reliability, corrosion, fouling and maintenance.

2. Cloud-response experiments: about 58%

Cloud-response campaigns are more expensive because they require suitable clouds, accurate forecast and targeting, simultaneous aerosol and cloud measurements, treated and control regions, and enough repetitions to separate the aerosol signal from normal meteorological variability.

Each campaign should include several release and no-release periods under matched conditions. Randomization or alternating on/off patterns can improve causal attribution. A second untreated cloud line or nearby control region is desirable when meteorology permits.

The most important metric is top-of-atmosphere or cloud-top shortwave reflection attributable to the known aerosol perturbation, with secondary metrics covering droplet number, droplet size, liquid-water path, cloud fraction, drizzle and cloud lifetime.

Sampling sequence

- **Pre-release:** 2–6 hours of background aerosol, cloud and radiation measurements.
- **Near-source:** seconds to 30 minutes after emission.
- **Cloud-base interception:** repeated aircraft or drone transects as the plume enters cloud.
- **In-cloud response:** repeated transects through treated and control cloud elements.
- **Cloud-top and radiative response:** aircraft, lidar, radar and satellite observations over 1–8 hours.
- **Follow-up:** next-day or multi-day observations only when the perturbation remains detectable and scientific value justifies it.

The highest-value design: paired campaigns

The strongest tests would conduct a source-and-plume campaign immediately followed by a cloud-response campaign using the same generator, particle settings, site, forecast system and observing platforms. Four to six paired campaigns could directly compare the number of particles produced, the fraction reaching cloud base, the fraction activating as droplets, the change in cloud optical depth, and the measured reflected sunlight.

Sequencing over five years

- **Years 1–2:** approximately 70% source-and-plume and 30% cloud-response.
- **Year 3:** approximately equal effort, including paired campaigns.
- **Years 4–5:** approximately 30% source-and-plume and 70% cloud-response, emphasizing replication and radiative closure.
- **Across the dedicated controlled-field Areas: approximately 42% source-and-plume and 58% cloud-response.**

Detectability, Statistical Power, and Experimental Controls

Prompt to AI: How should MCB field experiments be designed so a treatment signal can be distinguished from ordinary cloud and weather variability?

Response From AI:

Every release campaign should be approved only if the proposed treatment can answer a defined question with a preregistered design. High-frequency measurements alone do not create statistical power; the program needs genuinely independent release/control comparisons, appropriate controls, and an uncertainty budget that includes source, sampling, retrieval, calibration, and meteorological variability.

Design element	Required approach
Primary outcome	Name one primary decision-relevant endpoint before the campaign. For source-and-plume work, this can be useful particle delivery to cloud-base height; for cloud-response work, the primary endpoint should be a radiative or cloud response tied to the known source perturbation.
Expected effect and minimum detectable effect	Use prior observations, laboratory data, LES, pilot work, and instrument performance to estimate the expected effect and variance. Calculate the minimum detectable effect before mobilization. If the scientifically important effect is not detectable, redesign or defer the release.
Experimental unit and independence	Define what counts as an independent comparison: release period, plume interception, cloud element, flight leg, day, or campaign. Do not treat thousands of correlated instrument samples as thousands of independent experiments.
Controls and randomization	Use randomized or alternating release/no-release periods where feasible, nearby untreated cloud lines or control regions, and matched meteorological conditions. Record the randomization or assignment procedure before the campaign.
Baseline and covariates	Measure background aerosol, CCN, updraft, humidity, stability, cloud liquid water, drizzle, cloud regime, winds, and radiation before treatment so meteorological differences can be modeled rather than mistaken for treatment effects.
Preregistered exclusions	Define unusable-cloud conditions, plume misses, instrument failures, aircraft aborts, and other exclusion rules in advance. Preserve excluded data and the reason for exclusion in the public archive.
Sample size and replication	Estimate the number of independent treated/control comparisons needed for the primary endpoint and reserve enough weather/replacement days to obtain them. Replicate across days and, later, across cloud regimes and sites.
Multiple outcomes	Separate the primary endpoint from secondary and exploratory outcomes. Adjust or clearly label inference when many cloud, aerosol, dynamical, and radiative metrics are tested.
Blinding and withheld	Where practical, keep exact release timing or withheld observations from an independent

data	modeling/analysis team until its predictions and analysis code are locked.
Uncertainty and causal closure	Propagate uncertainty from source output through plume transport, activation, cloud response, and radiation. A bright image or a droplet-number change is not sufficient by itself.
Null and negative results	Publish null cloud responses, failed plume interceptions, generator failures, and campaigns that were adequately powered but did not detect the preregistered effect.

Campaign readiness rule

No outdoor release should proceed merely because ships, aircraft, or generators are available. This review is the basis for Gate G0. Before mobilization, the independent design review should confirm that the campaign has a plausible path to detecting the decision-relevant effect, that primary outcomes and exclusion rules are locked, that the control design can separate treatment from ordinary meteorological variability, and that the expected value of information justifies the smallest proposed release. Numerical thresholds should be set prospectively by the Scientific Advisory Panel for each cloud regime and instrument configuration.

Stage Gates and Go/No-Go Criteria

Prompt to AI: What explicit stage gates should control progression from generator development to plume experiments, cloud-response experiments, replication, and any later research?

Response From AI:

Passing a gate authorizes only the next research stage; it does not authorize deployment. Numerical thresholds should be established before each campaign by the scientific and independent oversight bodies and published with the preregistered plan. Failure at a gate should trigger redesign, repetition, scale reduction, or termination rather than automatic progression.

Gate	Required evidence	Decision enabled	If not met
G0. Observability and value of information	A decision-relevant uncertainty is identified; existing evidence and lower-risk alternatives are reviewed; expected effect, minimum detectable effect, independent experimental unit, controls, sample size/weather days, and the smallest informative release are defined.	Authorize the minimum experiment needed to answer the question, subject to RA for any outdoor release.	Use existing data/modeling, redesign for detectability, reduce scale, or defer/stop the experiment.
G1. Source readiness	Independent verification of particle size/number, coarse tail, composition, energy use, controls, reliability, calibration, and uncertainty across the intended campaign operating envelope.	Authorize bounded source-and-plume work, subject to RA.	Rework or replace the source; no cloud-response release.
G2. Plume delivery	Known releases can be detected and tracked; source inversion is credible; survival, dilution, deposition, vertical transport, and cloud-base delivery fraction are measured with stated uncertainty.	Authorize very small cloud-response experiments under approved conditions, subject to RA.	Repeat plume work or change source/release geometry.
G3. Cloud response	Preregistered treated/control comparisons show whether delivered particles alter droplet number/size, liquid water, drizzle, entrainment, or cloud organization in a defined regime.	Authorize campaigns designed for radiative closure and replication, subject to RA.	Do not infer efficacy; redesign dose, targeting, controls, or cloud-regime selection.
G4. Radiative closure	Measured shortwave response is reconciled quantitatively with source output, cloud-base aerosol/CCN, activation, cloud microphysics/dynamics, and the uncertainty budget.	Authorize independent replication and broader regime testing, subject to RA.	No claim of successful MCB response; repeat or stop the workstream.
G5. Independent replication	A team that did not control the original analysis reproduces the key source-to-cloud-to-radiation result across additional days and, where feasible, another season, site, or platform.	Authorize broader comparison across cloud regimes and operating conditions, subject to RA.	Treat the result as unconfirmed and retain the earlier scale.

G6. Model performance	Preregistered plume, LES, and regional models reproduce withheld campaign observations within published performance criteria and explain major discrepancies.	Use qualified models for bounded next-stage research design and scale-up sensitivity analysis.	Do not rely on failed models for regional or global efficacy claims.
G7. Five-year decision readiness	Independent synthesis of source delivery, cloud/radiative response, replication, model performance, environmental evidence, unresolved uncertainty, and remaining value of information.	Deliver proceed / redirect / pause / stop recommendations by workstream; no entitlement to deployment or Phase II.	Continue only targeted uncertainty reduction or stop pathways whose expected value no longer justifies added research.

Release Authorization Overlay (RA)

RA is not the last step in the scientific sequence. It is a separate authorization that must be satisfied before every deliberate outdoor release and before any increase in release scale. Passing a scientific gate means the next experiment is scientifically justified; passing RA means that a specific release is permitted to occur. Neither authorizes deployment.

RA evidence	Requirement
Scientific readiness	Applicable G0-G6 technical gate passed; preregistered protocol, release settings, controls, stop criteria and data plan frozen.
Environmental and legal	Permits, deposition/ecology monitoring, maritime/aviation requirements, jurisdictional and transboundary review where applicable.
Public and community process	Required public, Indigenous, local/jurisdictional and climate-vulnerable-region engagement completed and documented.
Operational safety	Emergency shutdown, incident response, platform safety, communications, independent monitoring and authority to stop the release demonstrated.
Independent approval	Independent Release and Safety Board issues written approval, conditions, delay, or refusal.

Program-level stop rule

The program should maintain the option to stop a workstream when repeated experiments fail to deliver useful particles to cloud base, when a reproducible cloud/radiative response cannot be demonstrated, when models cannot reproduce observed perturbations, when environmental or governance conditions cannot be satisfied, or when the expected value of additional information is lower than competing research uses of the funds.

Campaign Development and Execution Phases

Prompt to AI: With each experiment, what are the different phases, and how much might each phase cost?

