# Proposed $1B Global Climate Model Experimental Research Fund

By ChatGPT 5.6

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# What Is a Global Climate Model, and Why Improve It?

**Prompt to AI:** Explain why a major experimental research fund is needed to improve global climate models before deciding how much sunlight should be reflected (e.g., via SAI or MCB), from where, and when.

**Response From AI:**

A global climate model is a numerical representation of the atmosphere, oceans, land, sea ice and their interactions. It divides Earth into three-dimensional grid cells, calculates the movement of energy, water and momentum, and represents processes that occur below the grid scale through parameterizations. Modern Earth-system models also include atmospheric chemistry, aerosols, vegetation, the carbon cycle and other components.

These models are indispensable, but they are not perfect replicas of Earth. They reproduce many large-scale features and broad historical trends, yet important quantities still differ among models and from observations. The largest practical uncertainties for sunlight-reflection decisions include clouds, aerosol-cloud interactions, the preindustrial aerosol baseline, ocean heat uptake, regional precipitation, sea-ice feedbacks and circulation responses.

For ordinary climate projection, an ensemble of imperfect models can still provide useful risk information. A reflectivity program, however, would ask a more demanding control question:

> Given a proposed intervention, can we predict the resulting change in top-of-atmosphere radiation, global temperature, regional temperature gradients, precipitation, sea ice, ocean circulation and ecological risks with enough accuracy to choose a quantity, location and schedule?

That question cannot be answered by tuning a model to match global-mean temperature alone. Different combinations of cloud feedback, aerosol forcing, ocean heat uptake and natural variability can produce a similar temperature history. A model may appear correct because errors compensate. The research program must therefore test the physical links separately and jointly.

## The central scientific chain

The proposed program would connect observations to decisions through the following chain:

Energy entering Earth system → reflection by clouds, aerosols and the surface → absorption by the atmosphere and ocean → heat transport and storage → temperature and precipitation response → tipping-element and regional impacts → reflectivity control strategy

A reliable decision system must close the energy budget at the top of the atmosphere, explain where the energy goes, and reproduce how the climate responds over days, seasons, decades and centuries.

## Why observations alone are not enough

Measurements reveal what happened in the real atmosphere and ocean, but the historical record contains only one realization of climate and does not include a deliberate global sunlight-reflection program. Observations also contain sampling gaps and instrument discontinuities. Models are needed to separate causes, fill gaps, run counterfactual scenarios and estimate future outcomes. The goal is therefore not to replace models with observations; it is to use carefully designed experiments and observations to make models more physically constrained, independently testable and decision-ready.

## Why modeling alone is not enough

Model intercomparisons can identify robust behavior and disagreement, but models often share assumptions, parameterizations and training datasets. Agreement among related models is not the same as validation. The proposed fund would emphasize field campaigns, laboratory measurements, long-term observing systems, natural experiments and prospective predictions made before observations are revealed.

## What success would mean

The program would not claim that climate can be predicted perfectly. Success would mean that the dominant uncertainty sources are measured, bounded and propagated into decisions. A credible output would state, for example:

- How much additional reflected shortwave radiation is required to reduce a specified global warming rate, with an uncertainty range.
- How alternative latitude, season and geographic patterns affect regional temperature, precipitation and circulation.
- How much of the historical temperature trend is attributable to greenhouse gases, anthropogenic aerosols, natural variability and changes in ocean heat uptake.

- Whether an intervention designed to reduce one risk, such as extreme heat, increases another risk, such as regional drought or disruption of ocean circulation.
- Which observations would reveal early that the model prediction is failing and trigger adjustment or termination.

# Global Climate Model Experiments - $1B Fund

**Prompt to AI:** If a funding source wants to spend $1 billion over five years on experiments that improve global climate-model accuracy for sunlight-reflection decisions, what program should it consider?

**Response From AI:**

A $1 billion, five-year program should concentrate on the physical processes that most strongly limit estimates of Earth's energy imbalance, cloud and aerosol forcing, ocean heat uptake and regional climate response. It should combine measurements, controlled perturbations, natural experiments, laboratory work, high-resolution modeling and independent global-model evaluation.

The program should not be judged by the number of model runs or publications. It should be judged by whether it reduces uncertainty in a defined set of decision quantities: required radiative forcing, spatial and seasonal intervention pattern, temperature and precipitation response, ocean-circulation response, and the probability of crossing or avoiding major climate thresholds.

## Illustrative $1 billion portfolio

| Program | Five-year budget | Main purpose |
| --- | --- | --- |
| Area 1. Earth radiation budget and planetary-albedo benchmark | $100M | Measure and reconcile incoming and outgoing radiation, albedo trends and cloud radiative effects. |
| Area 2. Anthropogenic aerosol radiative-forcing closure | $175M | Measure direct and cloud-mediated reflection and absorption from pollution and its removal. |
| Area 3. Marine low-cloud and cloud-feedback experiments | $145M | Constrain subtropical low-cloud feedbacks and cloud susceptibility relevant to MCB. |
| Area 4. Mixed-phase, high-latitude cloud and surface-albedo experiments | $100M | Improve Arctic and Southern Ocean cloud, sea-ice and snow feedbacks. |
| Area 5. Deep convection, precipitation and tropical-organization experiments | $90M | Constrain convective aggregation, anvil clouds, humidity and rainfall response. |
| Area 6. AMOC, ocean heat uptake, freshwater and sea-ice observations | $120M | Measure circulation, mixing and thresholds that control heat uptake and AMOC risk. |

| Program | Five-year budget | Main purpose |
|---|---|---|
| Area 7. Rapid-response natural-perturbation program | $55M | Observe volcanic eruptions, wildfire smoke, shipping-fuel changes and major pollution shifts. |
| Area 8. Storm-resolving, large-eddy and process-model experiments | $70M | Translate observations into improved parameterizations and scale-aware physics. |
| Area 9. Model evaluation, data assimilation and uncertainty quantification | $55M | Run held-out tests, causal attribution, model weighting and decision-focused ensembles. |
| Area 10. Observing backbone, calibration and autonomous platforms | $45M | Maintain common radiometry, aircraft, ship, buoy, balloon and satellite-calibration systems. |
| Area 11. International participation, governance and open-data infrastructure | $25M | Support Global South leadership, independent review, engagement and permanent archives. |
| Area 12. Contingency and rapid-response reserve | $20M | Respond to rare events, failed instruments, ship or aircraft delays and unexpected findings. |
| Total | $1.000B | |

*These are order-of-magnitude planning estimates in 2026 dollars, not vendor quotations. Some facilities and satellite missions would be contributed through government or international agreements rather than conventional purchase orders.*

## Five-year sequence

| Period | Principal work |
|---|---|
| Year 1 | Governance, data audit, calibration, baseline models and campaign design. |
| Year 2 | Begin radiation, aerosol, low-cloud and AMOC campaigns; activate rapid response and prospective tests. |
| Year 3 | Major cloud, convection and aerosol campaigns; storm-resolving simulations and parameterization development. |
| Year 4 | Replicate contrasting regimes; test revised physics in multiple models; run reflectivity-control ensembles. |
| Year 5 | Independent replication, held-out validation, integrated energy-budget assessment and public decision-readiness report. Completion does not authorize deployment. |

## Program boundaries

The fund should explicitly prohibit:

- Any experiment intended to create detectable regional or global cooling.
- Using the climate-model program as an implicit authorization for SAI or MCB deployment.
- Tuning only to global-mean temperature while ignoring precipitation, radiation, ocean heat content or regional patterns.
- Withholding measurement data, model code or negative results for proprietary advantage.
- Treating agreement among models as validation when the models share parameterizations or calibration data.
- Continuing an expensive campaign after the decision-relevant uncertainty has already been resolved or the measurement cannot meet its required accuracy.

# Area 1. Earth Radiation Budget and Planetary-Albedo Benchmark - $100M

**Prompt to AI:** Describe a five-year, $100 million experimental program that establishes a decision-grade benchmark for Earth's radiation budget and planetary albedo.

**Response From AI:**

This chapter proposes a metrology-centered program for determining how much solar energy Earth reflects, how much infrared energy it emits, how the net imbalance changes through time, and which clouds, aerosols and surface changes cause the observed variations. Climate models reproduce many broad features of the energy budget, but sunlight-reflection decisions require a more demanding standard: the measured change in reflected shortwave radiation must be distinguishable from instrument drift, orbital sampling, cloud-regime shifts and changes in ocean heat uptake.

The program would not attempt to replace existing satellite missions. It would create a common calibration, validation and reconciliation system around them. The principal product would be a versioned global benchmark that links top-of-atmosphere fluxes to surface radiation, cloud properties, aerosol optical properties and ocean heat-content change, with uncertainty stated by region, season and timescale.

## Why this program is decision-critical

A reflectivity strategy is specified in watts per square metre, yet the quantity to be adjusted is not observed by one perfect instrument. Broadband radiometers measure outgoing flux, imagers classify clouds, polarimeters infer particle and droplet properties, surface networks measure downwelling and upwelling radiation, and the ocean integrates the remaining imbalance as heat. Each system has different sampling and calibration errors. A decision-grade benchmark must reconcile them rather than select whichever record best supports a preferred conclusion.

The program should answer two distinct questions. First, what is the present planetary energy imbalance and its trend? Second, what physical changes produced that trend: cloud amount, cloud optical depth, aerosol loading, snow and sea ice, water vapor, surface temperature or circulation? The second question matters because a model can match the net flux for the wrong reason. Such compensating errors would make estimates of required SAI or MCB forcing unreliable.

## Core scientific questions

- Can independent satellite and ocean records close the global energy budget within a predeclared uncertainty range?
- How rapidly is planetary albedo changing, and which cloud regimes, aerosol layers and surface regions account for the change?
- What calibration stability is required to detect a deliberate reflectivity change that is small relative to ordinary weather variability?
- Where do three-dimensional cloud effects, angular sampling and spectral assumptions bias broadband flux retrievals?
- Can models reproduce shortwave and longwave fluxes simultaneously without tuning away errors in cloud phase, humidity or surface albedo?
- Which observing variables provide the earliest reliable indication that a reflectivity intervention is producing a different forcing than predicted?

## Experimental portfolio

### A. Absolute radiometric calibration and cross-calibration

Establish a traceable calibration chain for broadband shortwave and longwave measurements. The work would combine laboratory standards, on-orbit calibration maneuvers, lunar and stellar observations, deep-space views, stable terrestrial targets and overlapping satellite records. Independent calibration teams would quantify instrument drift and produce correction histories rather than allowing each mission to define its own reference. Aircraft and high-altitude balloon radiometers would underfly selected satellite overpasses to test the entire measurement chain under known atmospheric conditions.

### B. Spectral and angular closure campaigns

Conduct repeated aircraft campaigns over representative scenes: clean ocean, marine stratocumulus, broken cumulus, desert, snow, sea ice, smoke above cloud and polluted continental boundary layers. Stacked flight legs above and below cloud would measure broadband and spectral flux, cloud geometry, aerosol extinction and surface reflectance. Multi-angle polarimetry and lidar would characterize the anisotropy and vertical structure that convert radiance into flux. The acceptance test would be whether measured scene properties predict the observed flux divergence within stated uncertainty.

### C. Surface-to-space energy-budget supersites

Upgrade a small network of marine, continental and high-latitude supersites with redundant shortwave and longwave radiometers, spectral instruments, radar, lidar, microwave radiometers, aerosol and cloud-condensation-nuclei measurements, radiosondes and surface-flux systems. The sites would provide continuous records for satellite validation and model process evaluation. At least one site should be located in a remote ocean regime and one in a high-albedo region where small cloud errors strongly affect the net flux.

### D. Ocean heat-content reconciliation

Use Argo, deep-Argo, hydrographic sections, satellite altimetry and ocean state estimation to compare the accumulated ocean heat gain with the top-of-atmosphere imbalance. The goal is not to force exact agreement by adjustment, but to identify where sampling gaps, deep-ocean uncertainty, freshwater effects or calibration offsets prevent closure. Independent teams would perform the reconciliation with different methods and publish the residual budget.

### E. Albedo attribution and benchmark dataset

Create a causal attribution system that decomposes reflected-shortwave changes by cloud regime, aerosol type, surface class, latitude and season. The dataset would preserve instrument-level uncertainty and sampling information rather than only providing monthly means. A protected subset of years and regions would be withheld from model developers so that revised models can be tested prospectively.

## Required measurements and products

| Measurement domain | Required observation | Decision use |
|---|---|---|
| Top of atmosphere | Broadband and spectral reflected shortwave, outgoing longwave and net flux | Defines the forcing that must be changed and detects intervention-scale anomalies. |
| Clouds | Fraction, optical depth, phase, top height, water path, droplet or ice properties | Attributes albedo changes and exposes compensating cloud errors. |
| Aerosols | Optical depth, absorption, size, composition, vertical profile and humidity growth | Separates aerosol reflection and absorption from cloud and surface effects. |

| Measurement domain | Required observation | Decision use |
| --- | --- | --- |
| Surface | Ocean state, snow and sea-ice albedo, vegetation, desert reflectance and emissivity | Closes the lower boundary and tracks high-latitude feedbacks. |
| Ocean heat | Heat content by basin and depth, steric change and air-sea flux | Independent integral check on the net planetary imbalance. |
| Calibration | Traceability, drift, overlap and uncertainty covariance | Determines whether apparent trends are physical or instrumental. |

## Five-year execution and budget

The first year would emphasize standards, data audits and observing-system simulations. Years two and three would conduct the principal closure campaigns and supersite upgrades. Year four would repeat the most informative cases under contrasting conditions. Year five would complete independent reconciliation and deliver a benchmark suitable for held-out model tests.

| Work package | Five-year allocation | Principal deliverable |
| --- | --- | --- |
| Radiometric standards and satellite cross-calibration | $22M | Traceable calibration chain and drift-corrected overlapping records. |
| Aircraft and balloon closure campaigns | $26M | Approximately 8–12 intensive deployments across key scene types. |
| Surface supersites and reference radiometers | $18M | Continuous surface-to-space closure datasets in diverse regimes. |
| Ocean heat-content reconciliation | $12M | Independent global and basin energy-budget assessments. |
| Albedo attribution, data engineering and benchmark archive | $14M | Versioned dataset, uncertainty model and protected validation cases. |
| Independent audit and contingency | $8M | Metrology audit, replication and replacement observations. |
| Total | $100M | |

## Deliverables and success criteria

- A public, version-controlled Earth energy-budget benchmark with raw, calibrated and derived products linked to provenance.
- A quantified trend in reflected shortwave radiation with regional, seasonal and instrument components of uncertainty.

- A cloud-regime and surface-regime attribution of albedo change that can be reproduced by independent teams.
- Prospective model tests showing whether revised models predict withheld flux and ocean-heat observations.
- Detection thresholds and monitoring requirements for identifying a specified SAI or MCB forcing anomaly.
- A documented residual budget that openly states where closure has not been achieved.

## Risks and boundaries

The main program risk is false precision. Combining many datasets can produce a narrow number while retaining shared calibration or retrieval assumptions. Therefore, uncertainty covariance, independent processing and disagreement among methods must be preserved. A second risk is optimizing only the global annual mean. The benchmark must retain regional and seasonal structure because intervention decisions depend on gradients and circulation.

No instrument or institution should be declared the reference by reputation alone. The reference should emerge from traceable standards, overlap, closure and independent audit. The program should publish negative closure results and should not adjust observations merely to make the energy budget agree.

# Area 2. Anthropogenic Aerosol Radiative-Forcing Closure - $175M

**Prompt to AI:** Describe a five-year, $175 million experimental program that measures the direct and cloud-mediated radiative forcing of anthropogenic air pollution.

**Response From AI:**

Anthropogenic aerosols cool and warm the climate through several pathways. Sulfate, nitrate, organics, black carbon, dust mixtures and industrial particles scatter or absorb sunlight; they also change cloud-droplet number, droplet size, precipitation, cloud water and cloud fraction. The net historical forcing is difficult to infer because emissions, meteorology and clouds change together and because the preindustrial aerosol baseline is poorly observed.

This program would build a chain of experiments from known emissions to aerosol properties, cloud response and measured radiative flux. It would combine regional gradients, policy-driven emissions changes, ship and industrial plumes, laboratory studies, satellite observations and carefully governed small perturbations only where natural variability cannot answer the question. The objective is not one global number obtained by statistical fitting. It is a physically decomposed forcing estimate that models can reproduce across regimes.

## Why this program is decision-critical

Historical aerosol cooling affects estimates of climate sensitivity, the warming rate expected as air pollution declines, and the amount of sunlight reflection that might be required to bend the temperature curve. If aerosol cooling has been stronger than assumed, future clean-air improvements could unmask more warming; if it has been weaker, models may be compensating with cloud or ocean errors. For MCB, the same aerosol-cloud physics determines whether added sea-salt particles brighten clouds or trigger adjustments that offset the initial effect.

The program should separate direct forcing from cloud-mediated forcing and rapid adjustments. It should also distinguish source sectors and particle types, because sulfur controls, black-carbon reductions, shipping rules and wildfire smoke do not produce interchangeable perturbations. Each flagship campaign should close the sequence: emissions or perturbation amount, plume transport and aging, aerosol optical properties, activation into cloud droplets, cloud macrophysical response, and shortwave and longwave flux change.

## Core scientific questions

- What is the radiative forcing per unit emission for major anthropogenic aerosol precursors and absorbing particles?
- How does aerosol hygroscopicity, mixing state and vertical placement change direct scattering and absorption?
- Under which cloud and meteorological regimes does added aerosol increase droplet number, suppress drizzle, thicken cloud, thin cloud or change cloud fraction?
- How much of observed aerosol-cloud correlation is causal rather than a response to shared meteorology?
- What forcing was present in the preindustrial atmosphere, and how sensitive is the historical forcing estimate to that baseline?
- Can multiple models reproduce the same measured plume-to-flux chain without regime-specific retuning?

## Experimental portfolio

### A. Regional pollution-gradient closure campaigns

Conduct paired campaigns in regions where polluted continental outflow transitions to cleaner marine air. Aircraft would sample upwind emissions, aging plumes, cloud inflow, in-cloud microphysics and above-cloud radiation while ships and surface stations measure boundary conditions. Repeated Lagrangian sampling would follow the same air mass for hours to days. Contrasting regions should include sulfate-dominated, carbonaceous, mixed industrial and biomass-burning environments.

### B. Shipping and industrial-plume natural experiments

Use shipping corridors, fuel-rule changes, port disruptions, power-plant closures and industrial operating schedules as quasi-controlled perturbations. The program would preregister expected plume locations and cloud regimes, acquire before-and-after satellite and aircraft observations, and use adjacent unaffected regions as controls. Ship tracks are valuable but should not be treated as globally representative; the work must identify the meteorological conditions under which visible tracks appear, disappear or produce surrounding cloud adjustments.

## C. Absorbing aerosol above cloud

Repeat and extend southeast Atlantic and other smoke-over-cloud campaigns with polarimetry, lidar, in-situ absorption, cloud probes and flux radiometers. The forcing sign depends on aerosol absorption, cloud brightness, layer separation and cloud response. The experiment should measure all four simultaneously and test whether satellite retrievals can distinguish absorption from cloud and surface effects.

## D. Cloud activation and drizzle-transition experiments

In clean and moderately polluted marine clouds, perform repeated stacked legs below cloud, at cloud base, in cloud and above cloud. Measure aerosol size and composition, cloud-condensation-nuclei spectra, cloud-base vertical velocity, droplet spectra, liquid water, drizzle and radiative flux. These observations would constrain activation functions and identify when additional particles cease to increase droplet number or begin to alter precipitation and entrainment.

## E. Metered perturbation option

Where natural experiments cannot establish causality, the program could consider small, independently governed releases of an environmentally acceptable tracer or sea-salt aerosol into a limited marine cloud field. The release would be designed to measure the plume-to-cloud-to-flux response, not to create regional cooling. It would proceed only after modeling, environmental review, public disclosure and a finding that the same question cannot be answered from existing emissions changes or observations.

## F. Preindustrial baseline and laboratory constraints

Combine ice-core and sediment proxies, remote-region measurements, emissions reconstruction, cloud-chamber studies and global aerosol modeling to constrain natural aerosol and nucleation. Laboratory work should determine optical properties, hygroscopic growth, cloud activation and ice-nucleating behavior for representative mixtures rather than idealized pure particles. The global forcing calculation should propagate uncertainty from the baseline instead of hiding it in model tuning.

## Measurement chain

| Link in causal chain | Minimum measurements | Closure test |
|---|---|---|
| Source and emissions | Mass, composition, timing, stack or ship conditions and co-emitted gases | Can the emitted aerosol and precursors be reconstructed independently? |
| Transport and aging | Wind, turbulence, chemistry, size distribution, mixing state and humidity growth | Does the model predict plume location and transformed particle properties? |
| Direct radiation | Extinction, scattering, absorption, single-scattering albedo and layer height | Do measured aerosol properties reproduce above- and below-layer flux changes? |
| Cloud activation | CCN spectrum, updraft distribution, droplet number and effective radius | Can activation be predicted from aerosol and dynamics? |
| Cloud adjustment | Liquid water, fraction, thickness, entrainment, drizzle and organization | Are persistence and precipitation responses causal and regime dependent? |
| Net forcing | Shortwave and longwave flux above and below cloud, plus satellite context | Does the complete measured state reproduce the observed radiative perturbation? |

## Five-year execution and budget

| Work package | Five-year allocation | Principal deliverable |
|---|---|---|
| Four regional pollution-gradient campaigns | $48M | Multi-regime plume, cloud and flux closure datasets. |
| Shipping, fuel-rule and industrial natural experiments | $28M | Before/after and matched-control forcing estimates. |
| Absorbing aerosol above-cloud campaigns | $22M | Constrained forcing sign and satellite retrieval validation. |
| Cloud activation, drizzle and adjustment experiments | $30M | Parameterizations and susceptibility curves across regimes. |
| Metered marine perturbation option | $15M | Governed causal test, exercised only if stage gates are met. |
| Preindustrial baseline, laboratory and synthesis work | $18M | Natural baseline distribution and particle-property database. |

| Work package | Five-year allocation | Principal deliverable |
|---|---|---|
| Independent replication, data systems and contingency | $14M | Blind model challenges, open archive and replacement operations. |
| Total | $175M | |

## Deliverables and success criteria

- A decomposed probability distribution for direct aerosol forcing and aerosol-cloud forcing by region, source class and cloud regime.
- Observed forcing efficiencies linked to emissions and particle properties rather than inferred solely from model residuals.
- Activation and cloud-adjustment relationships that improve held-out predictions in at least three structurally different models.
- A quantified preindustrial aerosol baseline with transparent proxy and model uncertainty.
- A public database of emissions events, plume observations, cloud response and radiative closure.
- Clear evidence showing which uncertainties remain irreducible without larger or longer observations.

## Risks and boundaries

Meteorology can create convincing but noncausal aerosol-cloud correlations. Every campaign should therefore use matched controls, Lagrangian sampling, causal designs and prospective model predictions. Another risk is selecting only visually obvious ship tracks or strong pollution episodes, which biases susceptibility upward. Sampling must include cases where added aerosol produces no visible track or where cloud adjustments offset the initial brightening.

Any deliberate perturbation must remain far below a scale intended to affect regional climate and must be optional, not a spending obligation. The program should not equate a narrower global forcing range with complete knowledge of regional health, precipitation or ecosystem effects.

# Area 3. Marine Low-Cloud and Cloud-Feedback Experiments - $145M

**Prompt to AI:** Describe a five-year, $145 million experimental program that improves the representation of marine low clouds, cloud feedback and MCB susceptibility in global climate models.

**Response From AI:**

Subtropical stratocumulus, trade cumulus and the transition between them exert strong control over planetary albedo. Their response to warming is a major source of uncertainty in climate sensitivity, and their response to additional cloud-condensation nuclei is central to marine cloud brightening. Global models cannot explicitly resolve many of the turbulent eddies, entrainment processes, drizzle cells and mesoscale organizations that determine cloud amount and reflectivity.

The proposed program would combine three flagship field campaigns, persistent ocean observing sites, large-eddy simulations, satellite retrieval evaluation and parameterization teams embedded in multiple global models. The goal is to predict cloud radiative response from measurable environmental conditions, not to derive one universal susceptibility number.

## Why this program is decision-critical

MCB effectiveness depends on whether added particles reach cloud base, activate into droplets and increase reflectivity without causing compensating changes in liquid water, entrainment, drizzle or cloud fraction. The same physical processes govern low-cloud feedback under greenhouse warming. A model that brightens clouds by prescribing droplet number but misrepresents boundary-layer dynamics may overstate both MCB cooling and ordinary climate feedback.

The program should therefore characterize a multidimensional response surface: cloud radiative effect as a function of aerosol, cloud-base updraft, inversion strength, free-tropospheric humidity, sea-surface temperature, surface flux, precipitation state and mesoscale organization. Observations must follow cloud systems through time because an initially brightened cloud can later thin, reorganize or dissipate.

## Core scientific questions

- What controls the transition among solid stratocumulus, open cells, closed cells, broken cumulus and clear sky?
- How do entrainment and free-tropospheric humidity change liquid water path and cloud fraction as the climate warms?
- How does cloud-base vertical-velocity variability control aerosol activation and droplet number?
- When does drizzle suppression increase cloud lifetime, and when do dynamical adjustments offset the Twomey brightening?
- How rapidly does a localized aerosol perturbation spread, dilute and interact with mesoscale circulation?
- Which variables can a global model use to predict susceptibility without resolving every turbulent eddy?

## Experimental portfolio

### A. Eastern-boundary stratocumulus campaign

Conduct an intensive campaign in a persistent stratocumulus deck using two research aircraft, a ship, autonomous surface vehicles and coordinated satellite overpasses. Flight stacks would sample sub-cloud aerosol, cloud-base activation, in-cloud droplet and drizzle spectra, cloud-top entrainment and above-cloud flux. Lagrangian sequences would follow the same cloud field from morning through afternoon and, where feasible, across multiple days. The campaign should intentionally sample clean, moderately polluted and high-aerosol conditions.

### B. Stratocumulus-to-cumulus transition campaign

Follow air masses moving from cool upwelling regions toward warmer open ocean. The transition reorganizes cloud fraction and may dominate regional albedo response. Aircraft and autonomous platforms would measure surface flux, inversion weakening, free-tropospheric humidity, drizzle, cold pools and mesoscale cellular organization. Models would be required to predict the location and timing of breakup before seeing the final observations.

### C. Trade-cumulus campaign

Study shallow cumulus in a region where cloud fields are sparse, rapidly evolving and strongly coupled to circulation. Dense radiosonde arrays, scanning radar, lidar, aircraft and surface flux measurements would constrain mass flux, cloud-core properties, detrainment and organization. This campaign is essential because MCB applied outside solid stratocumulus could have a smaller, more variable or even counterproductive response.

### D. Cloud susceptibility and metered-aerosol cases

First exploit natural aerosol gradients, ship plumes and changing wind direction to estimate susceptibility. If a controlled case passes governance gates, release a small metered sea-salt plume from a vessel and sample it with stacked aircraft legs and an adjacent control region. Measure delivery efficiency to cloud base, droplet response, drizzle, cloud water, cloud fraction and reflected flux. The test should distinguish immediate microphysical brightening from later dynamical adjustment.

### E. Persistent low-cloud observatories

Maintain at least two ocean or island supersites with cloud radar, lidar, microwave radiometry, broadband flux, aerosol and CCN instruments, precipitation sensors and regular soundings. Autonomous surface vehicles would extend observations along Lagrangian trajectories. These long records would place short campaigns in climatological context and provide independent cases for satellite and model evaluation.

### F. LES-to-global-model parameterization strike teams

For each flagship campaign, run ensembles of large-eddy simulations initialized with observed meteorology and aerosol. Teams would identify which processes explain observed cloud evolution, then develop scale-aware parameterizations for turbulence, entrainment, shallow convection, microphysics and precipitation. At least three global models would implement the changes and test them on withheld regimes. A change would not be accepted if it improves low-cloud radiation while degrading precipitation, circulation or energy conservation.

## Observation and modeling matrix

| Domain | Key variables | Purpose |
|---|---|---|
| Aerosol and activation | Size, composition, hygroscopicity, CCN spectrum and cloud-base updraft | Predict how many particles become droplets. |
| Cloud microphysics | Droplet number, effective radius, spectral width, liquid water and drizzle | Quantify immediate brightening and precipitation response. |

| Domain | Key variables | Purpose |
|---|---|---|
| Boundary-layer dynamics | Turbulence, inversion strength, entrainment, humidity and surface flux | Explain cloud thickness, breakup and persistence. |
| Mesoscale organization | Open/closed cells, cold pools, cloud fraction and spatial covariance | Determine whether local brightening changes surrounding cloud. |
| Radiation | Above- and below-cloud shortwave and longwave flux, spectral reflectance | Close the measured cloud state to radiative effect. |
| Model hierarchy | LES, regional storm-resolving and global models | Translate process understanding across scales. |

## Five-year execution and budget

| Work package | Five-year allocation | Principal deliverable |
|---|---|---|
| Eastern-boundary stratocumulus campaign | \$30M | Radiative and process closure in persistent low clouds. |
| Transition-zone campaign | \$24M | Observed and predicted cloud breakup and organization. |
| Trade-cumulus campaign | \$24M | Mass-flux, organization and radiative-response constraints. |
| Susceptibility and optional metered-aerosol cases | \$18M | Causal response curves and delivery-efficiency measurements. |
| Persistent observatories and autonomous platforms | \$18M | Multi-year regime statistics and satellite validation. |
| LES, parameterization and global-model implementation | \$23M | Tested scale-aware physics in multiple models. |
| Independent replication and contingency | \$8M | Held-out evaluations, audit and replacement operations. |
| Total | \$145M | |

## Deliverables and success criteria

- Cloud-susceptibility distributions conditioned on meteorology and regime, not one global constant.
- Observed closure from aerosol and dynamics through droplet response, cloud adjustment and reflected flux.

- LES cases and forcing files that independent groups can reproduce.
- Global-model improvements that predict withheld low-cloud regimes and preserve other climate metrics.
- A practical map of where MCB is likely to be effective, ineffective or unusually uncertain.
- Monitoring variables that indicate when a brightening operation is departing from the predicted response.

## Risks and boundaries

Short campaigns can mistake weather sampling for climate feedback. The program must combine intensive process observations with multi-year statistics and repeated regimes. A second risk is designing experiments around conditions most favorable to MCB. Site selection should include marginal and unfavorable regimes so that the resulting model does not extrapolate optimistic cases globally.

Any aerosol release should be small, temporary and scientifically justified. The program should not test regional cooling, should not develop deployment-scale spray systems, and should report cases in which cloud response is weak, negative or dominated by dynamical adjustment.

# Area 4. Mixed-Phase, High-Latitude Cloud and Surface-Albedo Experiments - $100M

**Prompt to AI:** Describe a five-year, $100 million experimental program for mixed-phase clouds, high-latitude radiation, sea ice, snow and surface-albedo feedbacks.

**Response From AI:**

High-latitude climate is governed by tightly coupled cloud, radiation, sea-ice, snow, ocean and boundary-layer processes. Mixed-phase clouds can contain supercooled liquid water and ice for long periods, yet models differ in how quickly they glaciate, precipitate and dissipate. These differences contribute to persistent shortwave and longwave radiation biases over the Southern Ocean and Arctic and can be masked by compensating errors in surface albedo or heat transport.

The proposed program would observe the coupled column rather than treating cloud and surface as separate topics. It would combine aircraft and ship campaigns, year-round supersites, ice-tethered and autonomous platforms, laboratory ice-nucleation work, satellite validation and coupled model experiments. The output would improve both ordinary climate projections and estimates of how sunlight reflection interacts with polar amplification and AMOC-related risks.

## Why this program is decision-critical

A reflectivity intervention may cool the globe while producing different high-latitude responses depending on season, cloud phase and surface state. Additional reflected sunlight has little direct effect during polar night, but summer cooling can alter melt, snow cover and ocean stratification. Cloud longwave warming can dominate in winter, while cloud shortwave cooling dominates over dark open water in summer. Models must capture these sign changes to evaluate targeted strategies.

Southern Ocean cloud errors also influence the amount of sunlight absorbed by the ocean and therefore affect heat uptake, circulation and climate sensitivity. Correcting the top-of-atmosphere shortwave bias by artificially changing surface albedo or cloud amount can yield the right global temperature for the wrong reason. The program should require simultaneous closure of cloud phase, precipitation, surface radiation and ocean response.

## Core scientific questions

- What maintains supercooled liquid water in mixed-phase clouds, and what triggers glaciation or precipitation?
- How do ice-nucleating particles, secondary ice production, turbulence and aerosol removal affect cloud lifetime?
- How do cloud errors interact with sea-ice concentration, thickness, snow cover and melt ponds?
- What is the seasonal net cloud radiative effect over open ocean, marginal ice zones, pack ice and snow-covered land?
- How do Southern Ocean frontal systems and cold-air outbreaks organize cloud and precipitation?
- Can coupled models reproduce radiation, cloud phase and surface energy balance without compensating errors?

## Experimental portfolio

### A. Southern Ocean frontal and cold-air-outbreak campaign

Operate a research vessel and one or two aircraft across frontal zones and post-frontal cold-air outbreaks. Measure cloud phase, supercooled liquid, ice number and habit, precipitation, aerosol and ice-nucleating particles, surface fluxes and above-cloud radiation. Repeat transects through comparable meteorological structures to separate systematic model errors from case-to-case variability. Satellite underflights would evaluate cloud-phase and radiation retrievals in conditions where passive sensors often struggle.

### B. Arctic seasonal transition campaign

Conduct coordinated observations during spring melt onset, summer open water and autumn freeze-up. Aircraft, ice-tethered buoys, autonomous surface vehicles, radar, lidar and frequent soundings would measure boundary-layer structure, cloud phase, radiation, sea-ice state and ocean heat flux. The campaign should follow the same region through transitions rather than sampling one season in isolation.

### C. Year-round polar supersites

Strengthen at least two long-duration sites, one Arctic and one Southern Ocean or Antarctic, with redundant cloud radar and lidar, microwave radiometers, broadband and spectral flux instruments, aerosol and ice-nucleating-particle measurements and surface energy-budget systems. The sites would provide statistics on cloud persistence, phase occurrence and radiative sign by season and surface type.

### D. Ice-nucleation and microphysics laboratory program

Collect representative sea spray, mineral dust, biological particles and mixed aerosols from field sites and test them in chambers spanning relevant temperature, humidity and cloud-processing histories. The work would evaluate primary and secondary ice production, riming, aggregation and aerosol scavenging. Parameterizations should be tested against observed cloud evolution, not only laboratory freezing spectra.

### E. Coupled cloud-sea-ice-ocean process experiments

Use local and regional coupled models to test how cloud radiative errors alter melt ponds, snow persistence, upper-ocean stratification and ice formation. Observed surface heat budgets would constrain the models. Perturbation experiments would separate the effects of cloud phase, precipitation, ocean mixing and surface albedo. Results would then be implemented in multiple global models and evaluated on withheld seasons and regions.

## Measurement matrix

| Component | Required measurements | Model constraint |
|---|---|---|
| Cloud phase and microphysics | Liquid and ice water, droplet and crystal spectra, habits, temperature and vertical velocity | Persistence, glaciation, precipitation and optical properties. |
| Aerosol and INP | Number, size, composition, ice-nucleating activity and scavenging | Aerosol control of mixed-phase cloud lifetime. |
| Radiation | Surface and above-cloud SW/LW flux, spectral albedo and cloud radiative effect | Seasonal energy-budget closure. |
| Surface state | Sea-ice concentration/thickness, snow depth, melt ponds, ocean temperature and waves | Albedo and conductive/latent heat feedbacks. |
| Boundary layer | Turbulence, inversions, humidity, surface flux and advection | Cloud maintenance and coupling to surface. |
| Precipitation | Snowfall, drizzle, radar Doppler velocity and accumulation | Water removal and cloud adjustment. |

## Five-year execution and budget

| Work package | Five-year allocation | Principal deliverable |
|---|---|---|
| Southern Ocean campaign | $26M | Frontal and cold-air-outbreak cloud/radiation closure. |
| Arctic seasonal transition campaign | $22M | Coupled melt, open-water and freeze-up observations. |
| Year-round polar supersites | $18M | Multi-season cloud-phase and surface-energy records. |
| Laboratory ice-nucleation and microphysics | $10M | Field-linked microphysical parameterizations. |
| Coupled process and global-model experiments | $16M | Reduced Southern Ocean and Arctic radiation biases without compensation. |
| Independent validation and contingency | $8M | Satellite validation, blind tests and replacement operations. |
| Total | $100M | |

## Deliverables and success criteria

- Seasonal cloud-phase and radiative-effect benchmarks over major polar surface regimes.
- Field-tested parameterizations for mixed-phase persistence, ice formation and precipitation.
- A closed surface energy budget linking cloud, snow, sea ice and upper-ocean heat.
- Reduced Southern Ocean shortwave bias and Arctic seasonal radiation bias in held-out tests.
- Quantified sensitivity of polar amplification and sea-ice response to alternative reflectivity patterns.
- Clear attribution of remaining model disagreement to observable processes.

## Risks and boundaries

Polar field work is vulnerable to weather, icing, darkness, sea-ice hazards and limited aircraft or ship availability. The program should use redundant platforms, multi-year windows and contingency sites. It should not interpret a single unusual season as a representative climate response.

The program must avoid tuning cloud phase solely to improve top-of-atmosphere radiation. Improvements must also reproduce precipitation, boundary-layer structure, surface flux and sea-ice evolution. It should distinguish research on climate response from any proposal to deliberately alter polar clouds or ice.

# Area 5. Deep Convection, Precipitation and Tropical-Organization Experiments - $90M

**Prompt to AI:** Describe a five-year, $90 million experimental program that improves deep convection, tropical organization, precipitation and hydrological response in global climate models.

**Response From AI:**

Deep convection transports heat, water, momentum and trace gases through the tropical atmosphere. It creates anvils, cold pools and organized storm systems that affect both reflected sunlight and outgoing infrared radiation. Most global models still represent important convective processes through parameterizations, and even kilometre-scale models require uncertain microphysics and turbulence assumptions.

This program would observe tropical convection as an evolving system from initiation through organization, anvil production and precipitation. It would pair field campaigns with convection-permitting regional and global simulations, water-budget closure and prospective prediction challenges. The objective is to improve estimates of regional rainfall and circulation response to both greenhouse forcing and spatially patterned sunlight reflection.

## Why this program is decision-critical

Solar forcing and greenhouse forcing do not affect the hydrological cycle identically. A reflectivity intervention that restores global-mean temperature can still alter evaporation, precipitation, monsoons and the position of the intertropical convergence zone. These changes depend on how convection responds to surface flux, atmospheric stability, humidity and temperature gradients. A model that is adequate for global temperature may therefore be inadequate for rainfall and regional risk.

The program should connect local convective physics to large-scale circulation. It must measure the distribution of storm sizes, lifetimes and organization rather than only average rain. Anvil-cloud radiative effects, convective aggregation and cold-pool interactions can feed back on the environment and affect the sensitivity of the tropical atmosphere to forcing.

## Core scientific questions

- What environmental conditions control convective initiation, inhibition and transition to deep storms?
- How do cold pools, boundary-layer moisture and mesoscale circulations organize convection?
- What controls anvil area, ice microphysics, lifetime and net shortwave/longwave effect?
- How does convective aggregation change humidity, radiation and precipitation efficiency?
- Can models close column water and energy budgets during active and suppressed periods?
- How do alternative latitude and seasonal patterns of sunlight reflection shift monsoons and tropical rain belts?

## Experimental portfolio

### A. Tropical ocean convection campaign

Deploy a research vessel, aircraft, radar network, autonomous surface vehicles and dense radiosondes in a tropical ocean region that samples suppressed, developing and organized convection. Aircraft would measure boundary-layer moisture, cloud microphysics, anvil outflow and radiative flux. Doppler radar and satellite observations would map storm populations and mesoscale organization. The campaign should last long enough to capture multiple large-scale environmental states.

### B. Continental monsoon and land-convection campaign

Conduct a complementary campaign in a monsoon or tropical continental region where surface heterogeneity, aerosols and orography affect initiation and precipitation. Measure soil moisture, surface flux, boundary-layer growth, aerosol, updrafts, lightning, precipitation microphysics and cold pools. The comparison with the ocean campaign would test whether parameterizations transfer across fundamentally different environments.

### C. Anvil-cloud and upper-tropospheric humidity experiment

Use high-altitude aircraft and satellite underflights to measure anvil ice, particle size and habit, cloud-top temperature, outflow humidity and broadband radiation. Track anvils after convective cores decay to determine lifetime and radiative effect. Models would predict anvil coverage and humidity evolution using only the observed large-scale environment and convective history.

### D. Convective organization and cold-pool arrays

Create temporary dense arrays of scanning radar, surface meteorology, disdrometers, microwave radiometers and unmanned systems to resolve cold-pool propagation and storm interactions. The goal is to derive observable organization metrics that can be used to evaluate kilometre-scale models and inform coarser parameterizations.

### E. Storm-resolving model intercomparison

Run coordinated regional and global storm-resolving simulations at multiple grid spacings using standardized initial conditions and observations. Require teams to submit predictions before selected periods are released. Diagnose whether differences arise from dynamics, microphysics, turbulence, radiation or surface coupling. Parameterization teams would then test reduced representations in conventional global models.

### F. Reflectivity-pattern hydrology experiments

Use validated models to compare uniform solar reduction with latitude-, hemisphere- and season-dependent forcing patterns. Analyze monsoon rainfall, ITCZ position, tropical cyclone environment, drought and extreme precipitation. The program should present probability distributions and model disagreement, not select a single optimal pattern from one model.

## Measurement and closure framework

| Process | Measurements | Closure objective |
|---|---|---|
| Initiation | Profiles of temperature/humidity, inhibition, surface flux, aerosol and boundary-layer convergence | Predict when and where convection begins. |
| Dynamics and organization | 3-D winds, cold pools, updrafts, mesoscale circulations and storm tracking | Predict storm size, lifetime and aggregation. |
| Microphysics | Liquid/ice spectra, mixed-phase processes, precipitation and latent heating | Predict rain efficiency and anvil production. |
| Radiation | Anvil optical properties, SW/LW flux and upper-tropospheric humidity | Close convective radiative effect. |

| Process | Measurements | Closure objective |
| --- | --- | --- |
| Water and energy budgets | Moisture convergence, evaporation, storage, precipitation and radiative/sensible flux | Test conservation and hydrological sensitivity. |
| Large-scale response | Monsoon indices, ITCZ, circulation and extremes | Translate process improvements to regional risk. |

## Five-year execution and budget

| Work package | Five-year allocation | Principal deliverable |
| --- | --- | --- |
| Tropical ocean campaign | \$22M | Full life-cycle convection and water-budget dataset. |
| Continental monsoon campaign | \$18M | Land-aerosol-convection and precipitation constraints. |
| Anvil and upper-troposphere experiment | \$12M | Anvil lifetime, humidity and radiative closure. |
| Cold-pool and organization arrays | \$10M | Observed organization metrics and process statistics. |
| Storm-resolving intercomparison and parameterization | \$18M | Prospective simulations and transferable physics. |
| Reflectivity-pattern hydrology ensembles | \$6M | Regional precipitation tradeoff distributions. |
| Independent validation and contingency | \$4M | Audit, held-out tests and weather reserve. |
| Total | \$90M | |

## Deliverables and success criteria

- Observed convective life-cycle cases with closed water, energy and radiative budgets.
- Metrics for initiation, organization, anvil response and precipitation efficiency that models can predict prospectively.
- Improved storm statistics and tropical rainfall in multiple model frameworks without degrading global energy balance.
- Quantified hydrological differences between greenhouse warming and alternative sunlight-reflection patterns.
- Regional monsoon and ITCZ uncertainty distributions suitable for governance and risk evaluation.
- Open simulation outputs, forcing files and diagnostics that allow independent reproduction.

## Risks and boundaries

Convection is noisy and field campaigns can miss the intended regime. Observing-system simulations, long deployment windows and multiple regions are necessary. The program should not claim that kilometre-scale resolution automatically produces truth; microphysics, turbulence and surface coupling remain uncertain.

A model improvement should be rejected if it matches rainfall by violating energy or water conservation or by compensating errors in cloud radiation. Reflectivity-pattern experiments should be framed as sensitivity analysis, not as authorization to manipulate monsoons or tropical circulation.

# Area 6. AMOC, Ocean Heat Uptake, Freshwater and Sea-Ice Observations - $120M

**Prompt to AI:** Describe a five-year, $120 million experimental program that reduces uncertainty in AMOC behavior, ocean heat uptake, freshwater pathways and sea-ice coupling.

**Response From AI:**

The ocean stores most of the excess heat associated with Earth's energy imbalance and redistributes heat and freshwater through currents and mixing. The Atlantic Meridional Overturning Circulation influences North Atlantic climate, sea level, ecosystems and atmospheric circulation. Its future behavior depends on processes that are incompletely observed: deep-water formation, boundary currents, overflows, interior mixing, freshwater storage and export, Greenland meltwater pathways and remote Southern Ocean changes.

This program would strengthen existing observing arrays rather than replace them. It would add targeted measurements in formation, overflow and freshwater-control regions, expand autonomous coverage, conduct process experiments and assimilate the results into multiple ocean and coupled models. The objective is to connect observable warning indicators to physically plausible AMOC responses and to determine how alternative reflectivity patterns affect ocean heat and freshwater forcing.

## Why this program is decision-critical

A sunlight-reflection strategy could reduce surface warming quickly while the deep ocean retains heat accumulated over decades. The spatial pattern of cooling may alter air-sea heat loss, sea ice, precipitation and freshwater transport. These effects could strengthen or weaken particular components of overturning even if global-mean temperature is held fixed. Models therefore need a correct ocean state and credible process sensitivity, not merely a global surface-temperature target.

Claims about preventing or causing an AMOC collapse are currently much less certain than global temperature response. A five-year program cannot observe a century-scale tipping event, but it can reduce uncertainty in present transports, freshwater feedbacks, mixing and model drift. It can also establish which measurements would reveal movement toward dangerous states and how quickly an intervention could be adjusted.

## Core scientific questions

- What are the mean, variability and uncertainty of overturning, heat and freshwater transports across key Atlantic sections?
- Which regions and processes control deep-water formation and the transformation of water masses?
- How do boundary currents, overflows, eddies and interior mixing transmit anomalies?
- Where does Greenland and Arctic freshwater travel, mix and accumulate?
- How much ocean heat uptake occurs by basin and depth, and which processes set the uptake efficiency?
- Which observable indicators distinguish temporary variability from a persistent weakening or threshold approach?
- How do different spatial and seasonal reflectivity patterns alter air-sea flux, freshwater and overturning in multiple models?

## Experimental portfolio

### A. Enhanced trans-basin transport arrays

Add targeted moorings, bottom-pressure instruments, gliders and repeat hydrography to existing subtropical and subpolar observing systems. Measurements should resolve boundary currents, interior geostrophic transport, Ekman transport, heat and freshwater flux. Common calibration and processing would allow independent estimates and identify structural differences among array methods.

### B. Deep-water formation and overflow process studies

Conduct winter and shoulder-season observations in key convection and overflow regions using ships, gliders, profiling floats, moorings and turbulence instruments. Measure surface heat loss, restratification, mixed-layer depth, water-mass transformation, entrainment and overflow mixing. Tracer-release or deliberate inert-tracer studies could be considered where they provide unique mixing constraints and pass environmental review.

### C. Greenland and Arctic freshwater pathways

Deploy autonomous platforms and shelf-to-basin sections to trace meltwater, river input, sea-ice melt and freshwater storage. Use salinity, oxygen isotopes or other tracers, velocity, sea-surface height and hydrographic structure to distinguish sources and pathways. The goal is to determine how much freshwater reaches sensitive formation regions, on what timescale and through which boundary currents or interior routes.

### D. Ocean heat-content and abyssal uptake

Expand deep-Argo and repeat full-depth hydrography in regions that dominate deep heat uptake and uncertainty. Combine these observations with altimetry, gravimetry and air-sea flux products. Independent state-estimation teams would close basin heat budgets and quantify the residual between observed heat storage and modeled transport and mixing.

### E. Sea-ice-ocean coupling

Observe ice concentration, thickness, drift, snow, brine rejection, upper-ocean stratification and air-sea flux in the Labrador, Nordic and Arctic gateways. These measurements would constrain how changing ice cover affects winter heat loss and freshwater input. Coupled process models would test whether cloud and surface-radiation biases are contaminating AMOC sensitivity.

### F. Initialized prediction and threshold experiments

Assimilate observations into several ocean and coupled models and issue seasonal-to-decadal predictions before later observations are available. Perform standardized freshwater, heat-flux and wind perturbations to diagnose feedbacks and threshold behavior. The purpose is not to assign a single collapse date, but to identify robust mechanisms, model-dependent assumptions and monitoring variables.

## Observing system and model links

| Domain | Measurements | Decision relevance |
|---|---|---|
| Overturning and transport | Velocity, density, pressure, wind and hydrographic sections | Current AMOC strength, variability and heat/freshwater transport. |
| Formation and mixing | Surface flux, mixed layers, turbulence, tracers and water-mass transformation | Sensitivity of dense-water production and overflow. |
| Freshwater | Salinity, source tracers, sea-ice export, meltwater and river inputs | Location and timing of freshwater forcing. |

| Domain | Measurements | Decision relevance |
|---|---|---|
| Heat uptake | Full-depth temperature, steric change, air-sea flux and state estimates | Ocean commitment and delayed response after surface cooling. |
| Sea ice | Thickness, concentration, snow, drift and brine processes | Coupling among radiation, freshwater and winter heat loss. |
| Prediction | Initialized ensembles and standardized perturbations | Early-warning skill and intervention-pattern sensitivity. |

## Five-year execution and budget

| Work package | Five-year allocation | Principal deliverable |
|---|---|---|
| Enhanced transport arrays and repeat sections | $30M | Improved AMOC, heat and freshwater transport estimates. |
| Formation, overflow and mixing process studies | $24M | Field-constrained transformation and mixing physics. |
| Greenland and Arctic freshwater pathways | $18M | Source-attributed freshwater budgets and transit times. |
| Deep-ocean heat uptake and deep-Argo | $18M | Basin/depth heat-budget closure. |
| Sea-ice-ocean coupling observations | $10M | Winter flux and freshwater coupling constraints. |
| Assimilation, prediction and threshold experiments | $14M | Prospective forecasts and standardized sensitivity ensembles. |
| Independent audit and contingency | $6M | Sensor loss reserve, calibration and replication. |
| Total | $120M | |

## Deliverables and success criteria

- A reconciled, uncertainty-qualified estimate of AMOC, heat and freshwater transports across key sections.
- Improved parameterizations for overflow, mixing, restratification and water-mass transformation validated against process data.
- A source-to-basin map of Greenland and Arctic freshwater pathways and timescales.
- Closed basin and depth-resolved ocean heat budgets connected to top-of-atmosphere energy imbalance.

- Prospective initialized forecasts and documented skill limits.
- A set of observable AMOC risk indicators tied to model mechanisms rather than simple trend extrapolation.
- Multi-model sensitivity of AMOC and ocean heat uptake to alternative reflectivity patterns.