Response From AI:

An experiment should be defined as a complete campaign containing multiple release and control periods. The figures below are order-of-magnitude planning estimates in constant 2026 dollars. They assume access to a research vessel, a second sampling vessel or aircraft, drones, remote sensing and a common program instrument suite. These campaign cost models are bottom-up planning views that draw from the $1 billion Area budgets; they are not additive appropriations.

1. Source-and-plume campaign

Phase	Principal work	Estimated cost
1. Scientific design	Hypotheses, release matrix, plume models, success criteria and uncertainty budget	$0.8M–$1.5M
2. Governance and environmental review	Permits, maritime and airspace review, engagement, environmental monitoring and stop criteria	$0.7M–$1.8M
3. Aerosol-source preparation	Generator, seawater intake, filtration, controls, calibration and ground testing	$1.5M–$3.0M
4. Instrument preparation	Particle sizing, CCN, chemistry, meteorology, lidar, drone payloads and calibration	$2.0M–$4.0M
5. Vessel and platform integration	Deck installation, power, data, structural, electrical and safety integration	$1.5M–$3.0M
6. Baseline and rehearsal	Background transects, inert or low-output tests, drone and vessel coordination	$1.0M–$2.0M
7. Release operations	Multiple release and control runs over 1–2 weeks	$2.5M–$5.0M
8. Plume tracking	Downwind vessel, drones, lidar, balloons and trajectory assimilation	$1.5M–$3.5M
9. Data and laboratory analysis	Particle survival, vertical transport, deposition and model comparison	$2.0M–$4.0M
10. Independent evaluation	Data audit, blinded prediction comparison, archive and review	$0.5M–$1.0M
11. Prepriced campaign recovery options	Weather, ship time, generator failure, instrument repair and replacement days	$2.0M–$4.0M

Repeat campaign after common capability exists: approximately $18M–$28M. First-of-a-kind campaign with substantial new generator and instrument development: approximately $28M–$40M.

2. Cloud-response campaign

Phase	Principal work	Estimated cost
1. Scientific design	Cloud-regime selection, causal design, release pattern, measurement matrix and preregistered predictions	$1.2M–$2.5M
2. Governance and environmental review	Expanded consultation, environmental assessment, aviation and maritime approvals	$1.2M–$3.0M
3. Generator and source validation	Flight/ship-ready source, particle-output verification, controls and safety	$2.0M–$4.0M
4. Cloud and aerosol instrument preparation	In-situ cloud probes, aerosol instruments, radar, lidar, radiometers and satellite products	$4.0M–$8.0M
5. Aircraft and vessel integration	Research aircraft, ship, drones, data links, certification and mission systems	$3.0M–$6.0M
6. Baseline characterization	Several days of untreated cloud, aerosol, radiation and meteorology observations	$2.0M–$4.0M
7. Release-day operations	Ship release, chase aircraft, drones, radar/lidar and mission center	$3.0M–$6.0M
8. Repeated cloud sampling	Multiple release/control days and control-region observations	$8.0M–$15.0M
9. Radiative and dynamical closure	Cloud microphysics, liquid-water path, drizzle, cloud fraction and radiation analysis	$4.0M–$8.0M
10. Regional modeling and attribution	Large-eddy simulations, data assimilation and causal/statistical analysis	$3.0M–$6.0M
11. Independent evaluation	External audit, withheld-data challenge, public archive and workshop	$0.8M–$1.8M
12. Prepriced campaign recovery options	Weather, unsuitable clouds, aircraft/ship downtime and replacement sorties	$5.0M–$10.0M

Repeat campaign after common capability exists: approximately $40M–$55M. First-of-a-kind campaign: approximately $55M–$75M.

3. Shared capability that should not be rebuilt for every experiment

Shared program capability	Five-year initial investment
Common sea-salt generator test and calibration facility	$20M–$35M
Modular shipboard generator and certified integration package	$20M–$40M
Aircraft aerosol and cloud microphysics payload	$30M–$50M

Shared program capability	Five-year initial investment
Drone, balloon and autonomous-vessel observing systems	$15M–$30M
Cloud radar, lidar and radiometer network	$20M–$40M
Forecasting, mission control and real-time data assimilation	$10M–$20M
Open data, governance and environmental-review infrastructure	$10M–$20M

Practical budgeting conclusion

- Source-and-plume repeat campaign: use approximately $22M as a central planning value.
- Cloud-response repeat campaign: use approximately $48M as a central planning value.
- Paired source/cloud campaign at one site: approximately $55M–$70M because ships, instruments, governance and forecasts can be shared.
- Incremental release during an active source campaign: approximately $300,000–$1M, but only if the scientific design benefits from replication.
- Incremental cloud-response day: approximately $1M–$3M because aircraft, ship, forecast and instrument teams must all remain deployed.

Purchase Orders

Prompt to AI: With each phase of each experiment, what are the different Purchase Orders (POs), grants, task orders, or subawards that might be issued?

Response From AI:

Below is an illustrative procurement structure for one repeat source-and-plume campaign costing approximately $22 million and one cloud-response campaign costing approximately $48 million. These are representative campaign cost models and procurement packages that draw from the Area budgets; they are not additional to the $1 billion portfolio. "PO" is used broadly; government aircraft, university research and international partners may require reimbursable agreements, grants, cooperative agreements or subawards.

A. Source-and-plume campaign

Phase 1: Scientific design — $1.20M

Procurement package	Deliverable	Estimate
SP1-01 Integrated science-design subaward	Hypotheses, release matrix, science traceability matrix and success criteria	$500,000
SP1-02 Near-field and boundary-layer modeling	Predictions of evaporation, crystallization, coagulation, plume rise and dispersion	$400,000
SP1-03 Independent design review	Published review and authorization, revision or refusal to proceed	$300,000

Phase 2: Governance and environmental review — $1.10M

Procurement package	Deliverable	Estimate
SP2-01 Regulatory and maritime legal services	Permit map, maritime jurisdiction, airspace and liability analysis	$250,000
SP2-02 Environmental assessment	Salt deposition, exposure, alternatives and monitoring plan	$350,000
SP2-03 Stakeholder and Indigenous engagement	Meetings, accessible materials, comment record and response document	$300,000
SP2-04 Independent governance panel	Conflict disclosures, stop/go decision and conditions	$200,000

Phase 3: Aerosol-source preparation — $2.50M

Procurement package	Deliverable	Estimate
SP3-01 Seawater intake and filtration skid	Corrosion-resistant intake, pumps, filters, sensors and cleaning system	$450,000
SP3-02 Aerosol generator modules	Interchangeable generator/nozzle assemblies with characterized output	$800,000
SP3-03 Flow, pressure and control system	Calibrated water/air metering, controls, logging and emergency shutdown	$350,000
SP3-04 Ground plume test stand	Outdoor or chamber tests across the operating envelope	$400,000
SP3-05 Spares, materials and maintenance	Nozzles, pumps, corrosion components, filters and cleaning supplies	$250,000
SP3-06 Independent output calibration	Particle size, number, coarse-tail and energy verification	$250,000

Phase 4: Instrument preparation — $3.00M

Procurement package	Deliverable	Estimate
SP4-01 Aerosol size-distribution package	Nanometre-to-micrometre aerosol number and size measurements	$650,000
SP4-02 CCN and hygroscopicity package	Activation spectra and particle water uptake	$450,000
SP4-03 Aerosol composition package	Sea-salt composition, organics and contamination	$400,000
SP4-04 Meteorology and turbulence package	Fast wind, temperature, humidity and flux measurements	$350,000
SP4-05 Drone and balloon payloads	Vertical profiles of aerosol and meteorology	$450,000
SP4-06 Lidar and optical plume mapping	Plume geometry and boundary-layer structure	$400,000
SP4-07 Calibration and data system	Traceable calibration, synchronization, telemetry and spares	$300,000

Phase 5: Vessel and platform integration — $2.00M

Procurement package	Deliverable	Estimate
SP5-01 Generator-vessel integration	Deck mounts, power, seawater plumbing and release mast	$650,000

Procurement package	Deliverable	Estimate
SP5-02 Sampling-vessel integration	Instrument racks, inlets, drone operations and data links	$450,000
SP5-03 Safety and marine engineering	Structural, electrical, corrosion, stability and emergency review	$350,000
SP5-04 Communications and mission systems	Ship-to-ship, drone and shore communications	$250,000
SP5-05 Acceptance testing	Harbor tests, vibration, electromagnetic and operating checks	$300,000

Phase 6: Baseline and rehearsal — $1.20M

Procurement package	Deliverable	Estimate
SP6-01 Baseline cruise block	Untreated aerosol, meteorology and deposition observations	$450,000
SP6-02 Forecasting and mission planning	Boundary-layer forecasts, trajectories and daily operating plans	$200,000
SP6-03 Low-output rehearsal	Detection test, vessel formation and drone interception practice	$200,000
SP6-04 Field logistics	Port, shipping, lodging, vehicles and workspaces	$250,000
SP6-05 Airspace and maritime coordination	Notices, permits and liaison support	$100,000