## Risks and boundaries

Five years is short relative to low-frequency ocean variability, and severe conditions can cause instrument loss or sampling gaps. The program should use long-lived arrays, historical records and state estimation to place process campaigns in context. It should publish uncertainty and avoid interpreting one temporary weakening as evidence of an approaching collapse.

The program cannot guarantee that a particular reflectivity strategy would prevent an AMOC tipping event. Its proper outcome is narrower process uncertainty, better monitoring and clearer model disagreement. Any claimed prevention benefit should be presented probabilistically and alongside regional precipitation, sea-ice and termination risks.

# Area 7. Rapid-Response Natural-Perturbation Program - $55M

**Prompt to AI:** Describe a five-year, $55 million rapid-response program that studies natural and policy-driven atmospheric and ocean perturbations before their information is lost.

**Response From AI:**

Rare events often create stronger and more revealing perturbations than deliberate climate experiments could ethically produce. Volcanic eruptions inject sulfur and ash, wildfire smoke can reach the upper troposphere or stratosphere, abrupt emissions changes alter aerosol and cloud properties, and exceptional ocean or sea-ice events expose mixing and feedback processes. The scientific value is frequently lost because aircraft, instruments, permits, data agreements and teams are not ready when the event occurs.

This program would maintain a standing capability that can move from detection to measurement within days or weeks. It would fund readiness, not only deployments. Preapproved protocols, modular payloads, satellite tasking, balloon kits, autonomous platforms, model forecast teams and reserve agreements with aircraft and ships would allow the program to observe an event from its initial state through chemical, microphysical and climate evolution.

## Why this program is decision-critical

Natural perturbations provide scale tests for climate models. Volcanic aerosols test stratospheric transport, particle growth, radiation and temperature response. Wildfire smoke tests absorbing aerosol, cloud interaction and long residence times. Shipping-fuel changes and industrial shutdowns provide quasi-experiments for anthropogenic aerosol forcing. Extreme freshwater, convection or sea-ice events test ocean and cloud parameterizations under conditions outside the calibration mean.

Rapid response also supports prospective prediction. A model team can issue forecasts immediately after an event using only early observations, then compare them with later measurements. This is a stronger validation than explaining the event after all data are known. The program should preserve unsuccessful forecasts and missed deployments because they reveal observing and model limitations.

## Event classes and activation criteria

- Volcanic eruptions with material reaching the upper troposphere or stratosphere.
- Pyroconvective wildfire events that produce long-lived smoke layers.
- Large dust, pollution or biomass-burning episodes with unusual vertical placement or cloud interaction.
- Major shipping, fuel-standard, plant-closure or transport disruptions that create a measurable emissions discontinuity.
- Exceptional cloud-regime transitions, marine heat waves, sea-ice loss or freshwater anomalies.
- Instrument or satellite opportunities that provide a unique overlap or calibration event.

## Operational architecture

### A. Standing event-detection and triage center

Maintain automated monitoring of satellite aerosol, fire, cloud, radiation, ocean and sea-ice products; volcano and emissions alerts; and model forecasts. A rotating scientific duty team would score events against preregistered criteria: uniqueness, expected information value, observability, safety, cost and relevance to program uncertainties. Activation should require documented approval, but the process must be fast enough to capture early evolution.

### B. Modular aircraft and balloon payloads

Keep a core set of calibrated instruments in deployable modules: particle size and composition, SO2 and trace gases, ozone, water vapor, radiation, lidar, cloud probes and meteorology. Maintain balloon packages for aerosol, ozone and water vapor profiles and agreements with operators for launches from multiple latitudes. Instrument teams would perform regular readiness exercises so that a nominally available payload is actually flight ready.

### C. Satellite tasking and ground networks

Establish advance agreements for rapid satellite observations where tasking is possible and rapid processing of routine sensors. Coordinate surface sun photometers, lidars, radiation sites, radar and air-quality networks along predicted transport paths. Common formats and near-real-time quality control would allow daily assimilation and flight planning.

### D. Ocean and cryosphere response kits

Maintain autonomous floats, gliders, surface vehicles, expendable profilers and mooring spares that can be deployed during unusual freshwater, mixing, heat-content or sea-ice events. These assets would complement atmospheric deployments and help determine whether an event changes ocean heat uptake or surface coupling.

### E. Prospective model challenge

Within a specified time after activation, independent model teams would archive predictions of plume transport, aerosol evolution, radiative forcing, cloud response or ocean evolution. Later observations would remain withheld until predictions are fixed. The comparison would diagnose which model components failed and whether new observations improve forecasts.

### F. Event archive and synthesis

Each event would receive a complete package: initial conditions, measurement plan, raw and calibrated data, model forecasts, uncertainty, operational lessons and a final report. Cross-event synthesis would identify which parameterizations generalize across volcanoes, wildfire smoke, pollution changes and other perturbations.

## Readiness levels

| Readiness element | Requirement before an event | Activation deliverable |
|---|---|---|
| Governance and permits | Preapproved protocols, contacts and decision authority | Documented event-specific authorization. |
| Platforms | Framework agreements and availability windows | Confirmed aircraft, ship, balloon or autonomous assets. |
| Instruments | Calibrated modular payloads and spares | Flight-ready configuration and uncertainty record. |
| Forecasting | Operational trajectories and data-assimilation pipelines | Daily event-location and sampling products. |
| Data | Common formats, repositories and rapid QC | Open preliminary data and metadata on a fixed schedule. |
| Model validation | Registered teams and protected observations | Archived prospective predictions and later scorecard. |

## Five-year budget

| Work package | Five-year allocation | Principal deliverable |
|---|---|---|
| Standing center, readiness exercises and permits | $10M | Continuous event triage and annual deployment rehearsals. |
| Aircraft and instrument availability reserve | $16M | Rapid access to calibrated airborne measurements. |
| Balloon, lidar and surface-network reserve | $7M | Distributed vertical and transport observations. |
| Satellite processing and data assimilation | $6M | Near-real-time event products and targeting. |
| Ocean and cryosphere response assets | $5M | Autonomous deployment capability. |
| Prospective model challenges and archive | $6M | Forecast scorecards and permanent event datasets. |
| Unallocated event contingency | $5M | Additional flights, ship days or instrument replacement. |
| Total | $55M | |

## Deliverables and success criteria

- A documented ability to deploy a useful first measurement package within the event-specific scientific window.
- At least several fully observed natural or policy perturbations, while recognizing that event occurrence cannot be guaranteed.
- Prospective model predictions archived before the mature observations are released.
- Measured evolution from source through transport, chemistry or mixing to radiative or climate effect.
- Open event archives that can be reused by modeling groups worldwide.
- A readiness assessment showing which missing platforms or agreements prevented successful response.

## Risks and boundaries

The program may experience years with few qualifying events, followed by several simultaneous events. Funds should therefore be held in reserve and not spent merely to meet an annual target. Scientific triage must prevent deployment to spectacular but low-information events.

Rapid response does not waive environmental, aviation, safety or international requirements. The program would observe naturally occurring or independently caused events; it would not create a large perturbation to ensure that the reserve is used. Any small deliberate component would be governed under the relevant experiment program, not activated through an emergency shortcut.

# Area 8. Storm-Resolving, Large-Eddy and Process-Model Experiments - $70M

**Prompt to AI:** Describe a five-year, $70 million modeling-experiment program that converts field observations into improved, scale-aware physics for global climate models.

**Response From AI:**

Field observations do not automatically improve global models. Measurements are local and intermittent, while global models operate on grid cells far larger than individual clouds, plumes, eddies and turbulent layers. A hierarchy of models is needed to connect scales: laboratory and parcel models, plume and aerosol microphysics, large-eddy simulations, cloud-resolving regional models, global storm-resolving models and conventional Earth-system models.

This program would treat high-resolution simulations as experiments with preregistered hypotheses, controlled perturbations and validation data. Its purpose is not to produce the largest possible simulation. It is to identify which unresolved processes control decision-relevant responses and to create parameterizations that work across grid spacing, climate state and intervention scenario.

## Why this program is decision-critical

The amount of reflected sunlight required from SAI or MCB depends on processes that begin at centimetre-to-kilometre scales: particle formation, plume dilution, aerosol activation, cloud turbulence, drizzle, convection and ocean mixing. Global models must represent the aggregate effect. If the parameterization is calibrated only to present-day averages, it may fail when aerosols, temperature gradients or cloud regimes are deliberately changed.

High-resolution models can reveal mechanisms, but they are not automatically correct. They share uncertain microphysics, numerical diffusion and boundary conditions. The program should therefore use observations as constraints, multi-model ensembles to expose structural uncertainty and held-out cases to test transferability. The desired outcome is a documented chain from process evidence to global response.

## Core scientific questions

- Which subgrid processes dominate uncertainty in radiation, precipitation, aerosol forcing and ocean heat uptake?
- At what resolution do key structures emerge, and which behaviors remain parameterization dependent?
- Can process models reproduce complete observed budgets rather than one selected variable?
- Which reduced variables and closures transfer across regimes and climate states?
- How should parameterizations change with grid spacing so that model behavior is scale aware?
- Do revised process links alter estimates of required reflectivity, regional impacts or AMOC risk?

## Experimental portfolio

### A. Benchmark-case library

Convert field campaigns into standardized cases containing initial and boundary conditions, forcing, observations, uncertainty and protected validation variables. Cases would cover low clouds, mixed-phase clouds, deep convection, aerosol plumes, stratospheric aerosol evolution, ocean mixing and overflows. The library should include ordinary and extreme conditions and should retain failed closure cases that expose missing physics.

### B. Large-eddy simulation ensembles

Run multi-model LES ensembles for low-cloud, boundary-layer and mixed-phase cases. Vary grid spacing, microphysics, turbulence, radiation and aerosol assumptions in a designed experiment. Compare full distributions and budgets, not only mean cloud fraction. Use the ensemble to identify robust mechanisms and to quantify how uncertainty in observations propagates into inferred parameterizations.

### C. Convection-permitting regional experiments

Simulate tropical ocean, monsoon and cold-air-outbreak campaigns at kilometre scale with common forcing. Evaluate storm populations, precipitation extremes, organization, cloud radiation and water budgets. Nested experiments would examine how errors enter from large-scale boundary conditions versus local physics.

### D. Global storm-resolving intercomparison

Run coordinated short global simulations at several kilometre grid spacing for selected seasons and perturbations. Because such simulations are expensive, the program would focus on controlled comparisons and process diagnostics rather than century-scale projections. Teams would archive forecasts before evaluation periods and examine whether explicit convection reduces or merely relocates uncertainty.

### E. Aerosol and intervention process models

Develop coupled near-field plume, aerosol microphysics and radiative models for SAI, and plume-to-cloud LES for MCB. These models would translate release conditions into particle size, cloud activation and radiative effect. Field measurements from the aerosol and cloud programs would test the first minutes and hours that global models cannot resolve.

### F. Parameterization strike teams and global implementation

Small teams combining field scientists, process modelers and global-model developers would convert findings into code. Every proposed change would include a science traceability statement, conservation tests, computational cost, expected regime and failure conditions. At least three structurally different global models would implement the change and test it on data not used in development.

## Model-experiment standards

| Requirement | Implementation | Reason |
|---|---|---|
| Preregistration | Archive hypotheses, configurations, metrics and protected variables before runs | Separates prediction from retrospective explanation. |
| Budget closure | Track energy, water, aerosol mass and tracers | Prevents improvement through hidden conservation errors. |
| Multi-model design | Use independent dynamical cores and physics packages | Exposes structural rather than parametric uncertainty. |
| Resolution sweep | Repeat at several grid spacings | Determines convergence and scale dependence. |
| Observation uncertainty | Sample instrument and retrieval uncertainty in ensembles | Avoids treating observations as exact truth. |

| Requirement | Implementation | Reason |
|---|---|---|
| Transfer tests | Evaluate new regions, seasons and warmer states | Tests whether the closure generalizes. |

## Five-year budget

| Work package | Five-year allocation | Principal deliverable |
|---|---|---|
| Benchmark-case library and data engineering | $9M | Standardized, uncertainty-aware cases and protected tests. |
| LES and mixed-phase ensembles | $13M | Process sensitivities and transferable closures. |
| Regional convection-permitting experiments | $11M | Storm, precipitation and organization benchmarks. |
| Global storm-resolving intercomparison | $15M | Coordinated global high-resolution experiments. |
| SAI/MCB plume and microphysics models | $8M | Release-to-forcing process links. |
| Parameterization strike teams and implementation | $10M | Tested code in multiple global models. |
| Independent replication and computing contingency | $4M | Reproduction, code audit and failed-run reserve. |
| Total | $70M | |

## Deliverables and success criteria

- A public benchmark library with observations, uncertainty, forcing files and reference diagnostics.
- Multi-model process ensembles that identify the source of disagreement rather than only its magnitude.
- Scale-aware parameterizations linked to measured mechanisms and explicit failure conditions.
- Prospective improvement on held-out campaigns and regions in multiple global models.
- A tested release-to-radiative-forcing chain for physically realistic SAI and MCB scenarios.
- Quantified changes in reflectivity requirements and regional outcomes caused by the revised physics.

## Risks and boundaries

The principal risk is equating resolution with accuracy. High-resolution models can produce realistic-looking clouds while retaining biased microphysics or energy budgets. Visual realism is not an acceptance criterion. Models must predict measured distributions, fluxes and causal responses.

The program should avoid a single-model software monoculture. Shared libraries are useful, but independent implementations are needed to reveal structural uncertainty. Computational spending should be tied to specific information goals and stop if additional resolution does not change the decision-relevant result.

# Area 9. Model Evaluation, Data Assimilation and Uncertainty Quantification - $55M

**Prompt to AI:** Describe a five-year, $55 million program for rigorous climate-model evaluation, data assimilation, causal attribution and uncertainty quantification.

**Response From AI:**

A climate model can reproduce global temperature while misrepresenting clouds, aerosol forcing, ocean heat uptake or regional precipitation. Conventional evaluation often reports many metrics but does not determine whether the model can answer a specific decision. This program would create a validation and uncertainty system focused on the quantities needed to calculate how much sunlight to reflect, where and when, and how to monitor the response.

The program would combine held-out tests, prospective forecasts, causal attribution, perturbed-physics ensembles, multi-model structural comparisons, data assimilation and decision-focused emulators. It would explicitly penalize compensating errors and would report uncertainty as a distribution traceable to observations, model structure, scenario and internal variability.

## Why this program is decision-critical

Agreement among models is not validation when models share code, parameterizations, tuning targets or observational products. Conversely, disagreement does not necessarily mean every model is equally plausible. A decision framework needs evidence-based weighting that rewards successful out-of-sample prediction and process fidelity without collapsing uncertainty prematurely.

Data assimilation can produce the best estimate of the present climate state and can connect sparse observations to complete fields, but it can also inherit model bias. The program should therefore compare multiple assimilation systems and preserve the distinction between direct observation, model-constrained estimate and forecast. Uncertainty should be propagated into intervention quantities rather than added as an afterthought.

## Core scientific questions

- Which model errors matter most for required reflectivity and regional climate risk?

- Can models predict new campaigns, natural perturbations and later time periods before seeing the data?
- How much apparent skill results from tuning to the evaluation dataset?
- Where do models match observations through compensating errors?
- How should observations and model skill be used to weight ensembles without discarding plausible structural alternatives?
- How do uncertainty sources propagate into forcing quantity, spatial pattern, timing and monitoring thresholds?

## Program components

### A. Decision-focused benchmark suite

Define a small, stable suite of benchmarks for top-of-atmosphere radiation, cloud regimes, aerosol forcing, precipitation, ocean heat uptake, AMOC, sea ice and natural perturbations. Each benchmark would include uncertainty, independence, temporal and geographic coverage, and whether it was used for model development. The suite should be versioned slowly so that models cannot improve merely because the target changes.

### B. Protected and prospective tests

Hold back selected campaign periods, regions and variables. Require model teams to archive predictions before release. Additional tests would use time splits, geographic transfer and natural events. Scores should include calibration, bias, variability, extremes, causal response and conservation. Poor performance must be published even when it contradicts a favored model.

### C. No-compensating-error diagnostics

Develop joint metrics that require simultaneous agreement in related quantities. For example, a model should match reflected shortwave, cloud amount, cloud optical properties and aerosol loading together; match ocean heat content, air-sea flux and transport together; and match precipitation, evaporation and atmospheric moisture convergence together. An apparent success created by offsetting biases would be flagged rather than averaged away.

### D. Multi-system data assimilation and state estimation

Run several atmospheric and ocean data-assimilation systems with common observations and document their priors, bias corrections and spread. Compare reconstructed fluxes, aerosol fields, cloud regimes, ocean transports and heat content. Observation impact experiments would identify which new measurements most reduce uncertainty in the state and in short-term prediction.

### E. Causal attribution and emergent constraints

Use process-informed statistical methods to attribute observed changes in radiation, temperature, aerosols, clouds and ocean heat. Emergent constraints would be accepted only when the physical mechanism is clear, the relationship is robust across model families and it predicts data not used to discover the relationship. The program should publish failed constraints and sensitivity to model genealogy.

### F. Decision uncertainty engine

Build an open system that propagates observation, parameter, model-structure, scenario and internal-variability uncertainty into quantities such as required reflected flux, injection or spray patterns, temperature and precipitation response, AMOC risk and termination consequences. Fast emulators may be used, but they must be trained on transparent ensembles and checked against full models.

## Evaluation ladder

| Level | Question | Evidence required |
|---|---|---|
| 1. Integrity | Does the code conserve and reproduce its own result? | Versioned code, exact configurations and budget tests. |
| 2. Process | Does the model reproduce measured local physics? | Laboratory and field closure with uncertainty. |
| 3. Regime | Does it work in multiple regions and seasons? | Held-out geographic and regime tests. |
| 4. Historical cause | Does it explain observed changes for the right reasons? | Joint attribution of radiation, temperature, aerosol and ocean heat. |
| 5. Prospective prediction | Can it predict later observations? | Archived forecasts and independent scorecards. |
| 6. Intervention transfer | Can it translate physical SAI/MCB operations into climate response? | Validated process chain and cross-model replication. |
| 7. Decision readiness | Is uncertainty narrow enough for a specified choice? | Predeclared thresholds accepted by independent review. |

## Five-year budget

| Work package | Five-year allocation | Principal deliverable |
|---|---|---|
| Benchmark suite and protected-data governance | $8M | Stable decision-focused benchmarks and holdouts. |
| Prospective model challenges | $10M | Campaign, event and time-split prediction scorecards. |
| Joint metrics and no-compensating-error diagnostics | $7M | Process-linked evaluation tools. |
| Multi-system data assimilation and state estimation | $12M | Atmosphere-ocean state ensembles and observation-impact tests. |
| Causal attribution and model weighting | $8M | Mechanism-based constraints and genealogy-aware weights. |
| Decision uncertainty engine and emulators | $7M | Open probability distributions for reflectivity decisions. |
| Independent audit and contingency | $3M | Statistical review, replication and protected-data security. |
| Total | $55M | |

## Deliverables and success criteria

- A public benchmark and scoring system that distinguishes development data from independent validation data.
- Prospective scorecards for major field campaigns and natural events.
- Model weights and uncertainty ranges that are transparent, sensitivity tested and not based on consensus alone.
- A present-state estimate that clearly labels observed and model-constrained quantities.
- An open uncertainty engine connecting physical inputs to reflectivity quantity, pattern, timing and risk.
- Evidence that selected model changes improve decision metrics without compensating degradation elsewhere.

## Risks and boundaries

Metrics can be gamed if they become the sole target. The benchmark suite should therefore include physically linked quantities, rotating protected tests and expert review. Model ranking should not imply that one model is best for every question.

The program should not compress deep uncertainty into a deceptively precise probability. Where model structure cannot be assigned a defensible probability, results should present scenario ranges and qualitative confidence. Data assimilation should not be described as observation when the estimate depends strongly on model priors.

# Area 10. Observing Backbone, Calibration and Autonomous Platforms - $45M

**Prompt to AI:** Describe a five-year, $45 million shared observing and calibration backbone that supports the climate-model experimental fund.

**Response From AI:**

The flagship experiments depend on common capabilities: calibrated radiometers, aerosol and cloud instruments, aircraft and ship integration, autonomous ocean platforms, balloon systems, data synchronization, communications, maintenance and permanent archives. Rebuilding these capabilities separately for every campaign would waste money and produce incompatible measurements.

This program would fund a shared backbone that any approved experiment can use. It would not purchase a deployment fleet or duplicate entire government observing systems. Instead, it would close critical gaps, maintain modular payloads, provide traceable calibration and ensure that data from satellites, aircraft, ships, ground sites and autonomous platforms can be combined with known uncertainty.

## Why this program is decision-critical

Many apparent scientific disagreements originate in measurement inconsistency: different inlets lose different particles, radiometers drift, cloud probes shatter ice, clocks are misaligned, ship exhaust contaminates aerosol samples and autonomous sensors develop biofouling or pressure offsets. A shared backbone can reduce these errors and allow observations from different campaigns to be compared directly.

The backbone also improves responsiveness. Modular instruments and integration drawings shorten the time between scientific approval and field operations. Common data formats and real-time quick-look systems help teams adapt sampling while the event is occurring. Long-term stewardship prevents valuable measurements from becoming unreadable after the original investigators move on.

## Core capabilities

### A. Radiometry and optical metrology laboratory

Maintain traceable calibration for broadband and spectral shortwave and longwave radiometers, sun photometers, lidar and polarimetric instruments. The facility would provide pre- and post-campaign calibration, field transfer standards, angular-response characterization and uncertainty budgets. Intercomparisons would identify drift and instrument-to-instrument offsets.

### B. Modular airborne instrument suites

Develop standardized racks, power, timing, telemetry and inlets for aerosol, trace-gas, cloud, radiation and meteorological instruments. The suites would be configurable for high-altitude aerosol, marine cloud, mixed-phase cloud or convection missions. Aircraft-specific airworthiness approval would still be required, but reusable mechanical and electrical interfaces would reduce repeated engineering.

### C. Ship, buoy and autonomous surface packages

Create robust packages for broadband radiation, meteorology, sea-surface temperature, waves, aerosol and cloud-base observations on research vessels, buoys and unmanned surface vehicles. Designs would address motion correction, salt contamination, exhaust avoidance, biofouling, power and satellite communications. Reference deployments alongside research ships would quantify autonomous-system bias.

### D. Balloon and profiling systems

Maintain balloon payloads for aerosol, ozone, water vapor, radiation and meteorology, together with launch kits and data systems. Expand expendable and reusable ocean profilers for temperature, salinity, oxygen, turbulence and optical properties. Standard operating procedures would allow rapid deployment by partner institutions in multiple countries.

### E. Calibration field sites and intercomparison exercises

Conduct annual exercises where satellite, aircraft, surface and autonomous instruments observe the same scene. Include clear sky, aerosol layers, low cloud and mixed-phase cloud when feasible. The objective is to quantify cross-platform bias before a flagship campaign relies on small differences between perturbed and control regions.

### F. Common data and operations infrastructure

Provide synchronized time standards, mission planning, real-time displays, data transfer, automated quality checks, metadata templates and persistent storage. Each instrument would have a machine-readable calibration and configuration history. The system should support embargo-free operational metadata while allowing a short, fixed period for quality control of raw science data.

## Backbone service catalog

| Shared service | Users | Acceptance criterion |
|---|---|---|
| Radiometric calibration | Radiation-budget, cloud and aerosol campaigns | Traceable uncertainty and pre/post drift record. |
| Airborne payload integration | Aerosol, cloud, convection and rapid-response teams | Approved interfaces, synchronized data and airworthiness documentation. |
| Autonomous ocean platforms | Low-cloud, AMOC, polar and rapid-response programs | Reference comparison, uptime and calibrated data return. |
| Balloon/profiling kits | Stratosphere, polar, aerosol and event programs | Deployment-ready package and standardized processing. |
| Intercomparison exercises | All observing programs | Published bias and uncertainty across platforms. |
| Data operations | All recipients | Common formats, provenance, quick-look and permanent archive. |

## Five-year budget

| Work package | Five-year allocation | Principal deliverable |
|---|---|---|
| Radiometry and optical metrology | $8M | Traceable calibration and transfer standards. |
| Modular airborne suites and integration | $10M | Reusable payload interfaces and instrument modules. |
| Ship, buoy and autonomous surface systems | $8M | Validated remote observing packages. |
| Balloon and ocean profiling systems | $6M | Rapid, distributed vertical measurements. |
| Annual field intercomparisons | $5M | Cross-platform bias and uncertainty records. |

| Work package | Five-year allocation | Principal deliverable |
|---|---|---|
| Common data and mission operations | $6M | Synchronized processing, quick-look and archive. |
| Spares and contingency | $2M | Replacement sensors and urgent calibration. |
| Total | $45M | |

## Deliverables and success criteria

- A catalog of shared instruments and platforms with readiness, calibration and availability status.
- Traceable uncertainty and configuration records for every measurement used in a major closure claim.
- Reduced integration time and cost for repeated campaigns.
- Cross-platform intercomparison datasets linking satellite, aircraft, ship, surface and autonomous observations.
- Common metadata and time synchronization sufficient to combine measurements at process timescales.
- Permanent archives that remain usable without proprietary software or undocumented expert knowledge.

## Risks and boundaries

A central facility can become a bottleneck or suppress instrument innovation. The backbone should support external instruments through documented interfaces and should competitively select calibration and integration providers. Readiness claims should be tested through exercises rather than accepted from inventory lists.

The program should not purchase expensive platforms without a utilization plan and life-cycle budget. Equipment ownership, maintenance, access and disposition must be specified in advance. Shared infrastructure should serve measurement and validation, not become an undeclared SAI or MCB deployment capability.

# Area 11. International Participation, Governance and Open-Data Infrastructure - $25M

**Prompt to AI:** Describe a five-year, $25 million program for international participation, independent governance, public engagement and open scientific infrastructure.

**Response From AI:**

Sunlight-reflection research has global implications, while many of the most consequential climate risks occur in regions with limited access to high-performance computing, aircraft campaigns and major observing systems. A research program dominated by a few institutions could produce technically sophisticated results that lack legitimacy, omit regional priorities or cannot be independently checked.

This program would finance substantive scientific leadership from low- and middle-income countries, independent governance and ethics review, public and community engagement, multilingual communication, data stewardship and open tools. Participation would not mean asking representatives to endorse SAI or MCB. It would provide the resources needed to define questions, analyze regional impacts, challenge assumptions and decline unacceptable experiments.

## Why this program is decision-critical

Models used to optimize global temperature can underrepresent monsoons, small islands, mountain hydrology, African rainfall, South American river basins or local ocean circulation. Regional scientists often have the observations and contextual knowledge needed to detect such errors but lack stable funding or access to model ensembles. International leadership improves both scientific accuracy and governance.

Open data alone is insufficient if files are too large, undocumented or dependent on expensive software. The program should fund usable access: cloud-hosted subsets, analysis-ready formats, training, computing grants, reproducible notebooks and long-term repositories. Governance bodies must be independent of organizations that receive large research awards.

## Program components

### A. Regional science hubs and investigator grants

Support competitively selected hubs in Africa, South and Southeast Asia, Latin America, small-island regions and other underrepresented areas. Hubs would lead regional model evaluation, observation analysis and impact questions relevant to monsoons, food systems, water, heat and ocean circulation. Funding would cover principal investigators, students, data access, computing and participation in field campaigns.

### B. Independent scientific and safety review

Fund panels that are institutionally and financially separate from the program-management and experiment teams. Reviews would assess scientific value, environmental risk, ethics, transboundary implications, data rights and whether a controlled perturbation is necessary. Dissenting opinions, conflicts and recusals would be published.

### C. Public and affected-community engagement

For field campaigns and any proposed perturbation, provide accessible descriptions, local-language materials, meetings, response-to-comment documents and ongoing incident communication. Engagement should begin while alternatives remain open, not after a design is fixed. Communities and jurisdictions along likely observation or plume paths should have clear contacts and grievance procedures.

### D. Open data, software and hardware access

Maintain repositories for raw and calibrated measurements, model code, configurations, analysis workflows, CAD files and reports. Use open licenses, persistent identifiers and machine-readable metadata. Provide cloud-based analysis environments and reduced-size products so that participation does not require downloading petabytes or owning a supercomputer.

### E. Training and independent replication

Fund summer schools, fellowships, visiting scientists and replication grants. A meaningful share of validation work should be performed by teams that did not design the experiment or model. Training would cover instrument uncertainty, causal inference, high-performance computing, climate-model evaluation and research governance.

### F. International legal and institutional analysis

Support comparative analysis of aviation, marine, environmental, research and data rules that affect campaigns in different jurisdictions. The work would clarify notification, permitting, liability, transboundary consultation and information-sharing requirements. It would not attempt to create a private substitute for intergovernmental decision-making.

## Participation and openness requirements

| Area | Minimum requirement | Evidence |
|---|---|---|
| Scientific leadership | Regional investigators define and lead funded work | Named leadership, budget authority and authorship. |
| Access | Data, code and models usable without proprietary barriers | Open licenses, documentation and cloud-access options. |
| Independence | Review bodies separated from award recipients | Conflict disclosures, recusals and separate funding line. |
| Engagement | Potentially affected communities consulted before irreversible decisions | Meeting record, response document and grievance channel. |
| Replication | Important results checked by unaffiliated teams | Independent code, methods and published comparison. |
| Language and communication | Core materials available in relevant languages and nontechnical form | Public repository and communication audit. |

## Five-year budget

| Work package | Five-year allocation | Principal deliverable |
|---|---|---|
| Regional science hubs and investigator grants | $10M | Locally led regional evaluation and impact research. |
| Independent scientific, safety and ethics review | $4M | Published decisions, dissent and conflict records. |
| Public and community engagement | $3M | Accessible consultation and response processes. |
| Open repositories and analysis environments | $4M | Usable data, code and computing access. |
| Training, fellowships and replication grants | $3M | Expanded independent analytical capacity. |

| Work package | Five-year allocation | Principal deliverable |
|---|---|---|
| Legal/institutional analysis and contingency | $1M | Jurisdictional guidance and rapid consultation support. |
| Total | $25M | |

## Deliverables and success criteria

- Regional research products that materially change model evaluation, experiment design or risk framing.
- Independent panels with published reasoning, dissent and conflict management.
- Open data and code that can be reproduced by teams outside the original consortium.
- Demonstrated access through cloud-hosted tools, documentation and training, not merely file posting.
- Public records showing how comments and regional concerns altered or constrained research plans.
- A durable international network capable of continuing independent assessment after the five-year fund ends.

## Risks and boundaries

Token participation is a serious risk. The program should measure who controls research questions, budgets, data and publication, not only the number of countries represented. Another risk is using engagement as public-relations support for a predetermined intervention. The process must allow disagreement and cancellation.

Open access must respect narrow legitimate limits for personal data, aircraft security, export controls and pre-existing proprietary technology, but exceptions should be written, minimal and time limited. The program should not promise that philanthropic governance can authorize global deployment; its authority is limited to research funding and research conduct.

# Area 12. Contingency and Rapid-Response Reserve - $20M

**Prompt to AI:** Describe how a five-year, $20 million contingency reserve should be structured and governed within the climate-model experimental fund.

**Response From AI:**

Atmospheric and ocean field research is exposed to weather, aircraft and ship delays, lost instruments, failed satellite overpasses, calibration problems, geopolitical disruptions and rare scientific opportunities. A contingency reserve is therefore necessary, but an unrestricted pool can become a mechanism for avoiding competition or expanding weak projects. The reserve should be centrally controlled, stage gated and publicly accounted for.

The $20 million reserve would not be allocated evenly across years or programs. It would remain uncommitted until a documented event or failure creates a high-value need. Unused funds would return to the Funding Source or be reauthorized through the same governance process as other program funds.

## Purposes of the reserve

- Replace or repair a critical instrument whose failure would invalidate an approved campaign.
- Purchase limited replacement aircraft, ship or field days after weather or safety cancellations.
- Respond to a rare natural event that falls outside the standing rapid-response allocation.
- Extend observations when an unexpected result creates a time-limited, high-value scientific opportunity.
- Address a calibration or data-integrity problem discovered after field operations.
- Support transition, data rescue or closeout if a recipient or Managing Organization cannot complete its obligations.

## What the reserve should not fund

The reserve should not cover ordinary cost overruns, optimistic budgeting, late deliverables, unapproved scope growth or a desire to spend the full $1 billion. It should not be used to bypass competitive procurement, rescue a project that has failed its scientific gate, or finance an atmospheric perturbation that lacks independent approval. A recipient should bear costs caused by negligence or failure to meet contractual requirements where the agreement permits.

## Reserve categories

### A. Platform and weather replacement

Provide options for replacement sorties, ship days, balloon launches or temporary relocation when the intended meteorological regime is missed. The original contract should price these options where possible. Reserve approval would require evidence that the replacement still answers the registered question and that the campaign has not already collected sufficient information.

### B. Instrument and calibration failure

Fund replacement detectors, pumps, inlets, electronics, calibration work or independent reanalysis when a critical measurement fails. The program should first determine whether another instrument or existing dataset can answer the question more cheaply. Funds may also support a forensic review when data quality is uncertain.

### C. Rare scientific opportunity

Support additional observations of an unexpected volcano, wildfire, cloud transition, freshwater event or satellite overlap when the information value is unusually high. The request should include a rapid science case, cost, readiness, safety review and data-release plan. The reserve is not a substitute for the standing rapid-response program, but it can expand an activated response.

### D. Data rescue and reproducibility

Protect irreplaceable data if a storage system, contractor or institution fails. Eligible actions include copying raw data, reconstructing metadata, recovering calibration records, converting proprietary formats and completing an open archive. This category can also fund independent replication when a major result is disputed and a timely test would resolve the issue.

### E. Program transition and closeout

If a major recipient or the Managing Organization is replaced, the reserve can finance orderly transfer of equipment, records, contracts, staff knowledge and data. It should not pay termination penalties caused by avoidable misconduct unless necessary to protect the research assets, after which the program should pursue recovery where appropriate.

## Approval process

1. The Project Manager submits a written reserve request identifying the triggering event, alternatives, amount, schedule and decision value.
2. Scientific staff confirm that the request preserves or materially increases information value.
3. Finance and procurement staff verify price reasonableness, contract authority and whether another party is responsible for the cost.
4. Safety, environmental and governance review is repeated if the change affects operations or perturbation conditions.
5. The Agreement Oversight Board approves material requests and the Funding Source approves requests above the reserved threshold.
6. The program publishes the request, decision, amount and later outcome, subject only to narrow temporary safety restrictions.

## Illustrative allocation ceilings

| Reserve category | Illustrative ceiling | Control |
|---|---|---|
| Platform/weather replacement | $6M | Prepriced options and scientific reauthorization. |
| Instrument/calibration failure | $4M | Technical failure report and responsibility review. |
| Rare scientific opportunity | $5M | Rapid value-of-information and readiness decision. |
| Data rescue/independent replication | $3M | Open-archive or dispute-resolution plan. |
| Program transition/closeout | $2M | Oversight Board and Funding Source approval. |
| Total | $20M | Ceilings may be rebalanced by formal board action. |

## Payment and accountability

Reserve actions should use amendments or task-order options with measurable deliverables. Payment should remain milestone based, and the final holdback should depend on accepted data, documentation and open-access obligations. The public financial dashboard should show the original event, approved amount, recipient, deliverable, payments and whether the reserve action succeeded.

## Deliverables and success criteria

- Critical campaigns are not invalidated by foreseeable platform or instrument failures when a cost-effective remedy exists.
- Reserve decisions are fast enough for time-sensitive opportunities but retain documented scientific and financial review.
- No reserve expenditure is used to conceal routine overruns or failed stage gates.
- Every activation produces a defined scientific or data-protection deliverable and a public after-action report.
- Unused balances remain identifiable and are returned or explicitly reauthorized.
- Annual independent audit confirms that reserve spending followed thresholds and approval rules.

## Risks and boundaries

The central risk is moral hazard: teams may underbudget or take avoidable risks because they expect the reserve to rescue them. Contracts should distinguish unavoidable events from recipient responsibility and should require reasonable insurance, spares and contingency planning before reserve access.

A second risk is urgency being used to bypass governance. No reserve request should relax scientific, environmental, safety, open-data or conflict-of-interest requirements. If a rare opportunity cannot be pursued responsibly within the available time, the program should decline it rather than create a precedent for unreviewed experimentation.

# What a Reflectivity Decision System Must Calculate

**Prompt to AI:** What should an improved climate-model system calculate before anyone decides how much sunlight to reflect, from where, and when?

**Response From AI:**

A reflectivity decision system should be formulated as a constrained, uncertain control problem. It must connect an intervention pattern to radiative forcing, climate response, harms, benefits and monitoring signals. It should not output one deceptively precise number.

## 1. Required radiative forcing

The system should estimate how much additional reflected shortwave energy is required to meet an explicit objective, such as reducing the decadal global warming rate, limiting peak temperature, slowing ice loss or reducing the probability of an AMOC transition. It should report watts per square metre, uncertainty and the time dependence of the required forcing.

## 2. Spatial distribution

The same global-mean forcing can have different consequences depending on latitude, longitude and altitude. The model system should compare multiple spatial patterns and quantify effects on hemispheric temperature balance, equator-to-pole gradients, monsoons, storm tracks, tropical rainfall and ocean circulation.

## 3. Seasonal timing

Seasonal interventions could affect sea ice, snow, clouds and circulation differently from a year-round forcing. The system should test whether timing can reduce specific risks while avoiding large precipitation or ecological penalties.

## 4. Intervention physics

For SAI, models must translate material, particle size, altitude, latitude and release schedule into aerosol evolution and radiative forcing. For MCB, they must translate sea-salt emission, particle size and meteorological conditions into cloud droplet number, cloud brightness, lifetime, precipitation and regional radiation. The climate model should receive realistic forcing from validated process models rather than an idealized reduction in the solar constant alone.

## 5. Climate objectives and constraints

| Decision quantity | What should be calculated |
|---|---|
| Global mean surface temperature | Level and rate of change; land-ocean and day-night contrasts. |
| Temperature gradients | Interhemispheric and equator-to-pole differences that influence circulation. |
| Top-of-atmosphere radiation | Shortwave reflection, longwave emission and net planetary imbalance. |
| Precipitation and evaporation | Global hydrological sensitivity, monsoons, drought and extreme rainfall. |
| Ocean heat content | Heat uptake by basin and depth, including deep-ocean commitment. |
| AMOC and ocean circulation | Overturning strength, freshwater transport, convection and threshold indicators. |
| Sea ice, ice sheets and glaciers | Mass balance, albedo feedback and regional sea-level implications. |
| Ozone, air quality and deposition | Intervention-specific chemistry and surface exposure. |
| Ecosystems and food systems | Direct/diffuse sunlight, temperature, rainfall, crop and marine impacts. |
| Equity and regional risk | Distribution of benefits, harms and uncertainty among countries and communities. |

## 6. Counterfactual baseline

Every intervention outcome must be compared with a credible no-intervention pathway. The baseline should include uncertainty in emissions, greenhouse-gas concentrations, aerosol emissions, land use, volcanic activity and natural variability. Otherwise the apparent benefit or harm may be an artifact of the chosen baseline.

## 7. Uncertainty and probability

The system should propagate observational, parametric, structural, scenario and internal-variability uncertainty. It should present probability distributions and robust ranges rather than simply averaging models. Where models share code or assumptions, they should not be counted as statistically independent.

## 8. Monitoring and adaptive control

A real program would need feedback: observe the climate, compare it with predictions, update the model and adjust or stop the intervention. The model system should identify which signals emerge fastest and which instruments are needed to detect divergence from predictions.

- Top-of-atmosphere reflected shortwave radiation.
- Aerosol or cloud-property changes attributable to the intervention.
- Global and regional temperature gradients.
- Precipitation and circulation indicators.
- Ocean heat-content and AMOC precursor indicators.
- Ozone, air-quality and ecological warning signals.

## 9. Stress tests and failure modes

The decision system should be tested against abrupt volcanic eruptions, El Niño and La Niña, wildfire smoke, unexpected aerosol-emission changes, satellite gaps, instrument drift, model bias and intervention interruption. It should show what happens when a forecast is wrong, when a delivery system underperforms or when international participation changes.

## 10. A decision-ready output

A final model assessment should produce a transparent portfolio rather than a single optimal plan. Each option should include the expected climate outcome, uncertainty, regional tradeoffs, monitoring plan, reversibility, termination risk and conditions under which the option should not proceed.

# Policymaking Questions

**Prompt to AI:** We have 5 key proposals that are designed to help policymakers make decisions about climate change.

These proposals are: (a) Proposed $1B SAI Experimental Research Fund (“sai_experiments_research_fund_ai, v1q.docx”), (b) Proposed $1B SAI Equipment Development Fund ("sai_equipment_development_fund_ai, v1j.docx"), (c) Proposed $1B MCB Experimental Research Fund (“mcb_experiments_research_fund_ai, v1g.docx”), (d) Proposed $1B MCB Equipment Development Fund ("mcb_equipment_development_fund_ai, v1g.docx"), and (e) Proposed $1B GCM Experimental Research Fund (“gcm_experiments_research_fund_ai, v1d.docx”).

What are the 4 most important questions that each of these hope to answer?

What else do policymakers need to know, to tackle climate change?

**Response From AI:**

Yes. Looking across the five proposals together, I think they form a fairly coherent **decision-support package for the sunlight-reflection part of climate policy**. They are trying to answer three different levels of question:

> Does the physics work? → Can the machinery actually do it? → If it can, how much intervention would be needed, where, and when?

## The four most important questions for each proposal

| Proposal | Four most important questions it hopes to answer |
|---|---|
| **A. $1B SAI Experimental Research Fund** | **1. What actually happens after material is released into the stratosphere?** Can models correctly predict dilution, chemistry, nucleation, particle growth, coagulation, transport, optical properties and radiative forcing from a real release? **2. Which injection pathway works best?** Is $SO_2$ gas, direct $H_2SO_4$ aerosol/vapor, or some alternative particle preferable in terms of particle size, forcing per kg, forcing per dollar and controllability? **3. What harmful effects accompany the cooling?** Especially ozone chemistry, stratospheric heating, circulation changes, deposition and other atmospheric effects—and can they be detected before they become serious? **4. Can SAI be measured and controlled well enough to justify any larger experiment or eventual deployment?** Can we find the plume, independently verify the forcing, predict its evolution and establish meaningful stop/proceed criteria? The proposal explicitly defines its purpose as determining whether a specified pathway can be |

| Proposal | Four most important questions it hopes to answer |
|---|---|
| | "predicted, measured, controlled, and evaluated" well enough to decide whether research should continue, change direction or stop. |
| **B. $1B SAI Equipment Development Fund** | **1. Can aircraft actually put the required material at the required altitude and rate?** What can a modified 777-class aircraft accomplish, and what would require a purpose-built ~65,000-ft aircraft? **2. Can we reliably make the desired aerosol rather than merely deliver sulfur?** What material, nozzle, vaporizer, wake geometry and release system produce the particle-size distribution that gives the best forcing? **3. Can the entire industrial system operate safely, reliably and economically?** This includes sulfur supply, processing, airport storage/loading, aircraft turnaround, automation, maintenance, redundancy and fleet operations. **4. Can an independent monitoring/control system verify what was released, what aerosol formed, how much forcing resulted and whether dangerous side effects are developing?** The fund therefore covers aircraft, ground automation, high-altitude aircraft design, sulfur logistics and monitoring rather than just an airplane. |
| **C. $1B MCB Experimental Research Fund** | **1. Can we produce the right sea-salt particles and get them to cloud base?** How many survive evaporation, coagulation, dilution and deposition, and which particle sizes are actually useful CCN? **2. When those particles enter a cloud, does the cloud brighten predictably and repeatably?** Do droplet number, droplet radius, liquid-water content, drizzle, optical depth and reflected sunlight respond as predicted? **3. Under what meteorological/cloud conditions does MCB work—or fail?** Closed/open stratocumulus, precipitating/non-precipitating clouds, shallow cumulus, different background aerosol and turbulence can respond very differently. **4. Can the local response be scaled to regional climate consequences without unacceptable side effects?** This includes precipitation, circulation, cloud-field changes, deposition, ecology and distant teleconnections. The document summarizes the central chain as source → plume → cloud-base delivery → activation → cloud response → radiative/weather effects. |
| **D. $1B MCB Equipment Development Fund** | **1. Can equipment generate enormous quantities of correctly sized sea-salt aerosol efficiently and reliably from real seawater?** This includes particle-size control, energy efficiency, clogging, corrosion, biofouling and variable seawater chemistry. **2. Can vessels/platforms operate this equipment reliably for long periods at sea?** Crewed vessels, autonomous vessels and long-endurance platforms must integrate filtration, power, masts, generators and corrosion-resistant systems. **3. Can a fleet be operated intelligently and economically?** Can it find suitable clouds, route itself, coordinate vessels, survive failures, shut down rapidly, undergo maintenance and resupply, and operate with acceptable lifecycle cost and emissions? **4. Can the operating system independently prove what it is doing?** It needs to measure generator output, plume transport, delivery to cloud base, cloud response, radiation, precipitation and environmental effects. The proposal explicitly treats monitoring, autonomy, maintenance and a 30–90-day integrated demonstration as core equipment-development tasks. |
| **E. $1B GCM Experimental Research Fund** | **1. What is Earth's actual energy imbalance, and why is it changing?** How much sunlight is reflected by clouds, aerosols and the surface; how much is absorbed; and how much heat is accumulating in the oceans? **2. Can climate models reproduce the** |

| Proposal | Four most important questions it hopes to answer |
|---|---|
| | **important physical processes for the right reasons?** Especially aerosol forcing, marine clouds, mixed-phase/polar clouds, convection, precipitation, ocean heat uptake, sea ice and AMOC—without compensating errors. **3. If policymakers wanted to change Earth's radiative balance, how much sunlight would need to be reflected, where and when?** The answer needs uncertainty bounds rather than one number. **4. What would that intervention do to the rest of the climate system?** Regional temperature, precipitation, monsoons, sea ice, AMOC, ecological risk—and what measurements would reveal early that reality is departing from predictions? The proposal explicitly frames the problem as predicting radiation, temperature, precipitation, sea ice and ocean circulation accurately enough to select an intervention's quantity, location and schedule. |

## Put much more simply

The entire $5 billion package could be explained to a policymaker using five questions:

| Program | Policymaker's basic question |
|---|---|
| SAI experiments | What happens if we actually put candidate SAI material into the stratosphere? |
| SAI equipment | Could we actually build and operate an SAI system safely and economically? |
| MCB experiments | Does spraying suitable sea-salt aerosol actually brighten real clouds enough to matter? |
| MCB equipment | Could we build and operate a reliable fleet that does this at useful scale? |
| GCM experiments | If SAI or MCB works, how much should we do, where and when—and what else would happen? |

That is a strong division of labor.

## But these five proposals do not answer the whole climate-policy question

This is the important distinction I would make when presenting them to policymakers.

These five funds could substantially improve the answer to:

> "Could sunlight reflection become a usable climate-risk-management tool, and if so, how?"

They do **not** by themselves answer:

> "What should humanity actually do about climate change?"

That second question requires several additional bodies of information.

## 1. How fast can we eliminate greenhouse-gas emissions?

Policymakers need credible engineering/economic pathways for electricity, industrial heat, steel, cement, chemicals, fertilizer, transportation, buildings and land use.

This matters enormously for SAI/MCB decisions. Consider two worlds:

> **World A:** $CO_2$ emissions approach zero rapidly and atmospheric concentrations eventually stabilize.
>
> **World B:** emissions remain high for another century.

The appropriate role, duration and termination risk of sunlight reflection are radically different in those two worlds.

So policymakers need something analogous to your five research proposals for **deep decarbonization technology and deployment**.

## 2. How much $CO_2$ can actually be removed from the atmosphere?

SAI and MCB address **temperature**, not the underlying $CO_2$ concentration. Your own SAI and MCB documents repeatedly point out that sunlight reflection would not stop ocean acidification.

Policymakers therefore need to know:

> Can we economically remove 1, 5, 10 or more $GtCO_2$/year? At what cost? For how many decades? With what energy, land, minerals and storage requirements?

This determines whether sunlight reflection might be needed for decades, centuries, or not at all.

## 3. What happens if we do nothing beyond current mitigation?

There needs to be a continually updated **reference-risk assessment**.

Not merely "the world warms X°C," but:

> What happens to extreme heat? Crop yields? Water availability? Sea-level rise? Ice sheets? AMOC? Coral reefs? Human mortality? Migration? Economic damages?

The policy comparison isn't:

> SAI risk versus zero risk.

It is:

> SAI/MCB risks versus the risks of the climate trajectory that occurs without them.

That distinction should probably become much more prominent in the overall Climate Moonshot presentation.

## 4. What combination of interventions produces the least total harm?

This is perhaps the largest analytical layer missing from the five proposals.

Imagine policymakers eventually have:

- aggressive emissions reductions,
- nuclear/renewables/storage,
- carbon removal,
- SAI,
- MCB,
- adaptation.

The real decision isn't whether one of these is "good."

It is:

> What portfolio minimizes expected human and ecological harm over the next 20, 50, 100 and 500 years?

For example, a model might compare:

> **Scenario 1:** mitigation only
> **Scenario 2:** rapid mitigation + adaptation
> **Scenario 3:** rapid mitigation + CDR
> **Scenario 4:** mitigation + temporary 0.5°C SAI
> **Scenario 5:** mitigation + limited regional MCB
> **Scenario 6:** mitigation + SAI + MCB + CDR

That would convert the research portfolio into something policymakers can actually act upon.

## 5. What are the regional winners and losers?

Global-average temperature is an inadequate policy metric.

For every intervention policymakers need distributions for:

temperature, precipitation, drought, flood risk, agriculture, ecosystems, storms, sea ice and economic damages by region.

A global intervention that produces $10 trillion of aggregate benefit but badly damages one region creates an obvious political and ethical problem.

The GCM proposal goes substantially in this direction by demanding regional precipitation and circulation results rather than global-mean temperature alone. But ultimately these physical outputs need to connect to **people, food, water, ecosystems and economies**.

## 6. Who gets to decide?

This may become as important as the engineering.

Suppose the science eventually says:

> Injecting X Mt/year would probably lower global temperature by 0.7°C, reduce heat mortality substantially, but alter rainfall probabilities in several regions.

Then the scientific question is no longer the central question.

Policymakers need answers about **international authority, consent, liability, compensation, monitoring, enforcement, unilateral action and dispute resolution**.

Your individual proposals already contain governance structures for experiments. What is still needed is a **deployment-level international governance architecture**.

## 7. What happens if the system fails—or someone stops it?

For a long-running SAI program in particular, policymakers need a credible answer to:

> What happens if the aircraft fleet stops flying next year?

That means fuel/sulfur reserves, multiple bases, spare aircraft, political continuity, supply-chain redundancy, financial commitments and gradual phase-down planning—not merely an estimate of termination warming.

Your SAI proposals recognize termination shock. But at the policy level, this becomes an **institutional reliability question extending over generations**.

## 8. How do we know in real time whether the plan is working?

All five proposals point toward this, but I would elevate it into a separate global capability.

A climate intervention would need something analogous to a planetary **instrument panel**:

> $CO_2$ / $CH_4$ → Earth energy imbalance → reflected sunlight → aerosol/cloud state → ocean heat → global/regional temperature → precipitation → AMOC → sea ice → ecological indicators.

Models would continuously predict what those indicators should do.