Phase 7: Release operations — $3.00M

Procurement package	Deliverable	Estimate
SP7-01 Generator-vessel mission order	Vessel, crew and multiple release/control runs	$950,000
SP7-02 Sampling-vessel mission order	Downwind aerosol transects and plume interception	$700,000
SP7-03 Drone operations	Repeated horizontal and vertical plume mapping	$450,000
SP7-04 Lidar and coastal observing	Plume location, boundary-layer height and transport	$300,000
SP7-05 Mission control and meteorology	Real-time forecasts, guidance and data display	$250,000
SP7-06 Standby and weather option	Reserved vessel and personnel availability	$350,000

Phase 8: Plume tracking — $1.80M

Procurement package	Deliverable	Estimate
SP8-01 Extended downwind vessel block	Longer-range plume searches and deposition sampling	$600,000
SP8-02 Aircraft or long-range drone option	Cloud-base-height and regional plume sampling	$450,000
SP8-03 Distributed balloon/drone profiles	Vertical transport and plume dilution	$250,000
SP8-04 Trajectory data assimilation	Updated plume location and uncertainty envelope	$300,000
SP8-05 Deposition network	Ocean, vessel and coastal deposition measurements	$200,000

Phase 9: Data and laboratory analysis — $3.10M

Procurement package	Deliverable	Estimate
SP9-01 Particle survival and activation analysis	Useful particle number versus distance, height and time	$600,000
SP9-02 Plume microphysics analysis	Evaporation, crystallization, coagulation and entrainment	$600,000
SP9-03 Vertical transport and source inversion	Cloud-base delivery fraction and reconstructed source	$500,000
SP9-04 Composition and deposition laboratory work	Salt, organics, contamination and deposition	$350,000
SP9-05 University science subawards	PI, postdoctoral and graduate analysis	$650,000
SP9-06 Computing, archive and quality control	Processing, uncertainty, metadata and synchronized dataset	$400,000

Phase 10: Independent evaluation — $0.70M

Procurement package	Deliverable	Estimate
SP10-01 Data-quality audit	Calibration, completeness and exclusion audit	$200,000
SP10-02 Blinded model challenge	Predictions against withheld plume observations	$250,000
SP10-03 Public repository	Data, code, generator settings and documentation	$150,000
SP10-04 Review workshop	External review and final campaign report	$100,000

Phase 11: Prepriced campaign recovery options — $2.40M

Procurement package	Deliverable	Estimate
SP11-01 Prepriced campaign recovery option	Approved technical or schedule recovery within the campaign ceiling	$1,000,000
SP11-02 Replacement vessel or weather days	Missed plume, weather or mechanical downtime	$700,000
SP11-03 Generator and instrument repair options	Replacement nozzles, pumps, sensors and calibration	$450,000
SP11-04 Regulatory or schedule extension	Additional consultation, storage or delayed deployment	$250,000

Source-and-plume campaign total: approximately $22.0M.

B. Cloud-response campaign

Phase 1: Scientific design — $1.80M

Procurement package	Deliverable	Estimate
CR1-01 Integrated experiment design	Cloud regime, release/control design, traceability matrix and uncertainty budget	$700,000
CR1-02 Large-eddy and cloud-process modeling	Preregistered predictions of activation, drizzle, optical depth and cloud fraction	$600,000
CR1-03 Statistical and causal design	Randomization, controls, detectable effect and analysis plan	$250,000
CR1-04 Independent design review	Observability, environmental limits and stop/go decision	$250,000

Phase 2: Governance and environmental review — $1.80M

Procurement package	Deliverable	Estimate
CR2-01 Regulatory and legal services	Maritime, aviation, environmental and liability requirements	$350,000
CR2-02 Environmental assessment	Exposure, deposition, alternatives and cumulative-impact analysis	$450,000
CR2-03 Public, Indigenous and jurisdictional engagement	Meetings, accessible materials and response record	$500,000
CR2-04 Independent	Published conditions and authorization decision	$250,000

Procurement package	Deliverable	Estimate
governance panel		
CR2-05 International / transboundary consultation	Notification and consultation plan	$250,000

Phase 3: Generator and source validation — $2.80M

Procurement package	Deliverable	Estimate
CR3-01 Flight / ship-ready generator system	Validated modular source with known particle output	$1,000,000
CR3-02 Seawater conditioning and controls	Intake, filtration, salinity/temperature sensing and data logging	$400,000
CR3-03 Release mast and plume-placement system	Adjustable release height and direction	$350,000
CR3-04 Ground and harbor validation	Operating-envelope, failure and endurance tests	$450,000
CR3-05 Independent particle-output verification	Size, number, coarse-tail, composition and energy audit	$300,000
CR3-06 Spares and consumables	Critical generators, filters, pumps and corrosion components	$300,000

Phase 4: Cloud and aerosol instruments — $6.00M

Procurement package	Deliverable	Estimate
CR4-01 Aerosol and CCN package	Aerosol size, composition, hygroscopicity and cloud-base activation	$900,000
CR4-02 Cloud-droplet and precipitation probes	Droplet spectra, liquid water, drizzle and precipitation	$1,100,000
CR4-03 Cloud radar and lidar package	Cloud boundaries, drizzle, vertical velocity and plume structure	$900,000
CR4-04 Radiometer and spectral optical package	Surface, aircraft and cloud-top shortwave measurements	$700,000
CR4-05 Aircraft inlets and data acquisition	Characterized inlets, synchronization, telemetry and quick-look displays	$750,000
CR4-06 Satellite data and rapid processing	Cloud optical depth, effective radius, albedo and cloud fraction	$350,000
CR4-07 Calibration and intercomparison	Traceable calibration and instrument comparison campaign	$700,000
CR4-08 Spares and	Replacement probes, pumps, lasers and calibration standards	$600,000

Procurement package	Deliverable	Estimate
consumables		

Phase 5: Aircraft and vessel integration — $4.20M

Procurement package	Deliverable	Estimate
CR5-01 Release-vessel integration	Generator, mast, power, controls and seawater system	$700,000
CR5-02 Primary research-aircraft integration	Aerosol, cloud and radiation payload installation	$1,300,000
CR5-03 Remote-sensing aircraft or ground site	Radar/lidar/radiometer integration	$650,000
CR5-04 Drone and autonomous-platform integration	Payloads, timing, communications and recovery	$400,000
CR5-05 Safety, airworthiness and marine certification	Hazard analyses, tests and approvals	$750,000
CR5-06 Mission communications	Aircraft-vessel-ground data links	$400,000

Phase 6: Baseline characterization — $2.80M

Procurement package	Deliverable	Estimate
CR6-01 Untreated cloud flight series	Cloud, aerosol, radiation and meteorology baseline	$1,100,000
CR6-02 Baseline vessel and remote sensing	Boundary-layer and cloud observations	$500,000
CR6-03 Forecast-system setup	Cloud-regime and plume-placement forecasts	$350,000
CR6-04 Satellite and control-region baseline	Matched treated/control region dataset	$250,000
CR6-05 Field operations center and logistics	Facilities, communications, shipping and personnel	$600,000

Phase 7: Release-day operations — $4.20M

Procurement package	Deliverable	Estimate
CR7-01 Release-vessel task	Release/control patterns and certified emission record	$1,100,000

Procurement package	Deliverable	Estimate
order		
CR7-02 Primary cloud-sampling aircraft	Repeated below-cloud, in-cloud and above-cloud transects	$1,300,000
CR7-03 Remote-sensing aircraft or ground network	Cloud radar, lidar and radiative mapping	$600,000
CR7-04 Drone and balloon operations	Plume-to-cloud vertical profiles	$350,000
CR7-05 Mission-control center	Real-time forecasts, guidance and data display	$350,000
CR7-06 Standby and weather option	Reserved platforms and crews	$500,000

Phase 8: Repeated cloud sampling — $10.00M

Procurement package	Deliverable	Estimate
CR8-01 Primary aircraft block	Multiple release and control sorties	$3,600,000
CR8-02 Second aircraft or complementary platform	Cloud-top remote sensing or wider-area sampling	$1,600,000
CR8-03 Release-vessel operating block	Repeated source operation and control periods	$1,500,000
CR8-04 Radar/lidar/radiometer network	Continuous cloud and radiation observations	$800,000
CR8-05 Satellite rapid-response processing	Daily treated/control products	$300,000
CR8-06 Forecast and data assimilation center	Twice-daily mission targeting and nowcasts	$650,000
CR8-07 Field personnel, maintenance and logistics	Travel, facilities, repairs and spares	$900,000
CR8-08 Contingency sortie option	Replacement for unsuitable-cloud or aborted mission	$650,000

Phase 9: Radiative and dynamical closure — $5.00M

Procurement package	Deliverable	Estimate
CR9-01 Aerosol activation and droplet analysis	Emission-to-cloud-droplet transfer function	$800,000

Procurement package	Deliverable	Estimate
CR9-02 Cloud water, drizzle and lifetime analysis	Microphysical and dynamical response	$850,000
CR9-03 Shortwave radiative closure	Measured and modeled reflection attributable to treatment	$850,000
CR9-04 Cloud fraction and mesoscale organization	Open/closed-cell transitions and cloud-field response	$650,000
CR9-05 Laboratory sample and composition analysis	Sea salt, organics and contamination	$350,000
CR9-06 University science subawards	Independent PI and early-career analysis teams	$1,000,000
CR9-07 Data quality and uncertainty review	Validated final dataset and uncertainty budget	$500,000