Observations would continuously determine whether reality agrees.

If not:

> adjust → pause → diagnose → potentially terminate.

That is fundamentally different from simply "deploying geoengineering." It is **closed-loop climate risk management**.

## I would therefore describe the policymaker decision problem as eight questions

The five proposals cover questions 3–6 especially well:

1. **What happens if we continue on the present climate trajectory?**
2. **How far and how fast can emissions reduction, carbon removal and adaptation reduce that risk?**
3. **Can SAI physically produce predictable cooling, and what are its side effects?**
4. **Can MCB physically produce predictable cooling, and what are its side effects?**
5. **Can practical SAI and MCB systems be built, operated, monitored and stopped at acceptable cost and reliability?**
6. **How much radiative forcing would actually be needed, where and when, and what would it do regionally?**
7. **Which combination of mitigation, removal, adaptation, SAI and MCB produces the lowest total risk?**
8. **Who decides, who monitors, who pays, who is liable, and how is a centuries-scale commitment safely governed?**

That last synthesis is where I think the broader project should ultimately go.

The **five $1B proposals are not themselves "the climate plan."** They are closer to a **$5B program for eliminating the largest scientific and engineering uncertainties that prevent policymakers from intelligently evaluating sunlight reflection**. Combined with equally concrete work on emissions reduction, carbon removal and adaptation, they could become the technical foundation for a much broader climate decision system.

# Project Phases (i.e. what happens first)

**Prompt to AI:** For the proposed GCM experiments, what phases should occur first, and how much might representative campaigns cost?

**Response From AI:**

A field experiment should be treated as a complete scientific campaign, not merely as a flight, ship cruise or instrument deployment. Each campaign should begin with a decision question and end with an independent test of whether the new model prediction improved. The following costs are illustrative planning estimates in 2026 dollars.

## A. Anthropogenic aerosol radiative-forcing closure campaign - approximately $65M

Assumed campaign: six to eight weeks in a polluted-to-clean marine transition region, with two research aircraft, one research vessel or autonomous surface fleet, satellite coordination, ground sites, repeated plume and cloud transects, and model analysis extending through one year.

| Phase | Principal work | Estimated cost |
|---|---|---|
| 1. Decision question and science design | Define causal chain, required uncertainty, sites, meteorological regimes and stop criteria. | $2.5M |
| 2. Existing-data audit and target selection | Analyze emissions, satellites, reanalysis and previous campaigns; choose locations and dates. | $2.0M |
| 3. Governance, environmental and regulatory review | Permits, consultation, environmental review and any perturbation authorization. | $2.0M |
| 4. Instrument development and calibration | Aerosol, CCN, cloud microphysics, radiation, trace gases, lidar and radar. | $9.0M |
| 5. Aircraft, vessel and site integration | Payload installation, airworthiness, ship systems, synchronization and rehearsals. | $5.5M |
| 6. Baseline observations | Clean and polluted background, vertical profiles, surface flux and cloud-regime mapping. | $5.0M |
| 7. Intensive field operations | Aircraft sorties, vessel operations, cloud/plume transects and satellite underflights. | $18.0M |

| Phase | Principal work | Estimated cost |
|---|---|---|
| 8. Natural or metered perturbation component | Observe policy/emissions change or conduct a small, governed perturbation if justified. | $4.0M |
| 9. Laboratory and sample analysis | Composition, hygroscopicity, ice nucleation, morphology and optical properties. | $4.0M |
| 10. Data assimilation and radiative closure | Reconstruct emissions-to-aerosol-to-cloud-to-flux causal chain. | $5.0M |
| 11. Model challenge and parameterization testing | LES/CRM and global-model predictions using withheld observations. | $4.5M |
| 12. Independent audit, archive and publication | Calibration audit, uncertainty review, open repository and final report. | $2.0M |
| 13. Contingency | Weather, missed regimes, instrument failures and replacement operations. | $1.5M |
| Total | | $65.0M |

The core acceptance test should be a closed, quantified estimate of aerosol effective radiative forcing for the observed cases, with uncertainty decomposed among emissions, aerosol properties, cloud response, meteorology and radiative transfer.

## B. Marine low-cloud feedback and radiative-closure campaign - approximately $55M

Assumed campaign: four to six weeks in a subtropical low-cloud region, approximately 40–60 research-aircraft sorties, a vessel or autonomous surface platforms, radar and lidar, satellite coordination and extensive large-eddy simulation.

| Phase | Principal work | Estimated cost |
|---|---|---|
| 1. Science and decision design | Specify cloud-feedback and MCB-susceptibility questions, regimes and validation metrics. | $2.0M |
| 2. Site and season selection | Use satellite climatology, forecasts and model disagreement to select targets. | $1.5M |
| 3. Instrument and platform preparation | Cloud probes, aerosol/CCN, turbulence, radiation, radar, lidar and surface flux systems. | $8.0M |

| Phase | Principal work | Estimated cost |
| --- | --- | --- |
| 4. Integration and rehearsal | Aircraft certification, vessel installation, communications and coordinated test flights. | $4.0M |
| 5. Baseline and synoptic mapping | Characterize inversion, aerosol, cloud thickness, drizzle and mesoscale organization. | $4.0M |
| 6. Intensive aircraft and surface operations | Stacked legs below, within and above clouds; repeated Lagrangian sampling. | $15.0M |
| 7. Cloud-susceptibility observations | Natural gradients, ship tracks and any approved metered aerosol cases. | $3.0M |
| 8. LES/CRM simulations | Case simulations, ensemble perturbations and process attribution. | $5.0M |
| 9. Parameterization strike teams | Develop and implement improved cloud, turbulence and precipitation physics. | $4.5M |
| 10. Global-model testing | Run revised physics in multiple models and compare with withheld regimes. | $3.5M |
| 11. Independent closure and archive | Radiative-budget audit, reproducibility package and open data. | $2.0M |
| 12. Contingency | Weather, aircraft availability and failed instruments. | $2.5M |
| Total | | $55.0M |

The expensive elements are not sea salt or aircraft fuel alone. They are obtaining simultaneous measurements of aerosol, cloud microphysics, turbulence, precipitation and radiation; sampling the same evolving air mass repeatedly; and then testing whether models predict the observed transition.

## C. AMOC and ocean-heat-uptake campaign - approximately $60M

Assumed campaign: a five-year regional program strengthening an existing trans-basin or high-latitude array, adding autonomous platforms, conducting two major research cruises and assimilating the data into multiple ocean and coupled models.

| Phase | Principal work | Estimated cost |
| --- | --- | --- |
| 1. Observing-system design | Identify AMOC decision metrics, observing gaps, array design and forecast experiments. | $2.5M |
| 2. Mooring and sensor procurement | Current meters, temperature/salinity, pressure, acoustics and telemetry. | $11.0M |

| Phase | Principal work | Estimated cost |
| --- | --- | --- |
| 3. Autonomous platforms | Gliders, Argo/deep-Argo floats, surface vehicles and profiling systems. | $8.0M |
| 4. Deployment cruise | Install moorings, deploy floats/gliders and conduct hydrographic/tracer survey. | $7.5M |
| 5. Continuous operations and maintenance | Telemetry, calibration, recoveries, redeployments and quality control. | $6.0M |
| 6. Process and mixing experiment | Tracer, turbulence, overflow and convection measurements. | $6.5M |
| 7. Freshwater and Greenland pathway observations | River, meltwater, shelf and basin measurements and source attribution. | $4.0M |
| 8. Recovery and repeat cruise | Recover assets, repeat sections and close mass/heat/freshwater budgets. | $5.5M |
| 9. Data assimilation and state estimation | Multi-model reconstruction of overturning, heat and freshwater transports. | $4.0M |
| 10. Prediction challenge | Prospective seasonal-to-decadal forecasts and coupled-model sensitivity tests. | $2.5M |
| 11. Independent audit and open archive | Sensor audit, uncertainty, documentation and final assessment. | $1.5M |
| 12. Contingency | Lost instruments, ship delays and severe weather. | $1.0M |
| Total | | $60.0M |

## Common phase gates

| Gate | Required finding |
| --- | --- |
| Gate 0: Relevance | The uncertainty materially affects a reflectivity or climate-risk decision. |
| Gate 1: Existing evidence | The question cannot be answered adequately from existing data and published analysis. |
| Gate 2: Observability | Instruments and sampling can achieve the required accuracy and distinguish competing hypotheses. |
| Gate 3: Readiness | Platforms, calibration, permits, logistics, safety and data systems are ready. |
| Gate 4: Operations | Forecast conditions are suitable and the campaign can capture the intended regime. |
| Gate 5: Data quality | Measurements pass calibration, completeness and uncertainty requirements. |

| Gate | Required finding |
| --- | --- |
| Gate 6: Model test | Predictions are compared with held-out data and improvements are demonstrated without degrading other metrics. |
| Gate 7: Decision impact | The result changes an uncertainty range, model weighting, parameterization or future research decision. |

A failed gate should lead to redesign, postponement or cancellation. The program should not treat spending the approved amount as a measure of success.

# Purchase Orders

**Prompt to AI:** For representative climate-model experiments, what purchase orders, subawards or task orders might be issued?

**Response From AI:**

The term “purchase order” is used broadly below. Research universities would usually receive subawards or sponsored-research agreements. Government aircraft and ships may operate through reimbursable agreements. Commercial engineering, instruments, logistics and computing would use procurement contracts or task orders.

The following structures show how a project manager could convert a scientific campaign into measurable deliverables. Costs are illustrative and should be competed or independently evaluated.

## A. Aerosol radiative-forcing closure campaign - $65M

| PO | Procurement package | Deliverable | Estimate |
|---|---|---|---|
| A1-01 | Integrated science-design subaward | Science traceability matrix, hypotheses, required uncertainty, sampling plan and decision rules. | $1.2M |
| A1-02 | Observing-system simulation contract | Synthetic experiments showing whether proposed sampling distinguishes aerosol direct and cloud-mediated forcing. | $0.8M |
| A1-03 | Independent design review | Published review and proceed/redesign decision. | $0.5M |
| A2-01 | Emissions and satellite data audit | Regional emissions inventory, plume climatology, satellite retrieval assessment and target atlas. | $1.0M |
| A2-02 | Meteorological regime analysis | Probability of target cloud and transport conditions by site and season. | $0.5M |
| A2-03 | Prior-campaign synthesis | Harmonized dataset and gap analysis from relevant field campaigns. | $0.5M |
| A3-01 | Environmental and regulatory services | Permits, environmental review, airspace and maritime plan. | $0.8M |
| A3-02 | Public and jurisdictional engagement | Meetings, materials, comments and response record. | $0.7M |

| PO | Procurement package | Deliverable | Estimate |
|---|---|---|---|
| A3-03 | Independent governance panel | Conflict disclosures and authorization decision for any controlled perturbation. | $0.5M |
| A4-01 | Aerosol composition and size package | Calibrated measurements from nanometres through coarse particles, with composition and mixing state. | $2.3M |
| A4-02 | CCN and hygroscopicity package | Cloud-condensation-nuclei spectra and water-uptake characterization. | $1.2M |
| A4-03 | Absorption and optical-properties package | Scattering, absorption, extinction and single-scattering albedo. | $1.2M |
| A4-04 | Cloud microphysics package | Droplet number, size, liquid water, drizzle and ice measurements. | $1.4M |
| A4-05 | Radiometry and remote-sensing package | Broadband/spectral flux, lidar and radar measurements. | $1.7M |
| A4-06 | Calibration and intercomparison services | Traceable calibrations and side-by-side instrument comparisons. | $1.2M |
| A5-01 | Research-aircraft block 1 | Primary in-situ aircraft, crew and approximately 25–35 sorties. | $6.5M |
| A5-02 | Research-aircraft block 2 | Remote sensing and vertical-context aircraft, approximately 20–25 sorties. | $4.5M |
| A5-03 | Vessel or autonomous surface operations | Surface flux, aerosol source, cloud radar/lidar and trajectory support. | $4.0M |
| A5-04 | Ground supersite and mobile network | Continuous aerosol, cloud and radiation observations. | $1.5M |
| A5-05 | Satellite coordination and rapid products | Overpass planning and campaign-quality retrievals. | $1.0M |
| A6-01 | Baseline flight and surface series | Clean-background and polluted-background characterization. | $3.0M |
| A6-02 | Trajectory and forecast center | Daily plume, cloud-regime and flight-target products. | $1.0M |
| A6-03 | Formation and sampling rehearsals | Coordinated aircraft/vessel test and source-reconstruction exercise. | $1.0M |
| A7-01 | Intensive operations task order | Coordinated sorties and surface operations meeting the sampling matrix. | $10.0M |

| PO | Procurement package | Deliverable | Estimate |
|---|---|---|---|
| A7-02 | Plume and Lagrangian follow-up options | Repeat sampling of the same air mass and cloud system. | $3.0M |
| A7-03 | Field logistics and maintenance | Deployment, hangar, shipping, spares, lodging and communications. | $3.0M |
| A7-04 | Weather and replacement-flight options | Reserved platform availability for missed cases. | $2.0M |
| A8-01 | Natural-policy experiment analysis | Quantify radiative response to a documented emissions change. | $1.5M |
| A8-02 | Metered perturbation option | Small approved release and synchronized measurement package, only if gated. | $2.0M |
| A8-03 | Independent source verification | Mass, timing, location and composition audit. | $0.5M |
| A9-01 | Filter/sample laboratory analysis | Composition, morphology, isotopes and source markers. | $1.5M |
| A9-02 | Optical and hygroscopic laboratory analysis | Measured refractive index, absorption and water uptake. | $1.0M |
| A9-03 | Cloud-active-particle analysis | CCN/ice-nucleating properties and uncertainty. | $0.8M |
| A9-04 | Laboratory quality assurance | Blanks, standards, chain of custody and interlaboratory comparison. | $0.7M |
| A10-01 | Campaign data system | Synchronized aircraft, vessel, satellite and ground dataset. | $1.3M |
| A10-02 | Causal plume reconstruction | Emissions-to-aerosol transport and aging history. | $1.0M |
| A10-03 | Cloud response attribution | Meteorology-controlled estimate of aerosol effect on cloud properties. | $1.2M |
| A10-04 | Radiative-closure analysis | Top-of-atmosphere and surface forcing with uncertainty budget. | $1.5M |
| A11-01 | LES/CRM model challenge | Prospective simulations compared with withheld cloud and radiation data. | $1.5M |
| A11-02 | Global-model parameterization tests | Implementation in at least three independent global models. | $1.5M |
| A11-03 | Structural uncertainty comparison | Evaluate alternative aerosol-cloud formulations and emergent constraints. | $0.8M |
| A11-04 | Independent model evaluation | Firewalled evaluation of performance and compensating errors. | $0.7M |

| PO | Procurement package | Deliverable | Estimate |
|---|---|---|---|
| A12-01 | Data-quality and metrology audit | Calibration, completeness, exclusions and uncertainty audit. | $0.7M |
| A12-02 | Open repository and reproducibility package | Raw and calibrated data, code, metadata and persistent identifiers. | $0.6M |
| A12-03 | International review workshop | External review and final decision-focused report. | $0.7M |
| A13-01 | Program-manager reserve | Unforeseen technical and scheduling requirements. | $0.7M |
| A13-02 | Instrument and platform contingency | Repairs, replacements and additional operations. | $0.8M |

## B. Marine low-cloud campaign - $55M

| PO | Procurement package | Deliverable | Estimate |
|---|---|---|---|
| C1-01 | Integrated campaign design | Cloud-regime matrix, decision metrics, flight patterns and validation plan. | $1.0M |
| C1-02 | Observing-system simulation | Sampling sensitivity to cloud variability and mesoscale organization. | $0.6M |
| C1-03 | Independent design review | Proceed/redesign report. | $0.4M |
| C2-01 | Site and season atlas | Satellite and reanalysis assessment of target regimes. | $0.7M |
| C2-02 | Forecast-system development | Operational cloud-regime and trajectory forecasts. | $0.8M |
| C3-01 | Cloud probe and turbulence suite | Calibrated droplet, drizzle, liquid-water, temperature and turbulence measurements. | $2.5M |
| C3-02 | Aerosol/CCN suite | Below-cloud aerosol size, composition, CCN and sea-salt characterization. | $1.6M |
| C3-03 | Radiation suite | Broadband and spectral flux above, within and below cloud. | $1.4M |
| C3-04 | Radar, lidar and imaging suite | Cloud structure, drizzle, boundary-layer depth and mesoscale context. | $1.8M |
| C3-05 | Surface flux and autonomous platforms | Sensible/latent heat, aerosol source, SST and boundary-layer profiles. | $0.7M |
| C4-01 | Primary aircraft integration | Payload, inlets, power, airworthiness and data systems. | $1.5M |
| C4-02 | Secondary aircraft integration | Remote sensing and coordinated operations. | $1.0M |

| PO | Procurement package | Deliverable | Estimate |
|---|---|---|---|
| C4-03 | Vessel/autonomous integration | Radar, lidar, radiometry, aerosol and communications. | $0.8M |
| C4-04 | Calibration and rehearsal | Side-by-side flights and surface intercomparison. | $0.7M |
| C5-01 | Baseline mapping flights | Cloud deck, transition and cumulus environmental mapping. | $2.0M |
| C5-02 | Surface baseline period | Continuous cloud, aerosol, radiation and flux measurements. | $1.2M |
| C5-03 | Mission planning center | Daily targeting, trajectories and quick-look products. | $0.8M |
| C6-01 | Primary-aircraft sortie block | Approximately 30–40 stacked and Lagrangian sorties. | $7.0M |
| C6-02 | Secondary-aircraft sortie block | Approximately 15–20 remote-sensing and context sorties. | $3.5M |
| C6-03 | Vessel and autonomous operations | Continuous surface and boundary-layer observations. | $2.0M |
| C6-04 | Field logistics, spares and standby | Deployment support and replacement cases. | $2.5M |
| C7-01 | Ship-track and natural-gradient analysis | Cloud response as aerosol and meteorology evolve. | $1.2M |
| C7-02 | Metered sea-salt option | Governed small perturbation with source and cloud-response measurements. | $1.3M |
| C7-03 | Independent attribution analysis | Separate aerosol signal from meteorological variability. | $0.5M |
| C8-01 | Case LES ensemble | High-resolution simulations of all priority cases. | $2.0M |
| C8-02 | Uncertainty and process attribution | Entrainment, drizzle, organization and aerosol sensitivity. | $1.5M |
| C8-03 | Held-out flight prediction | Prospective LES predictions for selected withheld periods. | $1.5M |
| C9-01 | Cloud parameterization team 1 | Improved turbulence/entrainment treatment. | $1.4M |
| C9-02 | Cloud parameterization team 2 | Improved microphysics/drizzle treatment. | $1.4M |
| C9-03 | Scale-aware coupling team | Transfer physics from LES to global-model resolutions. | $1.0M |
| C9-04 | Independent code review | Numerical, conservation and reproducibility audit. | $0.7M |
| C10-01 | Multi-model implementation | At least three global models with revised physics. | $1.5M |
| C10-02 | Out-of-sample climate tests | Evaluate cloud radiative effect, feedback and precipitation in other regions. | $1.2M |
| C10-03 | Reflectivity sensitivity tests | Compare MCB-like forcing using physically constrained cloud response. | $0.8M |

| PO | Procurement package | Deliverable | Estimate |
|---|---|---|---|
| C11-01 | Radiative and water-budget closure | Independent campaign closure report. | $0.8M |
| C11-02 | Public archive and reproducibility | Complete data/code package. | $0.6M |
| C11-03 | Review workshop and assessment | External review and future-decision recommendations. | $0.6M |
| C12-01 | Contingency reserve | Weather, aircraft and instrument failures. | $2.5M |

## C. AMOC and ocean heat uptake - $60M

| PO | Procurement package | Deliverable | Estimate |
|---|---|---|---|
| O1-01 | Decision and observing-system design | Target variables, thresholds, array gaps and forecast experiments. | $1.2M |
| O1-02 | Array optimization modeling | Observing-system simulation and uncertainty reduction per instrument. | $0.8M |
| O1-03 | Independent design review | Proceed/redesign recommendation. | $0.5M |
| O2-01 | Mooring instrument packages | Current, temperature, salinity, pressure and oxygen sensors. | $5.5M |
| O2-02 | Mooring frames, lines and releases | Deep-ocean hardware and recovery systems. | $2.5M |
| O2-03 | Telemetry and data systems | Near-real-time data return and system-health monitoring. | $1.2M |
| O2-04 | Calibration and spares | Pre/post calibrations and replacement inventory. | $1.8M |
| O3-01 | Glider fleet | Long-duration sections across formation and boundary-current regions. | $2.5M |
| O3-02 | Argo and deep-Argo floats | Temperature, salinity, oxygen and deep-ocean profiles. | $2.0M |
| O3-03 | Autonomous surface vehicles | Air-sea flux, meteorology and upper-ocean observations. | $1.5M |
| O3-04 | Specialty profiling and turbulence systems | Mixing, microstructure and boundary-current observations. | $2.0M |
| O4-01 | Deployment research cruise | Mooring installation, hydrography, tracer and platform deployment. | $5.5M |
| O4-02 | Cruise science and laboratories | Shipboard chemistry, CTD, tracers and data processing. | $1.2M |

| PO | Procurement package | Deliverable | Estimate |
|---|---|---|---|
| O4-03 | International berthing and permits | Port, diplomatic and maritime coordination. | $0.8M |
| O5-01 | Array operations center | Telemetry, QA, instrument health and data release. | $2.0M |
| O5-02 | Glider/autonomous operations | Piloting, maintenance, recoveries and redeployments. | $1.5M |
| O5-03 | Annual servicing options | Targeted ship time and replacement deployments. | $1.5M |
| O5-04 | Data quality and calibration | Continuous quality control and cross-platform comparison. | $1.0M |
| O6-01 | Tracer-release experiment | Approved tracer release and multi-month sampling. | $2.5M |
| O6-02 | Turbulence and overflow survey | Mixing, entrainment and dense-water pathway measurements. | $2.0M |
| O6-03 | Convection process campaign | Wintertime air-sea flux and deep-mixing observations. | $2.0M |
| O7-01 | Greenland meltwater pathway study | Source markers, shelf transport and basin penetration. | $1.5M |
| O7-02 | Arctic freshwater export analysis | Strait transports, storage and attribution. | $1.2M |
| O7-03 | Freshwater-budget closure | Integrated freshwater inventory and uncertainty. | $1.3M |
| O8-01 | Recovery and repeat cruise | Recover instruments, repeat sections and redeploy selected assets. | $4.2M |
| O8-02 | Final calibrations and asset closeout | Post-deployment calibration and equipment disposition. | $1.3M |
| O9-01 | Ocean state estimation | Dynamically consistent heat, salt and transport reconstruction. | $1.5M |
| O9-02 | Multi-model assimilation comparison | Independent estimates and structural uncertainty. | $1.3M |
| O9-03 | Heat and freshwater budget analysis | Closed regional and basin budgets. | $1.2M |
| O10-01 | Seasonal prediction challenge | Prospective forecasts of convection and transport anomalies. | $0.8M |
| O10-02 | Decadal prediction challenge | Initialized forecasts and hindcast evaluation. | $0.8M |
| O10-03 | Reflectivity-response experiments | Coupled-model tests of spatial/seasonal cooling and AMOC response. | $0.9M |
| O11-01 | Independent instrument and data audit | Calibration, loss, drift and uncertainty assessment. | $0.5M |

| PO | Procurement package | Deliverable | Estimate |
|---|---|---|---|
| O11-02 | Open ocean-data archive | Standardized data, code and documentation. | $0.5M |
| O11-03 | International assessment workshop | Decision-focused AMOC and model-evaluation report. | $0.5M |
| O12-01 | Lost-instrument and ship-delay reserve | Replacement instruments, ship time and severe-weather response. | $1.0M |

## How to contract the program efficiently

Issuing hundreds of unrelated contracts would create excessive transaction cost and fragmented accountability. The Managing Organization should establish approximately ten master agreements with campaign-specific task orders:

| Master agreement | Task orders covered |
|---|---|
| Aircraft and airborne science | Aircraft access, payload integration, airworthiness, sorties and field support. |
| Research vessels and autonomous ocean platforms | Cruises, moorings, gliders, floats, surface vehicles and maritime logistics. |
| Atmospheric instrumentation and calibration | Aerosol, cloud, radiation, radar, lidar, gases and metrology. |
| Satellite products and calibration/validation | Overpass planning, retrievals, underflights and long-term data continuity. |
| Field-campaign logistics | Sites, shipping, facilities, communications and safety. |
| High-resolution and global modeling | LES, CRM, storm-resolving and Earth-system model development. |
| Data assimilation and scientific software | Common data systems, state estimation, visualization and HPC. |
| Scientific-analysis consortium | University and laboratory research subawards. |
| Environmental, legal and engagement services | Review, permits, consultation, public process and ethics. |
| Independent evaluation and open science | Audits, blinded challenges, replication, archives and assessment workshops. |

Each task order should specify a decision-relevant deliverable, measurable acceptance criteria, uncertainty requirements, open-data and code obligations, safety and stop-work clauses, payment milestones, change-control procedures and options that are exercised only when scientifically justified.

# Recipients of Purchase Orders

**Prompt to AI:** Who might receive the purchase orders, subawards and task orders described above?

**Response From AI:**

The fund should use competitive selection and should not assume that any named organization would participate. The examples below identify plausible capabilities rather than preselected winners. Government participation would often require cooperative or reimbursable agreements rather than ordinary commercial purchase orders.