Phase 10: Regional modeling and attribution — $3.40M

Procurement package	Deliverable	Estimate
CR10-01 Large-eddy simulation ensemble	Case-specific high-resolution simulations	$900,000
CR10-02 Data assimilation and state reconstruction	Four-dimensional cloud and aerosol analysis	$650,000
CR10-03 Statistical causal attribution	Treated/control comparison and meteorological adjustment	$500,000
CR10-04 Scale-up sensitivity analysis	Local-to-regional extrapolation limits	$500,000
CR10-05 Independent modeling team	Firewalled predictions and comparison	$600,000
CR10-06 Visualization and decision tools	Open 3-D products, uncertainty and dashboards	$250,000

Phase 11: Independent evaluation — $1.20M

Procurement package	Deliverable	Estimate
CR11-01 Data-quality and calibration audit	Completeness, calibration and exclusion review	$300,000
CR11-02 Withheld-data model challenge	Prospective predictions against observations	$400,000
CR11-03 Open repository	Raw/processed data, code, metadata and generator settings	$250,000

Procurement package	Deliverable	Estimate
and reproducibility package		
CR11-04 International review workshop	External review and final campaign report	$250,000

Phase 12: Prepriced campaign recovery options — $4.80M

Procurement package	Deliverable	Estimate
CR12-01 Prepriced campaign recovery option	Approved technical or operational recovery within the campaign ceiling	$1,800,000
CR12-02 Replacement aircraft and ship options	Weather, unsuitable clouds, aborts and downtime	$1,800,000
CR12-03 Instrument and generator repair	Replacement systems and emergency calibration	$800,000
CR12-04 Regulatory or deployment extension	Additional consultation or schedule extension	$400,000

Cloud-response campaign total: approximately $48.0M.

How I would actually contract it

Issuing more than one hundred unrelated contracts would be inefficient. I would establish approximately eight master agreements, with campaign-specific task orders:

Master agreement	Task orders covered
Research ships and marine operations	Release vessel, sampling vessel, port, crew and standby days
Research aircraft and flight operations	Baseline, cloud sampling, remote sensing and replacement sorties
Aerosol-source engineering	Generator modules, seawater systems, controls, calibration and maintenance
Atmospheric instrumentation	Aerosol, CCN, cloud, radar, lidar, radiation and calibration
Modeling, forecasting and data assimilation	Plume, LES, mission forecasts, causal analysis and source inversion
Drones, balloons and autonomous platforms	Vertical profiles, plume mapping and distributed observations
Scientific-analysis consortium	University, government-lab and international research subawards
Governance and independent review	Environmental review, engagement, audits and open-data oversight

- Each task order must specify measurable deliverables rather than only staff hours.
- Acceptance criteria should include uncertainty and data-completeness requirements.

- All foreground data, code and technical documentation should be open by default.
- Fixed-price milestones are suitable for defined hardware and reports; cost reimbursement is more appropriate for uncertain field operations.
- Replacement-day options should be pre-priced but exercised only when scientifically justified.

Recipients of Purchase Orders

Prompt to AI: With each purchase order or equivalent agreement, who might it be issued to?

Response From AI:

The recipients below are illustrative candidates, not endorsements or prequalified bidders. Many would participate through grants, cooperative agreements, reimbursable government agreements or international research subawards rather than ordinary commercial purchase orders.

A strong consortium would combine the University of Washington MCB Research Program, NOAA cloud and aerosol scientists, NSF NCAR/UCAR, Scripps Institution of Oceanography, Pacific Northwest National Laboratory, Southern Cross University and its Australian partners, NASA cloud-observation groups, DOE atmospheric-observation capabilities, and competitively selected engineering and instrument firms.

Role	Strong candidate organizations
Managing Organization	RTI International, Battelle, SRI International or UCAR after competition
Scientific integrator	UCAR/NCAR with NOAA, UW, Scripps, PNNL and international partners
Existing MCB field-experiment lead	Southern Cross University with RRAP, CSIRO, AIMS and partner universities
U.S. MCB science and generator program	University of Washington MCB Program with SRI International
Research ships and marine operations	Scripps, NOAA, Australian partners, university fleets or qualified commercial operators
Research aircraft	NSF NCAR Earth Observing Laboratory, NOAA aircraft programs, NASA research aircraft or qualified contractors
Cloud radar/lidar/radiation	NOAA, NCAR, DOE ARM, NASA Langley and university groups
Independent environmental review	AECOM, Ramboll, RTI or another competitively selected independent firm
Public and Indigenous engagement	Independent regional organizations selected with affected communities
Independent scientific review	National Academies-style panel or separately funded international committee

A. Source-and-plume campaign

Procurement area	Illustrative recipients
Scientific design and plume modeling	UW MCB Program; NOAA; NCAR; Scripps; PNNL; Southern Cross University; independent university teams
Environmental and governance review	Independent environmental consultancy; maritime/aviation counsel; community and Indigenous engagement organizations

Procurement area	Illustrative recipients
Aerosol generator and seawater systems	SRI/UW generator team; Southern Cross University and industry partners; competitively selected spray, pump, filtration and corrosion specialists
Aerosol and CCN instruments	NOAA and university instrument groups; Aerodyne Research; TSI; Droplet Measurement Technologies; Handix Scientific; other qualified suppliers
Vessel integration	Research-fleet operator; marine engineering firm; generator prime; independent marine-safety reviewer
Drone and balloon systems	University UAS teams; NOAA/NCAR; qualified commercial operators; Vaisala and specialist payload firms
Lidar and remote sensing	NOAA, NASA Langley, NCAR, DOE ARM or university lidar groups
Data assimilation and source inversion	NOAA, NCAR, PNNL, UW, Scripps and an independent modeling team
Laboratory and deposition analysis	NOAA, Scripps, university aerosol laboratories and independent analytical laboratories
Independent audit and archive	RTI or independent metrology/statistics team; UCAR, NOAA, NASA or a durable open repository

B. Cloud-response campaign

Procurement area	Illustrative recipients
Cloud-regime design and LES	NOAA, NCAR, UW, Scripps, PNNL, University of Arizona, University of Leeds/Manchester/Exeter and other cloud groups
Release vessel and generator	Southern Cross University team or UW/SRI team working with a qualified vessel operator and marine integrator
Primary cloud-sampling aircraft	NSF NCAR C-130 or University of Wyoming King Air 350i for primary cloud sampling; NSF NCAR Gulfstream V for above-cloud/context work; NOAA, NASA or SAFIRE aircraft where mission requirements fit
Aerosol and cloud probes	NOAA, NCAR, NASA, Droplet Measurement Technologies, SPEC and university instrument teams
Radar, lidar and radiometers	DOE ARM, NOAA, NCAR, NASA Langley and university remote-sensing groups
Satellite products	NASA and NOAA science teams; university retrieval groups
Cloud and radiative closure	NOAA, NCAR, Scripps, UW, NASA and independent international teams
Regional and global climate modeling	NCAR, PNNL, NOAA GFDL, UK Met Office/University of Exeter, Max Planck Institute, universities and GeoMIP participants
Marine ecology and deposition	AIMS, CSIRO, Scripps, Southern Cross University, coastal universities and independent ecological laboratories
Public archive and review	UCAR/NCAR, NOAA or NASA archive; National Academies-style international review

Recommended prime-contract arrangement

1. RTI International or another competitively selected nonprofit: fiduciary program management, procurement, finance, risk and reporting.
2. UCAR/NCAR: atmospheric-science integration, field-campaign coordination, models and data standards.
3. University of Washington MCB Program and NOAA/Scripps/PNNL partners: U.S. aerosol-cloud science and source research.
4. Southern Cross University/RRAP consortium: outdoor MCB experience, marine operations and regional ecological integration.
5. Research-aircraft and research-vessel operators: independently contracted platform services.
6. Independent oversight consortium: environmental review, public engagement, scientific audit and open-data compliance.

The organization operating a release must not control environmental authorization, public engagement, data audit, or the final decision on whether a larger experiment should proceed.

Project Management

Prompt to AI: What project-management provisions are specific to this MCB Experimental Research Initiative after incorporating the Climate Moonshot Portfolio Common Framework?

Response From AI:

Portfolio-wide governance, Managing Organization selection, fiduciary controls, procurement, financial controls, reserve governance, independent review, audit, conflicts, open-source/data rights, management oversight, and transition rules are specified in the Moonshot Common Framework. This chapter states only the additional management structure required by the MCB experimental-research program.

Initiative-specific management requirements

- The Managing Organization must be capable of large atmospheric field programs involving research ships, aircraft, drones, remote sensing, aerosol-source systems, cloud measurements, environmental review, international coordination, and acceptance of campaign data and technical deliverables.
- Maintain one integrated science-and-operations baseline across the twelve program areas and the linked source-and-plume and cloud-response experiment families. Requirements, release settings, control periods, instrument configuration, forecasts, calibration, exclusions, and data products must remain traceable from preregistration through final analysis.
- Maintain a clear separation among fiduciary program management, scientific integration, experiment execution, and the Independent Release and Safety Board. The team conducting a release may not authorize its own outdoor experiment or determine by itself that a larger release should proceed.
- Coordinate formally with the companion MCB Equipment Development Initiative. Experimental Research pays for campaign-specific capability and scientific operation; Equipment Development hardens, scales, automates, and improves reusable equipment. Shared generators, vessels/platforms, instruments, data systems, and other assets must have one lead budget and an auditable usage/transfer rule.
- Require preregistered treated/control designs, detectability and statistical-power review, independent calibration and data-quality review, publication of null and negative results, and independent replication before a claimed source-to-cloud-to-radiation result is used to justify a larger research stage.
- Completion of the five-year research program produces an independently reviewed stop/proceed decision package. It creates no entitlement to regional or global MCB deployment, and passing a

scientific gate does not substitute for environmental, legal, public-engagement, or transboundary authorization.