## Recommended program consortium

| Role | Plausible organizations |
|---|---|
| Fiduciary and program-management prime | RTI International, Battelle, or another independent nonprofit research institute with large-program procurement and audit systems. |
| Atmospheric-science integration | UCAR/NSF NCAR, working with NOAA laboratories, universities and international partners. |
| Model evaluation and intercomparison | Program for Climate Model Diagnosis and Intercomparison (PCMDI), GeoMIP/CMIP networks, NCAR and independent model centers. |
| Radiation and satellite calibration | NASA Langley, NASA Goddard, NOAA, DOE ARM, national metrology organizations and university remote-sensing groups. |
| Aerosol and cloud observations | NOAA Chemical Sciences Laboratory, DOE ARM, NASA airborne-science teams, NCAR Earth Observing Laboratory and university laboratories. |
| Ocean and AMOC integration | NOAA Atlantic Oceanographic and Meteorological Laboratory, Woods Hole Oceanographic Institution, Scripps, University of Miami, UK National Oceanography Centre and international array partners. |
| Independent environmental review | AECOM, Ramboll, RTI or another competitively selected environmental assessment organization separated from experiment leadership. |
| Public engagement and conflict resolution | Consensus Building Institute, Keystone Policy Center or comparable international organizations. |
| Independent scientific review | National Academies or a separately appointed international panel with disclosed conflicts. |

## A. Aerosol radiative-forcing closure campaign

| Procurement area | Plausible recipients |
|---|---|
| Science design and synthesis | NOAA CSL/CIRES, University of Washington, University of Leeds, University of Oxford, NASA GISS or NCAR-led consortium. |
| Aerosol composition and optical instruments | NOAA CSL instrument teams, Aerodyne Research, TSI, Droplet Measurement Technologies, Handix Scientific and university aerosol laboratories. |
| CCN and hygroscopicity | NOAA, DOE ARM, NCAR and university cloud-aerosol groups, with commercial instrument suppliers. |
| Cloud microphysics | NCAR EOL, DOE ARM, NASA airborne teams and experienced university cloud laboratories. |
| Airborne radiation and remote sensing | NASA Langley, NASA Goddard, NOAA and university lidar/radar groups. |
| Research aircraft | NASA airborne-science programs, NSF NCAR aircraft, NOAA Aircraft Operations Center, SAFIRE or other currently verified international operators. |
| Research vessel and autonomous surface platforms | NOAA fleet, UNOLS institutions, Saildrone or comparable autonomous-platform operators. |
| Satellite products | NASA, NOAA, EUMETSAT, ESA and university retrieval teams. |
| LES and process modeling | NCAR, University of Washington, Max Planck Institute for Meteorology, University of Hamburg, UK Met Office and selected university groups. |
| Independent model evaluation | PCMDI, a firewalled NCAR team, national metrology laboratories or an independent statistics consortium. |

## B. Marine low-cloud campaign

| Procurement area | Plausible recipients |
|---|---|
| Campaign science leadership | University of Washington cloud group, NCAR, NOAA, DOE ARM, University of Leeds, University of Miami and international low-cloud experts. |
| Aircraft platforms | NSF NCAR C-130 or University of Wyoming King Air for in-cloud work; NSF NCAR Gulfstream V for above-cloud/context work; NASA, NOAA, SAFIRE or other verified aircraft depending on payload and altitude. |
| Ship and surface observations | UNOLS research vessels, NOAA vessels, DOE ARM Mobile Facility, autonomous surface-vehicle operators. |

| Procurement area | Plausible recipients |
|---|---|
| Cloud radar and lidar | DOE ARM, NCAR EOL, NOAA/NASA groups and university radar laboratories. |
| Large-eddy simulation | University of Washington, NCAR, Max Planck Institute for Meteorology, University of Hamburg, Delft University of Technology and UK Met Office groups. |
| Parameterization development | GFDL, NCAR, NASA GISS, UK Met Office, ECMWF, MPI-M and university teams, through open competitive calls. |
| Independent closure | PCMDI, DOE ARM data quality office, national metrology institutes and independent radiative-transfer experts. |

## C. AMOC and ocean heat uptake

| Procurement area | Plausible recipients |
|---|---|
| Array and cruise leadership | WHOI, NOAA AOML, Scripps Institution of Oceanography, University of Miami, UK National Oceanography Centre and existing RAPID/OSNAP partners. |
| Mooring systems | WHOI, Scripps, NOC, NOAA laboratories and qualified ocean-instrument manufacturers. |
| Gliders, floats and autonomous vehicles | Scripps, WHOI, NOAA, Teledyne Webb Research, Saildrone and international Argo partners. |
| Tracer and mixing experiments | WHOI, Scripps, University of Washington, University of Southampton/NOC and specialist ocean-mixing groups. |
| Greenland and Arctic freshwater | WHOI, University of Washington, NOC, GEOMAR, Danish/Greenland institutions and Arctic research consortia. |
| Ocean state estimation | MIT, NASA JPL, NOAA/GFDL, NCAR, ECMWF and international ocean-assimilation centers. |
| Coupled-model experiments | GFDL, NCAR, NASA GISS, UK Met Office, MPI-M, IPSL and other CMIP centers. |
| Independent review | An international panel administered separately from array operators and model developers. |

## Selection principles

7. **Separate design from evaluation.** The team that builds a parameterization should not be the only team deciding whether it improved the model.

8. **Use existing infrastructure.** Strengthen proven aircraft, vessel, satellite, ARM, Argo and AMOC programs rather than duplicating them.
9. **Fund international replication.** At least one major campaign and model challenge should include independently led non-U.S. teams.
10. **Avoid institutional capture.** No single model center, university or laboratory should control the observing plan, analysis, funding decisions and final assessment.
11. **Require open deliverables.** Recipients should provide raw and calibrated data, code, configuration files, uncertainty calculations and documentation.
12. **Preserve critical expertise.** Long-term instrument, calibration and data-stewardship teams should receive stable support rather than one-off grants that disappear after a campaign.

# Project Management

**Prompt to AI:** Who should serve as the Managing Organization, and how should the $1 billion program be structured?

**Response From AI:**

The Managing Organization should be an established independent nonprofit research institute with strong procurement, audit, scientific-program and risk-management systems. It should not be a new organization receiving $1 billion at inception, and it should not be a model center that expects to win a large share of the research awards.

**Recommended structure: RTI International as fiduciary and program manager, with UCAR as the principal atmospheric-science integrator, PCMDI as a core model-evaluation partner, and an international ocean consortium for AMOC and heat-uptake work.**

RTI is an illustrative first choice, not a conclusion that it would accept the assignment. Battelle or another independent nonprofit research institute could be selected through a competitive process. UCAR could also serve as the Managing Organization if the Funding Source places the highest weight on atmospheric-science integration, provided procurement and evaluation are independently protected.

## Proposed organizational structure

| Entity | Principal responsibility |
|---|---|
| Funding Source | Sets mission, maximum commitment, restrictions, tranche conditions and major reserved decisions. |
| Agreement Oversight Board | Protects funds, approves annual plans and major awards, commissions audits and can replace the Managing Organization. |
| Managing Organization | Employs program staff, maintains accounts, issues awards, accepts deliverables, reports and enforces contracts. |
| Scientific Advisory Panel | Determines scientific priorities, experiment design quality, value of information and model-evaluation requirements. |
| Safety, Ethics and Governance Board | Approves or rejects controlled perturbations and other activities requiring heightened review. |

| Entity | Principal responsibility |
|---|---|
| UCAR/atmospheric integrator | Coordinates atmospheric field campaigns, model teams, data standards and cross-campaign synthesis. |
| PCMDI/model evaluation unit | Maintains benchmarks, held-out tests, model lineage information and independent performance assessment. |
| Ocean integration consortium | Coordinates AMOC, ocean heat uptake, freshwater, sea ice, arrays, cruises and ocean-model assimilation. |
| Research recipients and vendors | Perform defined science, engineering, observation, modeling, logistics and review work. |

## Why an independent nonprofit institute?

| Possible MO | Assessment |
|---|---|
| Independent nonprofit research institute | Best overall balance of fiduciary capacity, multidisciplinary staff, contracting flexibility and public-interest credibility. |
| Foundation | Better suited to be the Funding Source; usually not designed to run aircraft campaigns, ocean arrays, model software and hundreds of subawards. |
| University | Strong research performer but potentially both judge and beneficiary; procurement and institutional conflicts may be difficult at $1B scale. |
| Government laboratory | Essential performer, but a private Funding Source may have limited control and international contracting flexibility. |
| Model center | Deep expertise, but it should not control evaluation of its own model and allocation of funds to competing centers. |
| For-profit prime contractor | Can execute well, but creates concerns about profit, proprietary outputs and incentives to expand the program. |
| New special-purpose nonprofit | Could be appropriate later, after operating under an experienced host and demonstrating sound controls. |

## Program Management Office

A five-year, $1 billion program might require a central staff of approximately 70–110 full-time equivalents, supplemented by external reviewers. The office would include:

- Program director and deputy directors for atmospheric science, ocean science, modeling and operations.
- Project managers for each major campaign and model-development portfolio.
- Procurement officers and subaward specialists.
- Finance, audit, compliance and cost-analysis staff.
- Data, software, cyberinfrastructure and open-science staff.
- Safety, environmental, legal, ethics and engagement staff.
- Independent evaluation and performance-measurement staff.
- Communications staff responsible for factual public reporting rather than advocacy.

A program-management and common-service allowance of approximately 5%–7%—$50M to $70M over five years—would be plausible if separately budgeted and transparently reported. Direct research performed by the MO should be capped without Funding Source approval.

## Funding in tranches

| Funding stage | Amount | Purpose |
|---|---|---|
| Organization and design period | $30M | Select leadership, boards and integrators; establish metrics, procurement, data and ethics systems. |
| Year 1 authorization | $120M | Baseline observations, instrument/calibration work, data audit and campaign design. |
| Year 2 authorization | $190M | Initial aerosol, radiation, cloud and ocean field work; model baselines. |
| Year 3 authorization | $240M | Major intensive campaigns, high-resolution modeling and parameterization work. |
| Year 4 authorization | $240M | Replication across regimes, multi-model implementation and reflectivity-control tests. |
| Year 5 authorization | $180M | Held-out validation, integrated assessment, archive, transition and final reporting. |
| Maximum commitment | $1.000B | |

Each tranche should depend on an approved annual operating plan, accepted prior deliverables, independent audit, open-data compliance, updated risk analysis and evidence that the next activities have high expected information value.

## Ring-fenced accounting and limits on self-awards

- Separate program bank and accounting records or an equivalent legally identifiable restricted fund.
- Quarterly commitments, expenditures and forecasts by task order and recipient.
- Annual independent financial and performance audits reporting directly to the Oversight Board.
- Competitive procurement above defined thresholds and public sole-source justification.
- Disclosure of related-party transactions and organizational conflicts.
- Return or approved disposition of unused funds, equipment and interest earned.
- MO administrative costs separately identified and capped.
- Direct research by the MO limited to a small share unless independently competed and approved.

## Division of authority

| Authority | Central question |
|---|---|
| Funding Source | Why the program exists, maximum funding, prohibited uses and whether future tranches are released. |
| Managing Organization | How approved work is contracted, staffed, monitored and paid. |
| Scientific Advisory Panel | Whether a question matters and whether the proposed work can answer it. |
| Safety, Ethics and Governance Board | Whether a controlled perturbation or sensitive activity is acceptable to conduct. |
| Agreement Oversight Board | Whether the MO is complying, managing money well and delivering value. |
| Independent Model Evaluation Unit | Whether model performance improved on preregistered and held-out tests. |

No project manager, principal investigator or model-development team should be able to authorize a controlled atmospheric perturbation, accept its own deliverable and declare its own model improvement without independent approval.

# Funding Source Requirements

**Prompt to AI:** What requirements should the Funding Source impose to maximize climate benefit per dollar and make the results openly available?

**Response From AI:**

The Funding Source should require that the program produce a global public research asset. Open publication is essential, but it must be paired with decision-focused design, stage gates, independent validation, transparent procurement and explicit stop rules. Otherwise the program could openly publish a large amount of low-value work.

## Open by default

| Output | Recommended requirement |
|---|---|
| Papers, reports, presentations and protocols | CC BY 4.0 or an equivalent attribution license. |
| Measurement data and metadata | CC0 or equivalent public-use terms where legally possible. |
| Model source code, analysis code and software | OSI-approved license such as Apache-2.0, BSD-3-Clause or MIT. |
| Model configurations and inputs | Public release with versioned checksums and machine-readable documentation. |
| Hardware designs | Editable CAD, drawings, bills of material and test procedures under an open-hardware license. |
| Calibration and quality records | Public with narrow redactions only for legitimate safety or personal-information concerns. |
| Patents and inventions | Defensive publication or worldwide royalty-free, nonexclusive licensing for climate-research use. |

## Value-of-information requirement

Before authorizing each major activity, the MO should answer:

13. What important uncertainty will this work reduce?

14. What future decision depends on the result?
15. What competing hypotheses or model formulations will be distinguished?
16. What result would cause the program to stop, redesign or redirect funds?
17. Could existing data, a natural experiment or a less expensive model test answer the question?
18. What accuracy is required, and can the proposed instruments or simulations achieve it?
19. Why is the selected recipient and price the best available approach?
20. How will independent researchers reproduce and challenge the conclusion?

## Preregistration and held-out testing

Before data collection or before selected observations are revealed, the program should register hypotheses, primary metrics, model versions, parameter choices, exclusion rules, uncertainty methods and decision thresholds. Exploratory analysis remains valuable but should be labeled as exploratory.

At least 20%–30% of critical observations should be held out from model development where practical. Models should be evaluated on new regimes, later periods, different geographic regions and variables that were not used for tuning. This is essential for detecting overfitting and compensating errors.

## Open-data deadlines

| Material | Publication deadline |
|---|---|
| Experiment or campaign description | Before operations, except narrowly protected logistics. |
| Platform tracks, source records and preliminary metadata | Within 7–30 days. |
| Level-0 raw instrument data | Within 60–90 days. |
| Calibrated, quality-controlled data | Within 6 months. |
| Model source, configuration and exact experiment inputs | At the time results are first publicly reported, and no later than 9 months. |
| Final analysis dataset and reproducibility package | Within 12 months. |
| Preprint or complete technical report | Within 12 months, including negative and inconclusive results. |

## Complete reproducibility package

- Raw and calibrated observations, including quality flags and excluded records.
- Instrument configuration, firmware, calibration standards, inlet corrections and drift adjustments.
- Time, location, platform and meteorological metadata.
- Model source code, compiler information, external libraries and version identifiers.
- Initial conditions, boundary conditions, emissions, forcing files and namelists.
- Analysis scripts, notebooks, statistical models and uncertainty calculations.
- Machine-readable data dictionaries and provenance records.
- Instructions that allow an independent team to reproduce every major figure and table.

## Model-performance requirements

A model modification should not be accepted because it improves one preferred metric. The contract should require a broad scorecard and prohibit hidden compensation. For example, a cloud change that improves top-of-atmosphere radiation but worsens precipitation, boundary-layer structure or surface flux may not constitute progress.

| Criterion | Acceptance principle |
|---|---|
| Energy-budget closure | Top-of-atmosphere, atmospheric and surface shortwave/longwave fluxes close within stated uncertainty. |
| Process fidelity | Observed causal relationships are reproduced, not merely climatological averages. |
| Out-of-sample performance | Improvement persists in held-out periods, regimes and locations. |
| Cross-variable consistency | Temperature, clouds, precipitation, humidity, ocean heat and circulation improve together or tradeoffs are explicit. |
| Conservation and numerical integrity | Energy, water, mass and tracers are conserved to defined tolerances. |
| Structural robustness | Results are tested across independent models and parameterization families. |
| Decision relevance | Improvement narrows uncertainty in a reflectivity or climate-risk decision quantity. |

## Independent validation budget

Approximately 10% of the program should support independent replication, metrology, model challenges and evaluation. Original teams should not be the only groups assessing their own success.

- Prospective predictions made before selected observations are revealed.
- Duplicate measurements using different physical techniques.
- Independent reprocessing of raw data.
- Independent implementations of key parameterizations.
- Model-lineage analysis to avoid treating closely related models as independent evidence.
- External audits of calibration, data exclusions, uncertainty and code changes.

## Procurement and payment controls

- Measurable deliverables and objective acceptance criteria in every major award.
- Milestone payments with 10%–15% withheld until data, code, documentation and licenses are accepted.
- Competitive bidding above approximately $250,000, with documented price reasonableness.
- Board approval and public justification for sole-source awards above a defined threshold.
- Formal change orders for changes in cost, schedule, experimental conditions, key personnel, data rights or acceptance tests.
- Stop-work authority when scientific value, safety, observability or data quality no longer supports continuation.
- Audit rights extending to lower-tier subcontractors and subrecipients.

## Program-wide transparency dashboard

The MO should maintain a public dashboard showing every award above a defined threshold, recipient, original and current value, deliverables, milestone status, payments, administrative costs, sole-source justification, data products and links to reports and repositories. Protected personal data, export-controlled information and legitimate security details may be narrowly redacted.

## Suggested performance scorecard

| Metric | Illustrative target |
|---|---|
| Calibrated datasets released on schedule | At least 95% |
| Major results reproducible by an independent team | At least 90% |
| Critical experiments with preregistered decision criteria | 100% |
| Major model changes tested on held-out data | 100% |

| Metric | Illustrative target |
| --- | --- |
| POs/subawards with measurable acceptance tests | 100% |
| Negative and inconclusive results publicly reported | 100% |
| Major scientific claims with complete code/configuration package | 100% |
| Sole-source commercial spending | Below 20%, absent documented necessity |
| Unresolved audit findings older than six months | Zero |
| Research spending controlled by any one model center | Below a board-approved concentration limit |

The central contractual principle should be: the purpose is not to spend $1 billion or prove that sunlight reflection should be deployed. The purpose is to produce reliable, reusable knowledge that allows the world to make better decisions under uncertainty.

# Top 25 Papers

**Prompt to AI:** Summarize 25 papers that are especially useful for designing a research fund to improve climate models for clouds, aerosols, radiation, ocean circulation and sunlight-reflection decisions.

**Response From AI:**

“Top” is necessarily subjective. The list below emphasizes historical influence, scientific importance and direct usefulness for the proposed program. It is not a citation-count ranking and is not a complete literature review.

## 1. Bony et al., 2006 — “How Well Do We Understand and Evaluate Climate Change Feedback Processes?”

A foundational review of feedback diagnosis. It explains why clouds dominate uncertainty in climate sensitivity and why model evaluation must examine physical mechanisms rather than global averages alone.

## 2. Gleckler, Taylor and Doutriaux, 2008 — “Performance Metrics for Climate Models”

Introduces systematic multi-variable metrics for comparing models with observations. It is central to building transparent scorecards while avoiding reliance on a single metric.

## 3. Stephens et al., 2012 — “An Update on Earth’s Energy Balance in Light of the Latest Global Observations”

Synthesizes top-of-atmosphere, atmospheric and surface energy flows and their uncertainty. It shows why radiative closure and instrument calibration are prerequisites for detecting small changes in planetary albedo.

## 4. Stevens and Bony, 2013 — "What Are Climate Models Missing?"

Argues for closer integration of observations, theory and models, with particular attention to clouds and convection. The paper motivates process-focused experiments rather than simply increasing model complexity.

## 5. Bony et al., 2015 — "Clouds, Circulation and Climate Sensitivity"

Frames cloud feedback as inseparable from atmospheric circulation. It helped organize modern research around specific cloud regimes and dynamical controls.

## 6. Eyring et al., 2016 — "Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6)"

Defines the coordinated experimental framework used by global modeling centers. CMIP demonstrates the value—and limits—of common protocols for separating scenario, model and internal-variability effects.

## 7. Ceppi et al., 2017 — "Cloud Feedback Mechanisms and Their Representation in Global Climate Models"

A comprehensive review of low, high and mixed-phase cloud feedbacks. It maps which physical processes most need field and high-resolution constraints.

## 8. Bodas-Salcedo et al., 2014 — "Origins of the Solar Radiation Biases over the Southern Ocean in CFMIP2 Models"

Shows how cloud-phase and microphysical errors create major Southern Ocean radiation biases. It is a direct rationale for mixed-phase cloud campaigns and process-oriented satellite simulators.

## 9. Tan, Storelvmo and Zelinka, 2016 — "Observational Constraints on Mixed-Phase Clouds Imply Higher Climate Sensitivity"

Demonstrates how the representation of supercooled liquid water influences cloud feedback and climate sensitivity. It also illustrates the opportunities and limitations of observational constraints.

## 10. Brient and Schneider, 2016 — “Constraints on Climate Sensitivity from Space-Based Measurements of Low-Cloud Reflection”

Links observed low-cloud behavior to model feedback and sensitivity. It is relevant to designing held-out satellite and field tests for subtropical clouds.

## 11. Sherwood et al., 2020 — “An Assessment of Earth’s Climate Sensitivity Using Multiple Lines of Evidence”

Integrates process understanding, historical change, paleoclimate and emergent constraints. It provides a model for combining evidence without treating any one line as decisive.

## 12. Zelinka et al., 2020 — “Causes of Higher Climate Sensitivity in CMIP6 Models”

Identifies stronger positive cloud feedback—especially from low clouds—as a major reason some CMIP6 models are more sensitive. It shows how parameterization choices alter decision-relevant warming estimates.

## 13. Bellouin et al., 2020 — “Bounding Global Aerosol Radiative Forcing of Climate Change”

Provides a comprehensive assessment of aerosol direct, cloud and surface effects. It highlights the persistent uncertainty in anthropogenic aerosol forcing and the need for causal closure experiments.

## 14. Myhre et al., 2013 — “Radiative Forcing of the Direct Aerosol Effect from AeroCom Phase II Simulations”

Compares global aerosol models and observations. The spread demonstrates how emissions, optical properties, transport and humidity produce uncertainty even before cloud interactions are included.

## 15. Ghan, 2013 — “Technical Note: Estimating Aerosol Effects on Cloud Radiative Forcing”

Clarifies how to diagnose aerosol-cloud radiative effects while separating changes in clear-sky and cloudy-sky radiation. It is useful for defining campaign and model output requirements.

## 16. Malavelle et al., 2017 — “Strong Constraints on Aerosol-Cloud Interactions from Volcanic Eruptions”

Uses a volcanic natural experiment to test aerosol-cloud responses. It demonstrates both the power of large perturbations and the difficulty of extrapolating from one event or regime.

## 17. Christensen et al., 2022 — coordinated analyses of the 2020 marine-fuel sulfur change and ship-track response

Studies the global emissions perturbation created by low-sulfur shipping fuel. This class of work illustrates how policy changes can constrain aerosol-cloud forcing without deliberate climate-scale experiments.

## 18. Stevens et al., 2021 — “EUREC4A” campaign overview

Describes a major international field campaign designed around shallow trade-wind clouds, circulation and climate feedback. EUREC4A is a strong organizational and scientific precedent for the proposed low-cloud campaign.

## 19. Stevens et al., 2019 — “DYAMOND: The Dynamics of the Atmospheric General Circulation Modeled on Non-hydrostatic Domains”

Introduces coordinated global storm-resolving simulations. DYAMOND shows how kilometre-scale models can expose differences in convection and cloud organization that parameterized models hide.

## 20. Satoh et al., 2019 — review of global cloud-resolving modeling

Summarizes the development, promise and computational limitations of global storm-resolving models. It supports using them as experimental laboratories and parameterization guides, not automatically as truth.

## 21. Palmer and Stevens, 2019 — "The Scientific Challenge of Understanding and Estimating Climate Change"

Calls for a step change in computing, observations and physical modeling. It argues that climate science needs prediction systems whose uncertainty is connected to resolved processes.

## 22. Loeb et al., 2021 — "Satellite and Ocean Data Reveal Marked Increase in Earth's Heating Rate"

Combines satellite radiation and ocean heat observations to diagnose changes in Earth's energy imbalance. It underscores the importance of independent observing systems and careful attribution.

## 23. Lozier et al., 2019 — "A Sea Change in Our View of Overturning in the Subpolar North Atlantic"

Uses the OSNAP array to show that overturning variability is strongly influenced by the eastern subpolar gyre rather than only the Labrador Sea. It demonstrates how sustained observations can overturn model assumptions.

## 24. Frajka-Williams et al., 2019 — "Atlantic Meridional Overturning Circulation: Observed Transport and Variability"

Reviews AMOC observing arrays, methods and variability. It is a guide to what is measured, where uncertainty remains and how observations should constrain coupled models.

## 25. Weijer et al., 2020 — "Stability of the Atlantic Meridional Overturning Circulation: A Review and Synthesis"

Synthesizes theory, paleoclimate, observations and models concerning AMOC stability and thresholds. It is essential for defining what a reflectivity strategy intended to reduce AMOC risk must predict and monitor.

## Ten papers to read first

For program design, I would begin with Bony 2015; Ceppi 2017; Bellouin 2020; Stevens 2021 (EUREC4A); Stevens 2019 (DYAMOND); Palmer and Stevens 2019; Loeb 2021; Lozier 2019; Frajka-Williams 2019; and Weijer 2020. Together they connect the program's central needs: cloud processes, aerosol forcing, radiative closure, high-resolution modeling, sustained observations and ocean-circulation risk.

*Bibliographic details and paper selections should receive a final literature review by the Scientific Advisory Panel before publication or procurement use.*

# Top Researchers and Organizations

**Prompt to AI:** Who are leading researchers and organizations relevant to this climate-model experimental research program?

**Response From AI:**

There is no authoritative ranking. The examples below emphasize scientific influence, current leadership and relevance to clouds, aerosols, radiation, model evaluation, storm-resolving modeling, ocean heat uptake, AMOC and decision-focused climate prediction. Affiliations should be verified before outreach.

## Leading researchers

| Researcher | Current or recent base | Principal relevance |
|---|---|---|
| Björn Stevens | Max Planck Institute for Meteorology | Clouds, convection, climate sensitivity, field campaigns and storm-resolving modeling. |
| Sandrine Bony | LMD/IPSL and Sorbonne Université/CNRS | Cloud feedbacks, circulation, climate sensitivity and EUREC4A leadership. |
| Robert Wood | University of Washington | Marine boundary-layer clouds, aerosol-cloud interactions, field observations and cloud susceptibility. |
| Piers Forster | University of Leeds | Earth radiation budget, radiative forcing, climate sensitivity and assessment leadership. |
| Trude Storelvmo | University of Oslo | Aerosol-cloud interactions, mixed-phase clouds and climate feedback. |
| Mark Zelinka | Lawrence Livermore National Laboratory | Cloud feedback, climate sensitivity and model diagnosis. |
| Johannes Quaas | Leipzig University | Aerosol-cloud forcing, satellite constraints and climate-model evaluation. |
| Olivier Boucher | IPSL/Sorbonne Université | Aerosols, radiative forcing, climate modeling and assessments. |
| Jim Haywood | University of Exeter / UK Met Office community | Aerosol-radiation interactions, observations, volcanic analogues and climate intervention. |

| Researcher | Current or recent base | Principal relevance |
|---|---|---|
| Graham Feingold | NOAA Chemical Sciences Laboratory | Cloud-aerosol interactions, process modeling and observational analysis. |
| Zhanqing Li | University of Maryland | Aerosol, cloud, radiation and surface-observation networks. |
| Graeme Stephens | NASA JPL / Colorado State University community | Clouds, precipitation, satellite observations and Earth energy balance. |
| Norman Loeb | NASA Langley Research Center | CERES radiation measurements, Earth energy imbalance and calibration. |
| Christian Jakob | Monash University | Cloud and convection parameterization, model evaluation and process-oriented development. |
| Tapio Schneider | California Institute of Technology | Climate dynamics, cloud feedback and computational climate modeling. |
| Tim Palmer | University of Oxford | Ensembles, uncertainty, numerical prediction and high-resolution climate modeling. |
| Ruby Leung | Pacific Northwest National Laboratory | Earth-system modeling, convection, precipitation extremes and model development. |
| David Randall | Colorado State University | Cloud parameterization, atmospheric modeling and model hierarchy. |
| Laure Zanna | New York University | Ocean circulation, machine learning, parameterization and climate prediction. |
| Susan Lozier | Georgia Institute of Technology | AMOC observations and OSNAP leadership. |
| Eleanor Frajka-Williams | National Oceanography Centre / University of Southampton community | AMOC observing systems, transport and variability. |
| M. Susan Lozier / OSNAP consortium leaders | International consortium | Subpolar overturning, sustained arrays and ocean-observation strategy. |
| John Marshall | MIT | Ocean circulation, climate dynamics and state estimation. |
| Raffaele Ferrari | MIT | Ocean mixing, circulation and heat uptake. |
| Marika Holland | NSF NCAR | Sea ice, polar climate and coupled-model feedbacks. |
| Clara Deser | NSF NCAR | Internal variability, large ensembles and attribution. |

| Researcher | Current or recent base | Principal relevance |
| --- | --- | --- |
| Ben Kravitz | Indiana University | GeoMIP, multi-model climate intervention experiments and control strategies. |
| Douglas MacMartin | Cornell University | Climate intervention control, uncertainty and decision design. |
| Simone Tilmes | NSF NCAR | Chemistry-climate modeling, SAI scenarios and Earth-system impacts. |
| Daniele Visioni | Cornell University | Stratospheric aerosols, intervention scenarios and model uncertainty. |

## Top organizations and networks

| Organization or network | Principal strength |
| --- | --- |
| NSF National Center for Atmospheric Research (NCAR) and UCAR | Integrated atmosphere, ocean, chemistry and Earth-system modeling; aircraft; field campaigns; supercomputing; data stewardship. |
| NOAA Chemical Sciences Laboratory | Aerosol, cloud, radiation, atmospheric chemistry, high-altitude and airborne measurements. |
| NOAA Geophysical Fluid Dynamics Laboratory | Global coupled-model development, clouds, aerosols, ocean circulation and climate projections. |
| NASA Langley Research Center | CERES radiation, airborne remote sensing, cloud/aerosol instruments and satellite validation. |
| NASA Goddard Space Flight Center | Satellite missions, Earth-system observations, data assimilation and global modeling. |
| DOE Atmospheric Radiation Measurement user facility | Long-term ground and mobile observations of clouds, aerosols, radiation and precipitation. |
| Lawrence Livermore National Laboratory / PCMDI | CMIP infrastructure, model diagnostics, benchmarks and intercomparison. |
| Max Planck Institute for Meteorology | Clouds, convection, field campaigns, Earth-system modeling and global storm-resolving simulation. |
| LMD/IPSL | Cloud feedback, circulation, aerosols, Earth-system modeling and international assessment. |
| UK Met Office Hadley Centre | Operational and climate prediction, coupled modeling, convection and aerosol/cloud research. |

| Organization or network | Principal strength |
|---|---|
| European Centre for Medium-Range Weather Forecasts | Data assimilation, numerical prediction, reanalysis and Earth-system model development. |
| University of Washington atmospheric science groups | Marine low clouds, aerosol-cloud interaction and field campaigns. |
| University of Leeds | Radiative forcing, aerosols, clouds, climate sensitivity and assessments. |
| EUREC4A consortium | International field-campaign model for shallow clouds, circulation and open data. |
| DYAMOND consortium | Coordinated global storm-resolving model intercomparison. |
| Cloud Feedback Model Intercomparison Project (CFMIP) | Common diagnostics and experiments for cloud feedback and model evaluation. |
| Aerosol Comparisons between Observations and Models (AeroCom) | Global aerosol-model intercomparison and forcing analysis. |
| Woods Hole Oceanographic Institution | AMOC arrays, ocean mixing, floats, moorings, state estimation and ocean process studies. |
| Scripps Institution of Oceanography | Argo, ocean observations, gliders, mixing and climate dynamics. |
| NOAA Atlantic Oceanographic and Meteorological Laboratory | AMOC and Atlantic observing systems, ocean heat and operational monitoring. |
| UK National Oceanography Centre | RAPID array, AMOC observations, autonomous systems and ocean modeling. |
| OSNAP consortium | Subpolar North Atlantic overturning observations and international coordination. |
| Argo and Deep Argo programs | Global and deep-ocean temperature, salinity and biogeochemical profiles. |
| Geoengineering Model Intercomparison Project (GeoMIP) | Common sunlight-reflection scenarios and multi-model comparison. |
| Degrees Initiative and Global South research networks | Independent regional research capacity, equity and broad participation in SRM assessment. |

## Best scientific core for the proposed fund

| Function | Suggested scientific core |
|---|---|
| Earth radiation budget and calibration | NASA Langley, NOAA, NASA Goddard, DOE ARM and metrology partners. |

| Function | Suggested scientific core |
| --- | --- |
| Aerosol forcing | NOAA CSL, AeroCom, Leeds, Leipzig, IPSL and university observation groups. |
| Marine low clouds | University of Washington, NCAR, DOE ARM, MPI-M, LMD/IPSL and EUREC4A teams. |
| Mixed-phase and polar clouds | NCAR, DOE ARM, University of Oslo, UK groups and Southern Ocean/Arctic campaign teams. |
| Storm-resolving modeling | DYAMOND centers, MPI-M, NCAR, ECMWF, UK Met Office, JMA and selected university groups. |
| Global-model evaluation | PCMDI, CFMIP, CMIP, independent statistics/metrology teams and satellite-observation groups. |
| AMOC and ocean heat | WHOI, NOAA AOML, Scripps, NOC, OSNAP, RAPID, Argo and coupled-model centers. |
| Reflectivity-control scenarios | GeoMIP, Cornell, NCAR, UChicago and independent regional-impact teams. |
| Global participation | Degrees Initiative, IISc, African, Latin American, Pacific and other regional research institutions. |

No single organization has all required capabilities. The strongest program would deliberately distribute authority among observation teams, model developers, oceanographers, high-resolution modelers, model evaluators, regional-impact researchers and independent critics.

# Scientific Advisory Panel

**Prompt to AI:** If a scientific panel were established to oversee the program, who might serve on it and how should conflicts be managed?

**Response From AI:**

I would create a 15-member Scientific Advisory Panel. It should include leading experts in clouds, aerosols, radiation, ocean circulation, uncertainty and climate intervention, while maintaining institutional and intellectual diversity. No institution should hold more than two voting seats, and at least one-third of the panel should be scientists who are not primarily identified with sunlight-reflection research.

*The following names are illustrative. I do not know whether any individual would be willing or available to serve, and affiliations should be verified before outreach.*

| Role | Illustrative member | Why |
|---|---|---|
| Chair | Piers Forster, University of Leeds | Radiative forcing, Earth energy budget, climate sensitivity and major assessment experience; broad enough to bridge observations, models and policy. |
| Vice-chair | Sandrine Bony, LMD/IPSL | Cloud feedback, atmospheric circulation, field-campaign leadership and model evaluation. |
| Marine low clouds | Robert Wood, University of Washington | Boundary-layer clouds, aerosol-cloud interactions, field experiments and MCB-relevant susceptibility. |
| Cloud and convection | Björn Stevens, MPI-M | Clouds, convection, field campaigns, model hierarchy and storm-resolving modeling. |
| Mixed-phase clouds | Trude Storelvmo, University of Oslo | Mixed-phase cloud physics, aerosol-cloud interaction and climate feedback. |
| Aerosol forcing | Johannes Quaas, Leipzig University | Aerosol-cloud radiative forcing, satellite constraints and global-model evaluation. |
| Earth radiation budget | Norman Loeb, NASA Langley | Satellite broadband radiation, calibration and Earth energy imbalance. |
| Model evaluation | Mark Zelinka, Lawrence Livermore/PCMDI community | Cloud feedback diagnosis, model sensitivity and intercomparison. |

| Role | Illustrative member | Why |
|---|---|---|
| Prediction and uncertainty | Tim Palmer, University of Oxford | Ensembles, numerical prediction, model error and uncertainty communication. |
| Storm-resolving models | Ruby Leung, Pacific Northwest National Laboratory | Earth-system modeling, convection, precipitation and high-resolution simulations. |
| AMOC observations | Susan Lozier, Georgia Tech | OSNAP and sustained overturning observations. |
| Ocean dynamics and heat uptake | John Marshall, MIT | Ocean circulation, state estimation and coupled climate dynamics. |
| Sea ice and polar feedback | Marika Holland, NSF NCAR | Sea-ice processes, polar amplification and coupled-model evaluation. |
| Climate intervention modeling | Ben Kravitz, Indiana University | GeoMIP, common experiments, climate control and multi-model uncertainty. |
| Global South and monsoon impacts | Govindasamy Bala, Indian Institute of Science | Hydrological cycle, monsoons, regional impacts and independent Global South perspective. |

## Rotating non-voting advisers

- Principal scientists for proposed field campaigns.
- Representatives of satellite, aircraft, vessel, ARM, Argo, AMOC-array and computing facilities.
- Independent statisticians, metrologists and software-reproducibility experts.
- Public-health, ecological and agricultural specialists when relevant impacts are evaluated.
- Representatives from countries and communities where field work would occur.
- International law and governance experts for any controlled perturbation.
- Funding Source and Managing Organization observers, without authority over scientific conclusions.

## Conflict-of-interest rules

21. The chair and vice-chair should not receive program research funding during their terms, except for documented salary or expenses associated with panel service.
22. A member must recuse from discussion and voting on an award benefiting their institution, laboratory, close collaborators or current funded project.
23. A recused member should not receive confidential competing proposals or participate informally in the decision.
24. At least eight unconflicted voting members should be required for a funding recommendation.

25. Awards above $25 million should receive additional external review by experts who do not serve on the standing panel.
26. All financial, institutional and intellectual conflicts—and all recusals—should be published.
27. The panel should include independent critics who can argue that an experiment or model-development path is not worth pursuing.

## Panel authority

The Scientific Advisory Panel should determine:

- Whether the question is decision-relevant and not already resolved.
- Whether the experiment or model challenge can distinguish competing explanations.
- Whether the measurement accuracy, sampling plan and model hierarchy are adequate.
- Whether the cost is proportionate to the expected information value.
- Whether the validation plan can detect overfitting and compensating errors.
- Whether the result would change a future decision, uncertainty range or research priority.

It should not have sole authority to approve a controlled atmospheric perturbation. A separate Safety, Ethics and Governance Board should determine whether the activity is lawful, responsible and acceptable to conduct.

## Voting standard

| Decision | Scientific approval standard |
|---|---|
| Routine data analysis, modeling and instrument awards | Simple majority of unconflicted members. |
| Major field campaign above $25M | Two-thirds vote, written value-of-information finding and external review. |
| Controlled atmospheric perturbation | Two-thirds of full panel, written finding that alternatives are inadequate, plus separate safety/governance and Oversight Board approval. |
| Acceptance of a major model improvement | Independent evaluation unit recommendation and panel approval based on preregistered, held-out and cross-variable tests. |
| Change in program scientific priorities above $25M | Two-thirds vote and Funding Source/Oversight Board concurrence. |

# Management Advisory Panel

**Prompt to AI:** If a panel were established to oversee the agreement with the Managing Organization, who might serve and what authority should it have?

**Response From AI:**

The Agreement Oversight Board should be separate from the Scientific Advisory Panel. Its purpose is to protect the Funding Source's money, enforce the agreement, manage organizational conflicts and verify that the program is producing useful, open results.

I would use a nine-member board: seven independent members and two Funding Source representatives. The selected Managing Organization, UCAR, PCMDI, major model centers and major research recipients should have no voting seats. Their leaders may attend as non-voting participants when invited.

*The illustrative individuals below represent the type and caliber of experience to seek. Availability and current roles must be verified.*

| Seat | Illustrative candidate type | Reason |
|---|---|---|
| Independent chair | France Córdova | Former NSF director, NASA chief scientist and university president; experience overseeing large scientific institutions. |
| Audit and accountability | A former U.S. Comptroller General, inspector general or major research-audit leader | Financial controls, performance evaluation, waste prevention and independent reporting. |
| Procurement and contracting | A former senior federal acquisition-policy official | Competition, cost analysis, contract structure, conflicts and procurement workforces. |
| Large technical programs | A former leader from a major national laboratory, aerospace research organization or applied-physics laboratory | Execution of complex, multi-institution science and engineering programs. |
| Philanthropic effectiveness | A senior foundation evaluation and strategy leader | Mission alignment, learning, grant effectiveness and tranche decisions. |
| Nonprofit governance | A former BoardSource or comparable governance leader | Board accountability, executive oversight, conflicts and organizational design. |

| Seat | Illustrative candidate type | Reason |
|---|---|---|
| International science governance | Peter Gluckman or a comparable international science-advice leader | Science diplomacy, international legitimacy, risk and broad participation. |
| Funding Source finance representative | Selected by FS | Authority over finance, grants, investments, accounting and risk. |
| Funding Source mission representative | Selected by FS | Authority to ensure alignment with climate-benefit and public-interest objectives. |

## Reserved authority

28. Approve the MO’s annual operating plan, budget and major reallocations.
29. Approve appointment, compensation or removal of the program director.
30. Approve major purchase orders and subawards above defined thresholds.
31. Commission financial, performance, cybersecurity, safety and open-science audits.
32. Suspend payments, work packages or field operations.
33. Require corrective-action plans and verify their completion.
34. Reject excessive overhead, weak acceptance criteria, sole-source awards or unexplained cost growth.
35. Enforce open-data, code, intellectual-property and conflict-of-interest requirements.
36. Recommend termination or replacement of the Managing Organization.
37. Approve the final transition, archive and disposition of equipment and unspent funds.

## Approval thresholds

| Decision | Approval needed |
|---|---|
| Annual program plan and budget | Majority of full board plus Funding Source concurrence. |
| Individual award above $5M | Board majority including Audit or Procurement Committee chair. |
| Award above $25M | Two-thirds of full board plus Funding Source concurrence. |
| Sole-source award above $1M | Written public justification and board approval. |
| Budget increase above 10% | Board approval and updated value-of-information analysis. |
| Transfer above $10M between major research categories | Board approval. |

| Decision | Approval needed |
|---|---|
| Controlled atmospheric perturbation | Scientific and safety/governance approval plus two-thirds board authorization. |
| Change in MO indirect-cost rate | Board and Funding Source approval. |
| Suspension or replacement of MO | Two-thirds board vote plus Funding Source concurrence. |

## Committee structure

### Audit and Risk Committee

- Financial statements, commitments, cash and forecast.
- Indirect costs, executive compensation and related-party transactions.
- Fraud, whistleblower reports, cybersecurity, insurance and liability.
- Cost overruns, asset control and annual independent audits.
- External auditors report directly to this committee, not to the MO’s CFO.

### Procurement and Compensation Committee

- Competition plans and sole-source justifications.
- Contract type, price reasonableness and milestone design.
- Executive and project-manager compensation.
- Conflicts, recusals and contractor concentration.
- Major amendments and change orders.

### Program Performance and Open Science Committee

- Which uncertainties were reduced and which decisions changed.
- Whether weak projects were cancelled promptly.
- Whether data, model code and reproducibility packages were released.
- Whether independent validation supports claimed model improvement.
- Whether administrative activity is being mistaken for scientific progress.

## Compensation

| Role | Illustrative compensation |
| --- | --- |
| Board chair | $150,000–$250,000 per year |
| Committee chairs | $75,000–$125,000 per year |
| Other independent members | $40,000–$80,000 per year |
| Travel and professional expenses | Paid separately under published policy |

At approximately $1M–$1.5M per year, a serious oversight board would cost well below 1% of the program and could prevent much larger losses from weak procurement, institutional capture or ineffective research.

# Agreements

**Prompt to AI:** What might the agreement between the Funding Source and Managing Organization, and the agreements between the MO and research recipients or vendors, look like?

**Response From AI:**

The agreements should form an enforceable chain:

**Funding Source → Managing Organization → scientific subrecipients, facilities and vendors**

Every material promise made by the MO to the Funding Source—open data, independent validation, safety, audit access, intellectual-property rights, conflict rules and termination authority—must flow into downstream agreements. This is an illustrative framework, not a substitute for legal, tax, environmental, aviation, maritime, export-control or insurance counsel.

## 1. Funding Source–Managing Organization agreement

I would call this the Master Climate Model Research Funding and Stewardship Agreement. It might be 60–100 pages plus schedules and would combine a restricted grant, cooperative agreement and program-management contract.

| Article | Illustrative provision |
|---|---|
| Parties | Funding Source and competitively selected Managing Organization. |
| Purpose | Produce reliable, openly available observations, models and decision tools needed to evaluate climate risk and potential sunlight-reflection strategies. |
| Maximum commitment | Up to $1 billion over five years; only approved tranches are legally obligated. |
| Restricted use | Funds only for approved research, observation, model development, evaluation and program management. |
| Prohibited uses | No climate-scale deployment, political advocacy using program funds, proprietary control of foreground research outputs or concealed releases. |
| Governance | Agreement Oversight Board, Scientific Advisory Panel, Safety/Ethics/Governance Board and Independent Model Evaluation Unit. |
| MO overhead | Fixed or capped rate, separately identified, with changes requiring approval. |

| Article | Illustrative provision |
|---|---|
| Procurement | Competition, cost/price analysis, conflicts, approval thresholds, flow-down and contractor monitoring. |
| Open science | Mandatory publication of observations, metadata, code, configurations, reports and funded designs under specified licenses and deadlines. |
| Model validation | Preregistered metrics, held-out observations, independent evaluation and prohibition on unsupported performance claims. |
| Safety and controlled perturbations | No activity without all scientific, environmental, legal, ethical and board approvals. |
| Reporting | Monthly financial dashboard, quarterly performance reports and annual audited statements. |
| Audit and access | Funding Source, board and independent auditors receive records, systems and site access. |
| Remedies | Payment suspension, corrective action, replacement of personnel, recovery of misused funds, termination and transition. |
| Transition | Transfer of records, data, contracts, equipment, licenses and remaining funds if the MO is replaced or the program ends. |

## Funding and accounting definitions

| Term | Meaning |
|---|---|
| Maximum authorized program size | The ceiling that may be provided over five years. |
| Obligated amount | The amount the Funding Source is currently legally committed to provide. |
| Approved budget authority | The amount the MO may commit through awards during the approved period. |
| Cash advanced | Funds transferred to the MO but not yet spent. |
| Committed amount | Signed downstream obligations not yet fully paid. |
| Expenditure | Cost incurred and accepted under the agreement. |
| Uncommitted balance | Funds still controlled by the Funding Source or unavailable for award. |
| Program income and interest | Treatment of interest, fees, credits and recoveries. |

## Reserved decisions

| Decision | Required approval |
|---|---|
| Annual operating plan | Oversight Board and Funding Source. |
| Award above $5M | Oversight Board. |
| Award above $25M | Two-thirds Oversight Board and Funding Source. |
| Controlled perturbation | Scientific, safety/governance, legal and Oversight Board approvals. |
| Sole-source award above $1M | Written justification and Oversight Board approval. |
| Major budget-category transfer | Oversight Board. |
| Change in open-access or model-validation requirements | Funding Source and Oversight Board. |
| Program director appointment/removal | Oversight Board. |
| Use of funds for operational deployment | Prohibited absent formal amendment and entirely new authorization. |

## Program Results Framework

For each major research activity, the MO should document:

38. The uncertainty being addressed and the current evidence.
39. The reflectivity or climate-risk decision that depends on the result.
40. Competing physical hypotheses or model formulations.
41. Expected information value and estimated cost.
42. Measurable deliverables and acceptance criteria.
43. Required measurement and prediction accuracy.
44. Success, failure, redesign and stop criteria.
45. Data, code and publication deadlines.
46. Independent validation and replication plan.
47. How the result will alter model weighting, parameterization or future funding.

## Illustrative open-science clause

*All research outputs produced using Program Funds—including reports, manuscripts, measurement data, metadata, model source code, model configurations, analysis software, laboratory protocols, drawings, calibration records, uncertainty calculations and reproducibility materials—shall be made publicly available under the licenses and deadlines specified in the Open Science Schedule, subject only to narrow, written and time-limited exceptions.*

## 2. MO–recipient research subaward

Use a research subaward when a university, laboratory or nonprofit exercises scientific judgment, employs investigators and carries out a portion of the program. The subaward should include:

| Section | Contents |
|---|---|
| Award identification | Recipient, project, amount, period, principal investigator and MO manager. |
| Decision objective | Question being answered, uncertainty and future decision. |
| Statement of work | Tasks, methods, platforms, models, experiments and analysis. |
| Milestones | Dates and measurable completion criteria. |
| Budget | Personnel, travel, equipment, computing, facilities, indirect costs and lower-tier awards. |
| Key personnel | Named leaders and approval required for replacement. |
| Model and data plan | Versions, repositories, raw data, metadata, calibration, code and release dates. |
| Validation | Preregistration, held-out data, independent evaluation and no tuning after seeing protected observations. |
| Publications | Preprints, attribution and open licenses. |
| Intellectual property | Background IP, foreground IP and required public licenses. |
| Equipment | Title, inventory, maintenance, access and disposition. |
| Safety and ethics | Permits, environmental review, incidents and stop-work authority. |
| Audit and monitoring | Records access, site visits, corrective actions and risk-based monitoring. |
| Flow-down | Required terms in every lower-tier subaward and subcontract. |
| Termination | Cause, convenience, transition, final data and closeout. |

## 3. Procurement contract or purchase order

Use a procurement contract for defined goods or services: aircraft or ship time, instruments, calibration, cloud computing, engineering, autonomous platforms, environmental review or data processing. It should be shorter and acceptance-oriented.

| Term | Illustrative provision |
|---|---|
| Recipient | Selected research-aircraft operator and payload integrator |
| Maximum amount | $6,500,000 |
| Deliverable | Approximately 30 instrumented sorties; approved flight records; synchronized platform data; calibration and airworthiness records; accepted raw and preliminary datasets. |
| Period | Illustrative 18-month integration and field period |
| Payment basis | Milestones and accepted deliverables, not flight hours alone |
| Open-data obligation | Platform and instrument records released under program schedule |
| Stop-work | MO may postpone or cancel for scientific, weather, safety or readiness reasons |

| **Milestone** | **Deliverable** | **Payment** |
|---|---|---|
| Contract signing | Insurance, project plan and key personnel | 5% |
| Preliminary design review | Approved interfaces, payload plan and risk register | 10% |
| Critical design review | Final drawings, hazards and integration plan | 15% |
| Ground acceptance | Payload and data system demonstrated | 15% |
| Flight-readiness review | Airworthiness, calibration and operations authorization | 10% |
| Field operations | Approved sortie block completed | 25% |
| Preliminary dataset | Raw data, flight logs and metadata accepted | 10% |
| Final acceptance | Calibrated data, documentation and open-license package | 10% |

## Deliverable acceptance

Avoid vague deliverables such as “support climate-model research.” A measurable example would be:

> Deliver a calibrated dataset of shortwave and longwave radiative flux above, within and below marine boundary-layer clouds; synchronize measurements within one second; document

instrument drift, angular response and platform attitude corrections; report uncertainty by component; and provide data and processing code in the required repository format.

The agreement should identify the accepting official, review period, objective tests, correction period, partial-acceptance rules, payment holdback and consequences if deficiencies are not corrected.

## Change control and flow-down

Formal written change orders should be required for changes in amount, schedule, sites, platform, measurement accuracy, model version, key personnel, lower-tier recipients, data rights or acceptance criteria. Emergency field decisions may be documented afterward, but they may not increase the authorized amount or weaken open-science requirements without approval.