Funding Source Requirements

We assume the Funding Source aims to maximize climate benefit per dollar spent, as opposed to maximize financial return on an investment. This is sometimes referred to as “climate money”, and it differs from the traditional investment portfolio. Sources of climate money include high-net-worth individuals, foundations, and governments.

The portfolio-wide Funding Source requirements are specified in the Moonshot Common Framework. The additions below address the program's controlled-release boundary, preregistration, detectability, independent release approval, measurement traceability, open science, shared assets, replication, and final decision evidence.

Program-specific additions

- Keep the five-year appropriation limited to research, bounded field experiments, observations, modeling, environmental monitoring, reusable scientific capability, and decision support. It does not authorize a regional or global MCB intervention or a scale increase that has not passed the applicable scientific and governance gates.
- Require each deliberate release campaign to preregister its scientific question, primary endpoint, expected and minimum detectable effect, independent experimental unit, treated/control design, exclusion rules, sample-size logic, source settings, environmental limits, stop criteria, and analysis plan before mobilization.
- Require the Independent Release and Safety Board to approve, condition, delay, or prohibit every outdoor release. Environmental, maritime/aviation, community, Indigenous, jurisdictional, and transboundary requirements remain prerequisites where applicable and may not be waived by the experiment team.
- Require a reproducible evidence chain from known source output through plume transport and cloud-base delivery to droplet activation, cloud microphysics/dynamics, and reflected shortwave radiation, with traceable calibration and uncertainty at each link. A bright image or increased aerosol concentration alone is not sufficient evidence of successful cloud brightening.
- Require rapid public release of data, code, generator settings, calibration records, release and control logs, vessel/aircraft tracks, environmental measurements, exclusions, model predictions, null results, and failure reports under the common open-source/data policy, subject only to documented narrow exceptions.
- Apply the common shared-asset rule to the companion MCB Equipment Development Initiative: purchase each reusable physical or digital asset once; the other initiative pays only incremental adaptation, operating time, consumables, or intentionally independent capacity.

- Use the independent-replication and rapid-response reserve only for scientifically justified repetitions, unexpected natural analogues, instrument/platform failures, or other approved needs. Reserve use must not become an automatic source of extra release scale or contractor revenue.

Program-specific success metric

Measure success by reliable public knowledge: whether useful sea-salt particles can be produced and delivered to cloud base, whether defined cloud regimes show repeatable causal microphysical and radiative responses, whether models reproduce withheld observations, what environmental signals require attention, and where uncertainty remains too large to proceed. A scientifically credible negative result is a successful program outcome.

Top MCB Science Papers

Prompt to AI: Summarize the top papers most relevant to a proposed $1B Marine Cloud Brightening experiment initiative.

Response From AI:

The list emphasizes foundational aerosol–cloud physics, MCB source and particle-size requirements, cloud and climate modeling, natural analogues, field-research design, risks and the first published outdoor trial. It is not a citation-count ranking.

Foundations and Core Aerosol–Cloud Physics

Twomey, 1977 — “The Influence of Pollution on the Shortwave Albedo of Clouds”

Established the core microphysical relationship behind cloud brightening: for a fixed liquid-water amount, more cloud droplets generally produce a larger total scattering area and a brighter cloud. MCB experiments must test this response in real marine clouds while accounting for cloud dynamics and precipitation.

https://journals.ametsoc.org/view/journals/atsc/34/7/1520-0469_1977_034_1149_tiopot_2_0_co_2.xml

Albrecht, 1989 — “Aerosols, Cloud Microphysics, and Fractional Cloudiness”

Proposed that additional aerosol can suppress drizzle and alter cloud lifetime and cloud amount. This second indirect effect may amplify or oppose the immediate Twomey brightening, making measurements of precipitation, entrainment and cloud fraction essential.

https://doi.org/10.1126/science.245.4923.1227

Latham, 1990 — “Control of Global Warming?”

Introduced the modern proposal to counter greenhouse warming by increasing the reflectivity of marine clouds using sea-salt particles. The paper is conceptually foundational but does not resolve whether suitable particles can be delivered or whether regional climate consequences are acceptable.

https://doi.org/10.1038/347339b0

Latham, 2002 — "Amelioration of Global Warming by Controlled Enhancement of the Albedo and Longevity of Low-Level Maritime Clouds"

Developed the MCB concept and discussed targeted low marine clouds, cloud droplet number and possible climate effect. It frames the two central experimental questions: can the cloud be perturbed predictably, and does the perturbation persist long enough to matter?

https://doi.org/10.1006/asle.2002.0048

Source Engineering, Aerosol Microphysics, and Particle-Size Control

Bower, 2006 — computational assessment of marine stratocumulus albedo enhancement

Used detailed cloud modeling to examine how added particles might alter stratocumulus cloud properties. It helped move the concept from a simple droplet-number argument toward process-level simulations, and it highlights the importance of cloud regime and background aerosol.

https://doi.org/10.1016/j.atmosres.2005.11.013

Salter, 2008 — "Sea-Going Hardware for the Cloud Albedo Method of Reversing Global Warming"

Proposed wind-powered unmanned spray vessels and engineering concepts for producing submicron seawater droplets. Its fleet and hardware estimates are highly preliminary, but the paper defines the source-engineering challenge that a modern equipment and field program must test.

https://doi.org/10.1098/rsta.2008.0136

Korhonen, 2010 — "Enhancement of Marine Cloud Albedo via Controlled Sea Spray Injections"

Modeled the influence of emission rate, aerosol microphysics and transport. The study showed that source rate and particle evolution matter strongly and that the useful aerosol burden cannot be inferred simply from the amount of seawater sprayed.

https://doi.org/10.5194/acp-10-4133-2010

Partanen, 2012 — direct and indirect effects of sea-spray geoengineering and injected particle size

Separated direct scattering by injected salt aerosol from cloud-mediated effects and emphasized particle-size sensitivity. MCB experiments should therefore measure both clear-sky aerosol optical effects and cloud responses.

https://doi.org/10.1029/2011JD016428

Alterskjær, 2013 — "The Sign of the Radiative Forcing from Marine Cloud Brightening Depends on Both Particle Size and Injection Amount"

Showed that poorly chosen particle sizes or excessive injection can produce weak or even warming responses through complex aerosol–cloud and clear-sky effects. This makes particle-size control and dose-response experiments central.

https://doi.org/10.1029/2012GL054286

Stuart, 2013 — "Reduced Efficacy of Marine Cloud Brightening Geoengineering Due to In-Plume Aerosol Coagulation"

Showed that high particle concentrations near the source can coagulate before dilution, reducing the number of useful particles. It directly motivates metre-to-kilometre plume experiments and multiple distributed sources rather than one extremely intense sprayer.

https://doi.org/10.5194/acp-13-10385-2013

Connolly, 2014 — "Factors Determining the Most Efficient Spray Distribution for Marine Cloud Brightening"

Analyzed how particle-size distributions influence cloud activation and energy requirements. It provides practical metrics for source development: useful particles per energy and avoidance of both undersized and oversized particles.

https://doi.org/10.1098/rsta.2014.0056

Hoffmann, 2021 — "Cloud Microphysical Implications for Marine Cloud Brightening: The Importance of the Seeded Particle Size Distribution"

Demonstrated that a small number of coarse particles can accelerate precipitation and reduce cloud water. This is one of the most directly actionable papers for generator specifications and paired particle-size field experiments.

https://doi.org/10.1175/JAS-D-21-0077.1

Climate Modeling, Radiative Forcing, and Regional Effects

Latham, 2008 — "Global Temperature Stabilization via Controlled Albedo Enhancement of Low-Level Maritime Clouds"

Combined cloud physics and climate-model reasoning to estimate potential global cooling. It supports targeted research but also illustrates how strongly global conclusions depend on assumed cloud susceptibility and idealized aerosol delivery.

https://doi.org/10.1098/rsta.2008.0137

Rasch, 2009 — "Geoengineering by Cloud Seeding: Influence on Sea Ice and Climate System"

Examined climate-system responses to marine cloud brightening, including high-latitude effects. It showed that localized radiative forcing can generate broad circulation and hydrological responses, motivating regional and global modeling alongside field experiments.

https://doi.org/10.1088/1748-9326/4/4/045112

Jones, 2009 — "Climate Impacts of Geoengineering Marine Stratocumulus Clouds"

Demonstrated that brightening selected stratocumulus regions can cool global mean temperature but produce nonuniform regional temperature and precipitation changes. It is a key warning against treating global-average cooling as the sole performance metric.

https://doi.org/10.1029/2008JD011450

Hill, 2012 — "Nonlinear Climate Response to Regional Brightening of Tropical Marine Stratocumulus"

Found that targeted brightening can generate a La Niña-like response and important remote effects. This paper makes regional teleconnections and ENSO response a core requirement for climate-model evaluation.

https://doi.org/10.1029/2012GL052064

Kravitz, 2013 — "Sea Spray Geoengineering Experiments in the Geoengineering Model Intercomparison Project"

Established coordinated multi-model MCB experiments and documented substantial differences among models. The work supports standardized scenarios, common diagnostics and independent model comparison before any scale-up.

https://doi.org/10.1002/jgrd.50856

Ahlm, 2017 — "Marine Cloud Brightening—as Effective without Clouds"

Found that at high injection rates, direct scattering by sea salt can become an important part of the radiative forcing. This complicates attribution and requires experiments to distinguish marine sky brightening from cloud-mediated brightening.

https://doi.org/10.5194/acp-17-13071-2017

Horowitz, 2020 — "Effects of Sea Salt Aerosol Emissions for Marine Cloud Brightening on Atmospheric Chemistry"

Examined broader atmospheric consequences of adding sea salt, including chemical effects. It supports measuring composition, reactive chemistry and deposition rather than assuming seawater aerosol is chemically inert.

https://doi.org/10.1029/2019GL085838

Wood, 2021 — "Assessing the Potential Efficacy of Marine Cloud Brightening for Cooling Earth Using a Simple Heuristic Model"

Linked source particle number, plume lifetime, cloud updraft, background aerosol and sprayer count to potential forcing. It offers a transparent bridge from field-scale measurements to system-level estimates and identifies the parameters experiments must constrain.

https://doi.org/10.5194/acp-21-14507-2021

Natural Experiments, Field Feasibility, and Research Governance

Glassmeier, 2021 — "Aerosol-Cloud-Climate Cooling Overestimated by Ship-Track Data"

Used ship tracks to show that cloud adjustments can offset some initial brightening and that visible tracks can bias estimates of persistent climate forcing. Natural analogues are valuable, but field programs must measure the full cloud life cycle.

https://doi.org/10.1126/science.abd3980

Diamond, 2022 — “To Assess Marine Cloud Brightening’s Technical Feasibility, We Need to Know What to Study—and When to Stop”

Proposed a staged research logic and explicit stopping criteria. The paper is especially relevant to funding governance because it argues that research should be organized around falsifiable questions rather than an assumption of eventual deployment.

https://doi.org/10.1073/pnas.2118379119

Yuan, 2022 — “Global Reduction in Ship Tracks from Sulfur Regulations for Shipping Fuel”

Used satellite observations and shipping changes to create a large natural experiment in aerosol–cloud interactions. The work demonstrates the value of global ship-track detection, emissions data and policy-driven perturbations for constraining cloud response.

https://doi.org/10.1126/sciadv.abn7988

Feingold, 2024 — “Physical Science Research Needed to Evaluate the Viability and Risks of Marine Cloud Brightening”

Provides the most comprehensive recent research agenda, calling for coordinated laboratory, field, monitoring and multiscale modeling work. It emphasizes scale-up, regional distributions of benefits and risks, and the need to connect process observations to climate response.

https://doi.org/10.1126/sciadv.adi8594

Hernandez-Jaramillo, 2025 — “First Generation Outdoor Marine Cloud Brightening Trial Increases Aerosol Concentration at Cloud Base Height”

Reports outdoor generation and transport of sea-salt aerosol in the Great Barrier Reef program, including evidence of increased aerosol concentration at cloud-base height. It is a major proof-of-delivery result, while not by itself demonstrating repeatable cloud brightening or regional cooling.

https://doi.org/10.1088/1748-9326/adccd7

Most relevant to the proposed $1 billion program

- Feingold (2024) for the integrated research agenda.
- Diamond (2022) for staged feasibility and stopping criteria.
- Hoffmann and Feingold (2021), Alterskjær and Kristjánsson (2013), Connolly (2014) and Stuart (2013) for particle-size and source requirements.
- Glassmeier (2021) and Yuan (2022) for natural experiments and ship-track interpretation.
- Wood (2021) for linking field measurements to system-scale efficacy.
- Hernandez-Jaramillo (2025) for outdoor source-to-cloud-base delivery.
- Jones (2009), Hill and Ming (2012), Kravitz (2013) and Feingold (2024) for regional and global consequences.

Selected current research sources include the 2024 Science Advances research agenda, the University of Washington MCB Research Program, Southern Cross University’s outdoor program, the DOE–NOAA MCB workshop report, and the National Academies’ 2021 solar-geoengineering research report.

Top Researchers

Prompt to AI: Who are the top researchers in Marine Cloud Brightening and related fields? What are the leading organizations?

Response From AI:

The following names are illustrative candidates based on published work and leadership in aerosol–cloud science, MCB research, field observations, modeling or engineering. Inclusion does not imply endorsement, availability or agreement with deployment.

Leading researchers

Researcher	Relevance
Graham Feingold	NOAA cloud and aerosol process science; lead author of the 2024 MCB research agenda.
Robert Wood	University of Washington; marine low clouds, MCB efficacy and field-program leadership.
Sarah Doherty	University of Washington; MCB program direction, governance, engagement and research integration.
Lynn M. Russell	Scripps Institution of Oceanography; aerosol composition, marine aerosol and field observations.
Daniel P. Harrison	Southern Cross University; outdoor MCB experiments, spray systems and reef-focused field research.
Philip Rasch	Pacific Northwest National Laboratory; aerosol–cloud–climate modeling and geoengineering research.
Armin Sorooshian	University of Arizona; marine aerosol, cloud processing, aircraft observations and field campaigns.
Allison McComiskey	NSF NCAR Earth Observing Laboratory; aerosol–cloud observations and research infrastructure.
Michael S. Diamond	cloud and aerosol interactions, ship-track natural experiments and MCB feasibility framing.
Franziska Glassmeier	cloud adjustments and limits of inference from ship tracks.
Edward Gryspeerdt	satellite aerosol–cloud interactions and causal interpretation.
F. Hoffmann	cloud microphysics and seeded particle-size effects.
Andrew Gettelman	global cloud modeling, climate response and MCB feasibility.
Matthew Lebsock	satellite and aircraft observations of marine clouds and precipitation.
Jessica Wan	regional MCB climate impacts and time-dependent efficacy.

Researcher	Relevance
Chih-Chieh Chen	NCAR climate-model experiments, deployment strategy and regional response.
Dilip Ganguly	aerosol–climate modeling and Global South scientific perspective.
Nicolás Huneeus	aerosol science, South American perspective and research review.
Daniel Rosenfeld	cloud microphysics, aerosol effects and precipitation.
Ilona Riipinen	aerosol microphysics, particle growth and climate interactions.

Top organizations

1. University of Washington Marine Cloud Brightening Research Program

Dedicated MCB collaboration spanning aerosol generation, cloud studies, modeling, governance and engagement.

2. NOAA Chemical Sciences Laboratory and NOAA research programs

Cloud, aerosol, chemistry, ship-track and atmospheric-observation expertise.

3. NSF NCAR and UCAR

Research aircraft, observing systems, field-campaign management, cloud-resolving and global modeling.

4. Southern Cross University MCB program and RRAP partners

World-leading outdoor sea-salt generation and Great Barrier Reef field experiments.

5. Scripps Institution of Oceanography

Marine aerosol and cloud observations, research vessels and atmospheric chemistry.

6. Pacific Northwest National Laboratory

Aerosol–cloud–climate modeling and DOE atmospheric science.

7. DOE Atmospheric Radiation Measurement program

Cloud radar, lidar, radiometers, mobile facilities and long-term cloud observations.

8. NASA and NASA Langley atmospheric research groups

Satellite retrievals, airborne lidar, radiation and cloud remote sensing.

9. CSIRO and Australian Institute of Marine Science

Australian atmospheric, marine, ecological and Great Barrier Reef expertise.

10. UK Met Office, University of Exeter, Leeds and Manchester groups

Cloud modeling, climate response and aerosol–cloud process research.

11. Max Planck Institute for Meteorology and European cloud groups

Cloud-climate dynamics, process modeling and independent assessment.

12. Geoengineering Model Intercomparison Project and World Climate Research Programme networks

Standardized multi-model scenarios and climate-response comparison.

13. SRI International

Nonprofit engineering and aerosol-generator development partner.

14. SilverLining and Degrees Initiative

Research support, network building, governance and broader international participation.

Best consortium for the proposed program

A credible program would not be controlled by one laboratory. It would combine a neutral fiduciary MO; UCAR/NCAR field and model integration; NOAA, UW, Scripps and PNNL process science; Southern Cross University and Australian partners for outdoor MCB experience; NASA/DOE remote sensing; multiple independent modeling teams; marine ecologists; and strong participation from climate-vulnerable regions.

Scientific Advisory Panel

Prompt to AI: If a scientific panel were established to oversee the MCB research, who might serve on it and what expertise should be represented?

Response From AI:

Suggested scientific oversight panel

Seat	Required independent expertise
Independent chair	Senior Earth-system scientist with no current MCB contract; selected through an international search.
Marine low-cloud physics	Stratocumulus/cumulus dynamics, susceptibility, cloud organization and field requirements.
Marine aerosol and source microphysics	Sea-salt composition, hygroscopicity, activation, particle-size effects and plume evolution.
MCB field-experiment design	Outdoor source/plume work, marine operations, paired treated/control campaigns and experimental feasibility.
Atmospheric instrumentation and metrology	Aircraft inlets, aerosol/cloud probes, radar/lidar/radiometry, calibration and uncertainty.
Field-campaign operations	Aircraft, research-vessel, UAS, weather-risk and multi-platform campaign integration.
Statistics and causal inference	Power, experimental units, randomization/controls, preregistration, exclusions and multiplicity.
Cloud-process / LES modeling	Prospective high-resolution prediction, data assimilation and model falsification.
Regional and global climate response	Teleconnections, ENSO, precipitation, scale-up limits and connection to the GCM initiative.
Marine ecology and environmental monitoring	Salt deposition, coastal/marine exposure, ecological indicators and cumulative effects.
Global South atmospheric science	Regional consequences, capacity building, independent participation and distributional effects.
Community / Indigenous knowledge	Research-area legitimacy, local impacts, engagement quality and governance knowledge.

Non-voting technical advisers

- Research vessel operator and marine safety officer.
- Research aircraft and flight-safety representative.

- Aerosol-generator engineer.
- Environmental-law and permitting adviser.
- Data and open-source steward.
- Program statistician and causal-inference specialist.
- Funding Source and MO liaisons.

Critical conflict-of-interest rule

Scientists receiving large program awards should not form a voting majority. Members must disclose institutional and financial interests; recuse from reviews of their own work; and permit minority reports. The panel should review scientific adequacy, but an independent release and safety board should retain authority to prohibit an outdoor release.

Suggested voting standard

Ordinary scientific recommendations could use a two-thirds vote. A recommendation to increase release scale should require at least 75% support, no unresolved critical safety finding, and affirmative approval from the independent release board and the Funding Source.

Management Advisory Panel

Prompt to AI: What management-oversight expertise is uniquely needed for the MCB Experimental Research Initiative beyond the common Management Advisory Panel charter?

Response From AI:

The Moonshot Common Framework governs the panel charter, independence, fiduciary oversight, audit access, conflicts, procurement escalation, reserve review, corrective action, and Managing Organization succession. This initiative adds field-campaign, release-governance, and research-integrity capabilities needed to oversee a large marine atmospheric experiment program.

Initiative-specific oversight capabilities

- Large scientific field campaigns: research ships, aircraft, drones, remote sensing, weather risk, mobilization, international logistics, replacement days, instrument integration, calibration, and readiness evidence before expensive campaign commitments.
- Maritime, aviation, environmental, and community governance: independent release authorization, permits, emergency stop systems, public and Indigenous engagement, transboundary consultation, incident response, and strict separation between experiment execution and approval authority.
- Research integrity and decision evidence: preregistration, statistical power, treated/control design, blinded or withheld-data tests, open-data delivery, independent replication, publication of null/negative results, and protection against claiming efficacy from one favorable campaign.
- Cross-program coordination: prevent duplicate spending with the MCB Equipment Development Initiative and ensure that shared generators, vessels/platforms, observing systems, data infrastructure, and technical personnel have explicit ownership, cost, and usage rules.

All other management-panel seats and authorities are supplied by the common framework. Technology-specific scientific judgment remains with the Scientific Advisory Panel, while authority to approve or prohibit an outdoor release remains with the independent release and safety function.

Agreements

Prompt to AI: Which agreement provisions should remain inside this proposal after the portfolio-wide Funding Source-to-Managing Organization and Managing Organization-to-Recipient master terms are moved to the common framework?

Response From AI:

The generic master agreement terms are specified in the Moonshot Common Framework and are not repeated here. Final agreements would use those common terms plus the MCB experimental-research schedules below, adapted by counsel to the parties, jurisdictions, research platforms, government partners, environmental requirements, and the actual procurement or grant instrument.

Program-Specific Schedules to the Common Agreements

Experimental design, preregistration, and statistical schedule

Attach the approved scientific question, causal chain, primary and secondary endpoints, expected/minimum detectable effect, experimental unit, treated/control assignment, release/no-release pattern, exclusion rules, sample-size and weather-day logic, uncertainty budget, preregistered model predictions, analysis code plan, and conditions that trigger redesign, repetition, or termination.

Outdoor release, environmental, and governance schedule

Specify the seawater-derived material, particle-size/output limits, location, route, time, cloud and meteorological operating envelope, permits, maritime/aviation coordination, environmental and deposition monitoring, public/Indigenous/jurisdictional engagement, transboundary notification where applicable, stop conditions, emergency authority, incident reporting, and Independent Release and Safety Board approval.

Aircraft, vessel, UAS, and field-operations schedule

Specify platform availability, payloads, integration and certification, mission roles, flight/vessel hours, standby and weather options, replacement days, communications, mission control, safety responsibilities, sampling patterns, data synchronization, configuration control, and independent witnessing or readiness review.

Aerosol source, instrumentation, calibration, and measurement schedule

Specify generator settings and source metrology, seawater conditioning, particle-size and CCN requirements, cloud and radiation instruments, inlet transmission, calibration/intercomparison, uncertainty, spares, failure reporting, chain-of-custody for samples, and the evidence required to close source-to-plume-to-cloud-to-radiation claims.

Data, models, open-science, and reproducibility schedule

Specify repositories and release dates for raw and calibrated observations, metadata, source settings, tracks, environmental measurements, model configurations, forecast and preregistered prediction files, analysis code, exclusions, negative results, final uncertainty products, and the reproducibility package required for an unaffiliated team to repeat the analysis.

Shared-asset, independent-replication, and transition schedule

Identify ownership, maintenance, calibration, access, and cost allocation for equipment shared with the MCB Equipment Development Initiative; preserve the independence of replication teams; and define transfer of data, samples, instruments, software credentials, permits/records, and open technical documentation at campaign or program closeout.

No duplicate master terms

General competition, pricing, milestone payment, retainage, audit, conflicts, open-source/data rights, background/foreground IP, reserve, changes/claims, remedies, termination, step-in, succession, insurance, and routine reporting are governed by the common framework unless an approved MCB-specific schedule expressly adds or overrides a term.

Termination Shock — MCB-Specific Considerations

Prompt to AI: What termination-shock issues are specific to marine cloud brightening (MCB), and which parts should be handled in the Global Climate Model Experimental Research Initiative?

Response From AI:

Termination shock is fundamentally a climate-system response to removing a cooling forcing while greenhouse-gas concentrations remain high. The definitive cross-technology analysis therefore belongs in the Global Climate Model Experimental Research Initiative. This MCB proposal should retain the MCB-specific source, cloud, operational, and monitoring issues that determine how quickly its forcing can disappear.

What is specific to MCB

MCB has a much shorter physical memory than SAI. Sea-salt particles in the marine boundary layer and the cloud perturbations they create generally persist for days, not a year or more. If spraying stops, the deliberate radiative forcing can therefore diminish quickly as particles are removed, clouds evolve, and treated air masses move away. Ocean and atmospheric thermal inertia still spread the temperature response over years and decades, but the operational buffer between a fleet failure and loss of forcing is small.

This short lifetime is both an advantage and a risk. It improves controllability for bounded experiments because the perturbation does not persist for long after operations stop. At deployment scale, however, it means ship or generator outages, unsuitable meteorology, port or fuel disruptions, communications failures, cyber incidents, or political withdrawal could translate into a rapid reduction in effective forcing. Weather dependence can also change MCB forcing even when the equipment itself is functioning.

Illustrative termination cases

Illustrative calculations can be useful for intuition, but this proposal should not anchor its research case to one assumed greenhouse-gas trajectory, climate sensitivity, or abrupt-warming number. The definitive multi-year and multi-century termination analysis belongs in the Global Climate Model Experimental Research Initiative, using ensembles across greenhouse-gas pathways, ocean states, forcing patterns, gradual and abrupt phaseout, and model uncertainty.

What this MCB research program should deliver

The Global Climate Model Experimental Research Initiative should maintain the full Termination Shock analysis for both SAI and MCB, including global and regional temperature, precipitation, monsoons, sea ice, ocean heat, AMOC, ecosystems, abrupt versus gradual phaseout, greenhouse-gas trajectories, and carbon removal.

The MCB Experimental Research Initiative should measure the source-specific inputs needed by termination models: how quickly aerosol number, cloud-droplet perturbations, cloud optical depth, liquid-water path, drizzle response, and reflected shortwave radiation return toward background after a source is turned off; how those decay times vary by cloud regime and meteorology; and how reliably the system can detect a loss of forcing.

The program should also quantify practical control authority: how rapidly output can be reduced or restored, how many independent vessels or source regions are needed for continuity, how meteorological gaps affect effective forcing, and which monitoring signals distinguish normal cloud variability from a genuine interruption. These are MCB-specific experimental questions; they do not require duplicating multi-century climate-response ensembles inside this proposal.

MCB Aircraft, Instruments and Airborne Measurement Architecture

Prompt to AI: The MCB experimental research program needs aircraft to track sea-salt plumes, measure delivery to cloud base, sample treated and untreated clouds, and close the radiative response. What kinds of research aircraft are needed? What parameters should each measure, what instruments are needed, which existing research-aircraft operators might provide them, and what aircraft or airborne equipment should the program develop or modify?

Response From AI:

MCB needs a coordinated airborne measurement system rather than one special airplane. The intervention source is normally a ship or autonomous surface platform, while aircraft diagnose what happens between the source, cloud base, cloud interior and reflected sunlight. The most useful architecture is a primary in-situ cloud aircraft, an above-cloud remote-sensing/radiation aircraft, smaller plume or boundary-layer aircraft where useful, and uncrewed aircraft that fill vertical and near-source sampling gaps. The aircraft should be treated mainly as reusable sensor buses; most development money should go into modular instruments, characterized inlets, synchronization, plume/cloud targeting and aircraft-vessel-ground data fusion.

Four airborne roles

Airborne role	Key parameters	Representative instruments	Best platform characteristics
M1. Plume and cloud-base sampling	Sea-salt particle number and size; CCN spectrum; hygroscopicity; composition; plume dilution; fraction reaching cloud base; temperature, humidity, winds, turbulence and boundary-layer depth.	CPC and fast aerosol sizers; PCASP/UHSAS-class optical sizing; CCN counter; filter/sample chemistry; fast T/RH; 3-D gust probe; GPS/INS; optional lidar.	Agile low- to mid-tropospheric aircraft that can repeat cross-plume and stacked legs close to cloud base.
M2. Primary in-cloud microphysics	Cloud-droplet number and size; effective radius; spectral width; liquid-water content; drizzle and precipitation; entrainment; vertical velocity; cloud-base activation and any ice where relevant.	Cloud Droplet Probe or equivalent; cloud imaging/precipitation probes; hot-wire LWC; CAPS-class combined cloud probes; fast turbulence and thermodynamic package; aerosol/CCN instruments for below-cloud legs.	Cloud-penetrating aircraft with external probe mounts, good low-altitude handling, substantial cabin/power and repeatable flight control.
M3. Above-cloud	Up/down shortwave and	Broadband and spectral	Higher-altitude aircraft

Airborne role	Key parameters	Representative instruments	Best platform characteristics
radiation and remote sensing	longwave flux; spectral reflectance; cloud-top height; optical depth; cloud fraction; plume/cloud geometry; drizzle structure and aerosol layer height.	radiometers; multi-angle polarimeter/imager; HSRL/lidar; W/Ka-band cloud radar where available; microwave radiometer; precision GPS/INS.	able to remain above the cloud field for hours while the in-situ aircraft samples below.
M4. Wide-area context and control-region mapping	Mesoscale cloud organization; treated/control cloud fields; precipitation; inversion structure; background aerosol; large-scale winds and humidity; satellite-validation context.	Scanning radar/lidar; imagers; radiometers; dropsondes where useful; aerosol and meteorological suite.	Long-endurance aircraft with wide-area range, remote-sensing ports and reliable data links.

The central MCB causal chain

The aircraft program should be designed to close one sequence quantitatively: known source output -> particles surviving and reaching cloud base -> particles activating as cloud droplets -> changes in droplet spectra, liquid water, drizzle and cloud organization -> change in reflected shortwave radiation. A successful experiment should not rely on a bright satellite image alone. It should reconcile source metrology, cloud-base aerosol/CCN, in-cloud microphysics, cloud dynamics and radiation within a stated uncertainty budget.

For a cloud-response campaign, the primary aircraft should repeatedly fly below cloud, at cloud base, within cloud and near cloud top while following approximately the same air mass. A second aircraft should remain primarily above the cloud deck to measure radiation and remote-sensing structure. Drones can profile the plume between the ship and cloud base without forcing the main aircraft to spend all of its time on near-source sampling.

Illustrative current research-aircraft operators

Aircraft / operator	Illustrative capability	Best MCB role	Comment
NSF/NCAR C-130	Middle/lower troposphere; typical research configuration about 13,000 lb payload and 8-to-9-hour endurance.	Primary heavily instrumented in-cloud aircraft; cloud microphysics, turbulence, aerosol and precipitation.	Strong choice for the largest multi-instrument campaigns.
NSF / University of Wyoming King Air 350i	About 3-to-5-hour endurance, 2,100 nmi range, 33,000-35,000 ft ceiling and up to about 2,970 lbs. payload.	Agile primary or plume/cloud-base aircraft; cloud microphysics and radar/lidar work.	Attractive when a smaller, lower-cost aircraft can carry the required payload.

Aircraft / operator	Illustrative capability	Best MCB role	Comment
NSF/NCAR HIAPER Gulfstream V	About 10 hour endurance, 5,000 nmi range, 5,600 lb payload and altitude above 45,000 ft; optical ports and external mounts.	Above-cloud remote sensing, radiative closure, wider-area context and satellite underflights.	Better as aircraft #2 than as the default low-cloud penetration aircraft.
NOAA WP-3D Orion	Long-duration aircraft designed for severe-weather and atmospheric research, with Doppler/weather radar and dropsonde capability.	Mesoscale organization, precipitation, storm/cloud structure and large campaigns.	Especially useful when precipitation and organized weather are central.
NOAA Gulfstream IV-SP	High, fast, long-range platform; NOAA describes approximately 45,000 ft cruise altitude and 4,000 nmi range.	Wide-area meteorological context, dropsondes and remote sensing around cloud fields.	Less suited than C-130/King Air for routine in-cloud microphysics.
SAFIRE ATR42 (France)	Medium-troposphere research aircraft for chemistry, aerosol/cloud microphysics, remote sensing and turbulence; facility reports up to 9 scientists and about 2 tonnes of instruments.	International alternative for in-situ cloud and aerosol campaigns.	Useful for European/international replication and cross-platform comparison.

These organizations are research user facilities or government operators, not ordinary aircraft-rental suppliers. Access usually requires a scientific proposal, reimbursable agreement, cooperative arrangement or campaign task order. Availability, airworthiness and instrument compatibility should be verified for each campaign.

Airborne instrument suppliers and facility capabilities

Measurement	Illustrative instrument families / suppliers	MCB use
Aerosol number and size	TSI CPC/SMPS families; Droplet Measurement Technologies PCASP and related optical probes; facility fast aerosol instruments.	Quantify emitted and surviving particle distributions from nanometre to micrometre sizes.
Cloud condensation nuclei	Droplet Measurement Technologies CCN-100/200 or equivalent research CCN systems.	Measure which added/background particles activate at relevant supersaturations.
Cloud droplets, drizzle and liquid water	Droplet Measurement Technologies CDP, CIP/CAPS-class probes and hot-wire LWC; SPEC and research-facility probes where appropriate.	Measure droplet number, size, effective radius, precipitation development and liquid water.
Aerosol composition	Aerodyne AMS family for non-refractory aerosol plus filters/single-particle or elemental methods for sea-salt-specific Na/Cl and refractory material.	Separate injected sea salt from background aerosol and characterize organics/contaminants.
Cloud/aerosol vertical structure	NCAR, Wyoming, NOAA, NASA, DOE ARM and university HSRL/lidar and cloud-radar systems.	Map cloud top/base, plume height, drizzle and remote-sensing context.

Measurement	Illustrative instrument families / suppliers	MCB use
Radiation	Broadband SW/LW and spectral radiometers, polarimeters and calibrated imaging systems from facility/institutional teams.	Measure the actual radiative response rather than inferring it only from droplet changes.

A standard Aerodyne AMS is primarily a non-refractory aerosol composition instrument, so it should not be the only instrument used to quantify injected sea salt. The MCB program should explicitly include sodium/chloride or other sea-salt-specific measurements and characterize inlet transmission so that large hygroscopic or coarse particles are not silently lost before measurement.

What should be developed

- A modular MCB aerosol/cloud payload with standardized racks, power, cooling, timing, telemetry and data interfaces that can migrate among qualified aircraft.
- Characterized aerosol inlets and external probe installations with documented transmission versus particle size, humidity, airspeed and aircraft attitude.
- A cloud-response mission system that fuses the vessel source record, winds, trajectories, lidar/radar, aircraft observations, satellite imagery and control-region data into a real-time three-dimensional sampling display.
- A matched radiative-closure package for above-cloud, aircraft-level and surface measurements, with common calibration and high-rate attitude correction.
- Reusable cloud-microphysics and turbulence pallets, including droplet, drizzle, liquid-water and precipitation probes with cross-platform intercomparison procedures.
- Lightweight drone payloads for aerosol, CCN where practical, meteorology and vertical plume profiling between the ocean surface and cloud base.

A new purpose-built crewed airplane is not a five-year priority. The program should first exploit and improve existing research aircraft. A new aircraft becomes justified only if repeated campaigns demonstrate a persistent capability gap in low-altitude endurance, payload, external-probe accommodation, icing/severe-weather capability or operating cost that cannot be filled by existing facilities.

How this fits the existing $1B budget

The proposal already allocates $55M to shared aircraft, ships, drones, lidar, radar and instruments and includes aircraft/instrument integration and repeated primary/secondary-aircraft sortie blocks inside cloud-response campaigns. The aircraft chapter should therefore define the architecture and procurement requirements rather than add a new budget line. The program should use master agreements with aircraft facilities and prepriced integration, standby and replacement-sortie options so weather losses do not force emergency sole-source contracting.

Current-status note

Aircraft capabilities above are illustrative as of August 2026 and should be reverified before procurement. The former UK FAAM Airborne Laboratory is not a current provider: FAAM states that operational activity ended on March 31, 2026. International planning should therefore use currently operating facilities such as SAFIRE or other verified providers rather than treating the former FAAM BAe-146 as available.

The practical conclusion is that MCB aircraft are measurement platforms, not spray aircraft. The most valuable investment is a coordinated two-aircraft plus drone architecture that can measure the complete source-to-cloud-to-radiation chain repeatedly under treated and control conditions.