*Recipient shall incorporate the applicable Open Science, Data Management, Model Validation, Intellectual Property, Safety, Conflict-of-Interest, Audit, Records-Retention, Incident-Reporting and Prohibited-Use requirements into every lower-tier agreement supported by Program Funds.*

## Recommended agreement attachments

| Attachment | Contents |
|---|---|
| FS–MO Schedule A | Program purpose, decision quantities and prohibited activities. |
| Schedule B | Five-year budget, tranche plan and cost definitions. |
| Schedule C | Governance, boards, reserved decisions and conflicts. |
| Schedule D | Procurement, subaward and cost-allowability manual. |
| Schedule E | Open science, data, software, IP and licensing. |
| Schedule F | Scientific quality, model validation and held-out testing. |
| Schedule G | Safety, environmental review and controlled-perturbation process. |
| Schedule H | Performance metrics, reporting and audit. |
| Schedule I | Ethics, whistleblower, cybersecurity and information exceptions. |
| Schedule J | Termination, transition, equipment and archive plan. |
| MO–recipient Exhibit 1 | Statement of work and science traceability matrix. |
| Exhibit 2 | Deliverable and acceptance matrix. |

| Attachment | Contents |
| --- | --- |
| Exhibit 3 | Budget, milestones and payment schedule. |
| Exhibit 4 | Data/model management and publication plan. |
| Exhibit 5 | Background and foreground IP. |
| Exhibit 6 | Safety, environmental and field requirements. |
| Exhibit 7 | Required flow-down provisions. |
| Exhibit 8 | Reporting and repository templates. |

# Model Validation and Decision Readiness

**Prompt to AI:** How should the program determine whether climate models have improved enough to support decisions about reflecting sunlight?

**Response From AI:**

The program should not declare victory because a new model has finer resolution, more processes or better agreement with the historical global temperature curve. It should use a formal Model Validation and Decision Readiness framework with preregistered tests, held-out observations, cross-variable constraints and explicit uncertainty targets.

## Model Validation Ladder

| Level | Required evidence |
|---|---|
| Level 1: Numerical and conservation integrity | The model conserves energy, water, mass and tracers; results are reproducible across machines and documented versions. |
| Level 2: Process fidelity | Laboratory and field-scale processes—cloud microphysics, aerosol aging, turbulence, convection, mixing—match observations within stated uncertainty. |
| Level 3: Regime and regional fidelity | The model reproduces cloud regimes, radiation, precipitation, ocean transports and variability in multiple regions not used for tuning. |
| Level 4: Historical causal attribution | The model explains observed changes in temperature, radiation, aerosols, clouds and ocean heat without implausible compensating errors. |
| Level 5: Prospective prediction | The model successfully predicts withheld campaigns, natural perturbations or later periods before seeing the data. |
| Level 6: Intervention transferability | Validated process models translate realistic SAI or MCB operations into forcing, and global models reproduce responses across independent implementations. |
| Level 7: Decision readiness | Uncertainty in required forcing, spatial pattern, timing and major risks is narrow enough for a specified decision and monitoring system. |

## Core benchmark suite

| Benchmark family | Examples |
|---|---|
| Planetary energy budget | Reflected shortwave, outgoing longwave, net imbalance and trend consistency with ocean heat uptake. |
| Cloud radiative effect | By low-cloud, deep-convective, mixed-phase, polar and transition regimes. |
| Aerosol direct forcing | Optical depth, absorption, vertical profile, composition and clear-sky flux response. |
| Aerosol-cloud forcing | CCN-to-droplet-to-cloud-to-radiation chain under controlled meteorological conditions. |
| Hydrological cycle | Global and regional precipitation, evaporation, water vapor, monsoons and extremes. |
| Ocean heat uptake | Basin and depth distribution, mixing, air-sea flux and heat-content trends. |
| AMOC and transports | Mean state, variability, heat/freshwater transport and response to freshwater/heat forcing. |
| Sea ice and snow | Seasonal cycle, thickness, albedo, melt and coupling to clouds and ocean. |
| Natural perturbations | Volcanic aerosol, wildfire smoke, ENSO and rapid emissions changes. |
| Intervention experiments | Idealized and physically realistic SAI/MCB scenarios, including spatial patterns, termination and monitoring. |

## No-compensating-error rule

A model should not pass because a positive cloud bias cancels a negative aerosol-forcing bias, or because excessive ocean heat uptake hides excessive climate sensitivity. The evaluation unit should diagnose component budgets and causal relationships. Every claimed improvement should include a “what got worse?” report across the full benchmark suite.

## Prospective prediction challenges

| Challenge | Design |
|---|---|
| Campaign forecast | Before a field campaign, predict cloud, aerosol, radiation or ocean variables for specified cases and archive the prediction. |

| Challenge | Design |
|---|---|
| Natural-event forecast | When a volcano, wildfire or emissions perturbation occurs, issue predictions before the full observational record is available. |
| Time-split test | Develop on an earlier period; test on later years with independent instruments. |
| Geographic transfer | Develop in one region; test in a physically similar but independent region. |
| Variable holdout | Tune on state variables but test on radiative flux, precipitation, transport or other withheld responses. |
| Cross-model replication | Implement the same physical change in at least three structurally different models. |

## Reflectivity Decision Readiness Levels

| Readiness level | Meaning |
|---|---|
| RDRL 1 — Conceptual | Models can represent an idealized forcing, but observational constraints on key processes remain broad. |
| RDRL 2 — Process constrained | Relevant aerosol/cloud/radiative processes are measured in several regimes and process models reproduce them. |
| RDRL 3 — Global response constrained | Multiple global models with validated process links agree on broad response and explain disagreement. |
| RDRL 4 — Strategy comparison | Models can compare quantity, location and timing with quantified regional tradeoffs, monitoring and termination risk. |
| RDRL 5 — Decision support | For a specified limited decision, uncertainty and early-warning systems meet agreed thresholds; independent panels accept the evidence. |

The $1 billion fund should aim to move priority questions from RDRL 1–2 toward RDRL 3–4. It should not presume that RDRL 5 will be achieved in five years, and reaching RDRL 5 for one objective would not authorize deployment or imply readiness for all regions and risks.

## Illustrative quantitative targets

| Decision metric | Illustrative target |
|---|---|
| Top-of-atmosphere annual mean net flux | Bias and trend uncertainty small enough to detect intervention-scale changes; exact threshold set by metrology review. |

| Decision metric | Illustrative target |
| --- | --- |
| Historical anthropogenic aerosol forcing | Meaningful narrowing of the assessed uncertainty range, with regional and cloud-regime decomposition. |
| Marine low-cloud radiative response | Observed susceptibility reproduced across multiple regimes and held-out cases. |
| Southern Ocean cloud radiative bias | Substantial reduction without degrading precipitation, circulation or sea-ice performance. |
| Ocean heat uptake | Closed heat budgets by basin/depth and improved initialized prediction. |
| AMOC | Reduced disagreement in mean transports, variability and forcing response; monitoring variables tied to model thresholds. |
| Reflectivity requirement | Independent models produce an uncertainty distribution for required forcing and explain differences mechanistically. |
| Regional precipitation | Tradeoffs and uncertainty quantified for major monsoon and vulnerable regions; no single-model claims. |

## Final five-year assessment

At the end of Year 5, an independent international assessment should answer:

48. Which physical uncertainties were materially reduced?
49. Which model improvements passed held-out and cross-variable tests?
50. Which apparent improvements were rejected because of overfitting or compensation?
51. How much uncertainty remains in required reflected sunlight, location and timing?
52. What do models agree and disagree about for AMOC, precipitation, sea ice and regional harms?
53. Which observations would be required for adaptive monitoring?
54. Which controlled experiments, if any, have sufficient value to justify a future proposal?
55. Which research paths should be stopped?
56. What information is still too uncertain for a responsible decision?
57. How should the open observing and model-evaluation infrastructure continue after the fund ends?

The final report should distinguish scientific readiness from political, ethical and legal authorization. Better models can inform decisions; they cannot make the decision by themselves.

# GCM Aircraft, Instruments and Airborne Measurement Architecture

**Prompt to AI:** The Global Climate Model (GCM) experimental research program relies on aircraft in many of its campaigns. Tell me more about the airplanes it needs. What parameters should each type measure? What instruments are needed? Which existing research-aircraft operators might provide the aircraft? Do we need new aircraft, modifications, or new airborne instrumentation? How should the program organize aircraft so that the same capability can serve radiation, aerosol, cloud, convection, polar and rapid-response experiments?

**Response From AI:**

The GCM program needs the broadest aircraft portfolio of the sunlight-reflection research programs because it is not studying one plume or one cloud regime. It must measure Earth radiation, anthropogenic aerosol forcing, marine low clouds, mixed-phase/polar clouds, deep convection, upper-tropospheric humidity and rare natural perturbations. The efficient solution is not to buy one universal airplane. It is to maintain a small set of interoperable aircraft classes and modular payloads, with common calibration, data, timing and mission-planning systems.

## Six GCM airborne roles

| Airborne role | Decision-relevant parameters | Representative instruments | Typical experiments |
|---|---|---|---|
| G1. High-altitude radiation / satellite validation | Up/down SW/LW flux; spectral radiance/reflectance; polarization; cloud/aerosol optical depth; layer height; surface/cloud albedo; scene geometry. | Broadband/spectral radiometers; multi-angle polarimeter/imager; HSRL/lidar; precision GPS/INS; calibrated cameras. | Area 1 radiation-budget closure; satellite underflights; above-cloud aerosol/radiation cases. |
| G2. High-altitude in-situ aerosol and chemistry | Particle number/size/composition; scattering/absorption/extinction; SO2, ozone, NOy, H2O and trace gases; UTLS meteorology; volcanic/wildfire material; anvil ice. | CPC/fast sizers; aerosol mass spectrometry; absorption/nephelometry; trace-gas spectrometers; hygrometers; cloud/ice probes; gust package. | Area 2 aerosol forcing; Area 5 anvil/upper troposphere; Area 7 volcano/smoke rapid response. |

| Airborne role | Decision-relevant parameters | Representative instruments | Typical experiments |
|---|---|---|---|
| G3. Boundary-layer and cloud microphysics | Aerosol size/composition; CCN; cloud-base updraft; droplet/ice spectra; LWC/IWC; drizzle/precipitation; turbulence; inversion strength; T/RH and surface coupling. | CCN counter; optical aerosol sizers; cloud droplet/imaging probes; hot-wire water; precipitation probes; fast 3-D winds and thermodynamics. | Area 2 aerosol-cloud closure; Area 3 marine low clouds; Area 4 mixed-phase clouds. |
| G4. Cloud/storm remote sensing | 3-D cloud/precipitation structure; Doppler velocity; storm organization; cold pools; cloud top/base; anvil structure; precipitation microphysics. | Doppler/dual-polarization radar; cloud radar; HSRL/lidar; microwave radiometer; imagers; dropsondes. | Area 3 organization; Area 4 polar systems; Area 5 convection and precipitation. |
| G5. Polar / mixed-phase aircraft | Cloud phase; supercooled liquid; ice number/habit; snowfall/drizzle; aerosol/INP; radiation; boundary-layer coupling; sea-ice/surface context. | Cloud phase/imaging probes; LWC/IWC; INP/aerosol samplers; radar/lidar; radiometers; IR/surface imagers; turbulence package. | Southern Ocean and Arctic campaigns in Area 4. |
| G6. Rapid-response modular aircraft | Event-specific plume location, aerosol evolution, gases, cloud response, radiation and meteorology. | Deployable combinations of G1-G5 payloads plus satellite/trajectory mission system. | Volcanoes, pyroconvection, wildfire smoke, abrupt emissions changes and unique calibration events in Area 7. |

## Measurement packages should be modular

| Shared airborne pallet | Core measurements | Why it matters |
|---|---|---|
| Radiative-closure pallet | Up/down broadband SW/LW, spectral radiometry, polarimetry/imaging, attitude/GPS and traceable calibration. | Connects clouds/aerosols/surface state to the actual energy-budget quantity that GCMs must reproduce. |
| Aerosol/chemistry pallet | Particle number/size/composition, scattering, absorption, CCN where relevant, SO2, ozone, NOy, water vapor and related gases. | Constrains direct aerosol forcing, activation, natural perturbations and aerosol-cloud coupling. |
| Cloud-microphysics pallet | Droplet and ice spectra, LWC/IWC, drizzle/precipitation, phase and temperature. | Constrains low-cloud, mixed-phase, anvil and precipitation parameterizations. |

| Shared airborne pallet | Core measurements | Why it matters |
|---|---|---|
| Dynamics/turbulence pallet | 3-D winds, vertical velocity, T/RH/P, turbulence, surface/boundary-layer flux proxies. | Separates aerosol/cloud causality from meteorology and constrains entrainment and convection. |
| Active remote-sensing pallet | HSRL/lidar, cloud radar, Doppler/dual-pol radar where practical, microwave radiometry. | Supplies vertical and 3-D context that in-situ flight legs cannot provide alone. |
| Mission/data pallet | Common clocks, GPS/INS, aircraft state, telemetry, quick-look processing and aircraft-ship-ground-satellite synchronization. | Makes multi-platform closure and prospective model tests possible. |

## Illustrative current aircraft facilities

| Aircraft / operator | Illustrative current capability | Best GCM roles |
|---|---|---|
| NASA ER-2 | NASA lists about 70,000 ft maximum altitude, 8 hour duration and about 2,900 lb useful payload. | G1 radiation/remote sensing, satellite calibration/validation, high-altitude lidar/imaging. |
| NASA WB-57 | NASA lists roughly 6.5 hour duration and up to about 8,800 lb payload, with operation above 60,000 ft. | G2 high-altitude in-situ aerosol/chemistry, volcanic/smoke events, upper-tropospheric/stratospheric sampling. |
| NSF/NCAR HIAPER Gulfstream V | About 10 hour endurance, 5,000 nmi range, 5,600 lb payload and altitude above 45,000 ft; multiple optical ports and external mounts. | G1 radiation, G2 upper-tropospheric chemistry, above-cloud remote sensing, polar/long-range and convection context. |
| NSF/NCAR C-130 | Middle/lower troposphere; typical research configuration about 13,000 lb payload and 8-9 hour endurance. | G3 cloud/aerosol in-situ work and G4 precipitation/convection campaigns with heavy payloads. |
| NSF / University of Wyoming King Air 350i | About 3-5 hour endurance, 2,100 nmi range, 33,000-35,000 ft ceiling and roughly 2,970 lb maximum payload. | Agile G3 low/mid-level cloud, aerosol and turbulence sampling; radar/lidar missions. |
| NOAA WP-3D Orion | Severe-weather and atmospheric-research platform with tail/lower-fuselage radar, dropsondes and long missions. | G4 deep convection, precipitation, storm organization, aerosol/gas and ocean-atmosphere campaigns. |
| NOAA Gulfstream IV-SP | NOAA describes 45,000 ft cruise altitude and about 4,000 nmi range, with dropsonde and radar missions. | Wide-area upper-air context, atmospheric rivers, storm environment and large-scale control-region mapping. |
| SAFIRE ATR42 (France) | Medium-troposphere atmospheric laboratory for chemistry, aerosol/cloud microphysics, | International G3/G4 campaigns and independent replication. |

| Aircraft / operator | Illustrative current capability | Best GCM roles |
|---|---|---|
| | remote sensing and turbulence; up to about 9 scientists and 2 tonnes of instruments. | |

These are examples of operators/user facilities rather than preselected vendors. Government and university aircraft are commonly accessed by facility proposals, cooperative or reimbursable agreements and campaign-specific task orders. The program should contract for scientific capability - aircraft, integration, airworthiness, crew, instrument teams, calibration and data - rather than treat the airplane as an ordinary charter.

## How aircraft map to the GCM research areas

| GCM area | Primary aircraft need | Secondary / complementary aircraft |
|---|---|---|
| Area 1 - Earth radiation budget | ER-2 or GV-class high-altitude radiation/remote sensing and satellite underflights. | King Air/C-130 or surface/balloon platforms for below-cloud and scene closure. |
| Area 2 - Anthropogenic aerosol forcing | GV/C-130/King Air-class in-situ aerosol, CCN, cloud and radiation sampling. | High-altitude remote-sensing aircraft for above-cloud aerosol and radiation. |
| Area 3 - Marine low clouds | C-130 or King Air primary in-cloud aircraft. | GV/King Air remote-sensing aircraft above cloud plus vessel/autonomous platforms. |
| Area 4 - Mixed-phase/polar | C-130, King Air, GV or comparable aircraft selected for icing, range and campaign altitude. | High-altitude remote sensing/satellite underflight where useful. |
| Area 5 - Deep convection | C-130/WP-3D-class storm and precipitation aircraft plus remote sensing. | GV/ER-2-class aircraft for anvil, upper-troposphere and radiative measurements. |
| Area 7 - Rapid response | WB-57/ER-2/GV/C-130 chosen to match event altitude and payload. | Balloon, surface, satellite and autonomous assets with the same data system. |
| Area 10 - Observing backbone | Maintains modular interfaces, calibration and payload readiness rather than owning every aircraft. | Framework agreements and annual cross-platform intercomparisons. |

## Airborne instruments and suppliers

Many core instruments already exist commercially or within research facilities. Droplet Measurement Technologies supplies airborne CCN and cloud/aerosol probes such as CCN-100/200, CDP, PCASP and CAPS-family systems. Aerodyne supplies AMS systems that provide real-time non-refractory submicron aerosol composition and can be deployed on aircraft, while TSI supplies CPC and mobility-sizing families for particle number and size. Radar, lidar, specialized trace-gas, polarimetric and high-altitude instruments are often facility- or laboratory-built by NCAR, NOAA, NASA, DOE ARM and university teams. The procurement unit should therefore buy integrated measurement capability and instrument-team support, not merely boxes of hardware.

## What should be developed rather than a new airframe?

- Standard mechanical racks, external mounts, probe interfaces, optical-port documentation, power, cooling, Ethernet/data, timing, GPS/INS and telemetry that can move between participating aircraft.
- Characterized aerosol and trace-gas inlets with size-dependent transmission, humidity, heating/anti-icing and contamination documentation.
- A common radiometry and optical-metrology system with pre/post-flight calibration, attitude correction and cross-aircraft intercomparison.
- Reusable cloud/aerosol/chemistry payloads configured for low cloud, mixed phase, high-altitude aerosol and rapid-response missions.
- A shared mission computer and data-fusion system that merges aircraft, radar/lidar, ship, surface, balloon and satellite measurements in near real time.
- A high-value GCM-specific development program for rapid 3-D cloud and precipitation remote sensing. An electronically scanned dual-polarization airborne phased-array radar could materially improve deep-convection and storm-organization measurements if cost, weight, power and airworthiness are acceptable.

A new general-purpose GCM airframe should not be a first-line investment. Existing fleets cover most altitude/payload combinations. A purpose-built aircraft should be considered only after an observing-system analysis demonstrates a persistent unmet combination of altitude, payload, endurance, severe-weather/icing capability or operating cost and shows that the information gain justifies lifecycle ownership.

## Rapid-response readiness is an aircraft problem as well as an instrument problem

Volcanic eruptions, pyroconvective smoke and unusual pollution events may be scientifically valuable for only days or weeks. The GCM fund should maintain framework agreements, pre-engineered payload configurations, instrument readiness exercises, export/customs plans, spares and standing scientific triage. A nominally available aircraft is not a rapid-response capability if payload integration takes six months.

## Current-status correction for international aircraft

The proposal should not list the former UK FAAM BAe-146 as a current aircraft source. FAAM states that the Airborne Laboratory formally closed and all operational activity ended on March 31, 2026. International aircraft should be listed generically or by verified current facilities such as SAFIRE, with availability checked immediately before procurement.

## Recommended program structure

Area 10 should function as a Climate Moonshot Airborne Science Facility: maintain the shared payload standards, instrument pools, calibration, mission software, integration drawings, airworthiness records and aircraft-access agreements. Flagship Areas 1-7 then pay their campaign-specific aircraft hours, field integration and unique instruments. This avoids buying duplicate radar, lidar, radiometers and aerosol systems for each scientific topic while preserving independent operators and competing instrument teams.

The main conclusion is that the GCM program needs a fleet architecture, not one airplane. High-altitude remote sensing, high-altitude in-situ chemistry, cloud penetration, storm radar and rapid response are distinct jobs; common interfaces and modular instruments are the technology that makes the fleet act like one observing system.

# SAI / MCB / GCM Aircraft and Instrument Overlap

**Prompt to AI:** The SAI Experimental Research Fund, MCB Experimental Research Fund and GCM Experimental Research Fund all need research aircraft and atmospheric instruments. How much overlap is there among the aircraft, measurements and instrument packages? Which existing aircraft can be shared? What should be developed jointly, what remains unique to SAI or MCB, and how should the programs avoid buying the same capability three times?

**Response From AI:**

There is substantial overlap in the monitoring fleet and very little reason to build three separate airborne-science infrastructures. GCM has the broadest observing requirements; MCB concentrates on the marine boundary layer and cloud microphysics; SAI concentrates on the upper troposphere/lower stratosphere, sulfate chemistry and plume tracking. Most aircraft, radiometers, aerosol instruments, lidar, radar, cloud probes, meteorology, calibration and mission software can be shared. The unique hardware is mainly the SAI release aircraft/package and the MCB sea-salt release vessel/source system.

## Cross-program airborne roles

| Airborne role | SAI | MCB | GCM |
|---|---|---|---|
| High-altitude radiation / remote sensing | Core above-plume role: SW/LW, spectral/polarimetric imaging, lidar and plume geometry. | Useful above cloud for radiative closure and satellite validation; usually lower altitude than SAI. | Core Area 1 role and important for above-cloud aerosol, anvils and satellite validation. |
| High-altitude in-situ aerosol / chemistry | Core through-plume role: SO2/H2SO4, particle size/composition, ozone/NOy/H2O and microphysics. | Usually not central; MCB sea-salt/cloud work is much lower. | Core for volcanic aerosol, wildfire smoke, UTLS chemistry and anvil/upper-troposphere cases. |
| Boundary-layer aerosol / cloud-base sampling | Context role below SAI plume. | Core role: sea-salt plume, CCN, delivery to cloud base, turbulence and activation. | Core for aerosol forcing and marine low-cloud studies. |
| In-cloud microphysics | Limited direct SAI need except cloud context. | Core: droplet number/size, LWC, drizzle, entrainment and cloud response. | Core: low-cloud, mixed-phase, convection and precipitation parameterization. |

| Airborne role | SAI | MCB | GCM |
|---|---|---|---|
| Cloud/storm radar and lidar | Useful atmospheric context; not primary sulfate-plume detector. | Important for cloud top/base, drizzle, organization and treated/control mapping. | Core for convection, precipitation, mixed-phase clouds and mesoscale organization. |
| Rapid-response modular aircraft | Useful for SAI natural analogues and readiness exercises. | Useful for rare cloud/aerosol opportunities and independent replication. | Explicit core role for volcanoes, smoke, emissions changes and unusual events. |

## Aircraft classes that can be shared

| Platform class | SAI use | MCB use | GCM use |
|---|---|---|---|
| NASA ER-2-class high-altitude remote sensing | Above-plume radiation, lidar, imaging/polarimetry. | Occasional high-altitude satellite/scene validation; generally more altitude than needed for routine MCB. | Earth-radiation benchmark, satellite underflights, high-altitude remote sensing. |
| NASA WB-57-class high-altitude in-situ | Through-plume aerosol/chemistry and high-altitude context. | Little routine MCB need. | Volcanic aerosol, smoke, UTLS chemistry and natural-perturbation sampling. |
| NSF/NCAR HIAPER GV-class | Through/below lower-stratospheric plume where altitude permits; radiation/context. | Above-cloud radiation, remote sensing and wide-area context. | Aerosol gradients, polar/long-range work, upper troposphere, convection context and radiation. |
| NSF/NCAR C-130-class | Lower-atmosphere/context role; not primary stratospheric sampler. | Excellent primary in-cloud aircraft for heavily instrumented campaigns. | Cloud microphysics, aerosol, boundary layer, precipitation and convection. |
| King Air-class research aircraft | Below-plume radiation/context where altitude permits. | Excellent agile plume/cloud-base or primary in-cloud platform when payload fits. | Boundary-layer aerosol/cloud, turbulence and radar/lidar studies. |
| NOAA WP-3D / severe-weather class | Atmospheric context rather than direct stratospheric sulfate sampling. | Useful when precipitation, mesoscale cloud organization or severe weather matters. | Deep convection, precipitation, organized storms and atmosphere-ocean campaigns. |
| SAI injector aircraft | Precision release of SO2/H2SO4/C3 plus source metrology. | No normal role. | No normal observational GCM role. Keep separate from clean monitoring aircraft. |

## Shared instrument modules

| Shared module | SAI | MCB | GCM |
|---|---|---|---|
| Radiative-closure pallet | Above/below plume SW/LW and spectral response. | Above/below cloud and treated/control reflected sunlight. | Earth radiation budget, cloud/aerosol forcing and satellite closure. |
| Aerosol/chemistry pallet | SO2, sulfate, size/composition, scattering/absorption, ozone chemistry and H2O. | Sea-salt/background aerosol size, composition, CCN and plume evolution. | Anthropogenic aerosol, wildfire/volcano, CCN and chemistry. |
| Cloud-microphysics pallet | Mostly context. | Core droplet/LWC/drizzle/precipitation package. | Core low-cloud, mixed-phase and convection package. |
| Lidar / active remote sensing | Plume layer height and geometry. | Plume/cloud height, drizzle and cloud structure. | Aerosol layers, clouds, convection and satellite validation. |
| Meteorology / turbulence | Winds, T/RH/P and plume transport. | Cloud-base updraft, turbulence, boundary-layer mixing and transport. | Boundary layer, entrainment, convection, polar and plume transport. |
| Mission/data system | 3-D plume estimate and coordinated multi-aircraft navigation. | Vessel-plume-cloud-control-region targeting. | Multi-platform campaign planning, rapid response and held-out model tests. |

## What should be developed jointly

- Common airborne science interfaces: standardized racks, mounts, external probe interfaces, power, cooling, network/data, timing, GPS/INS, telemetry, optical ports and inlet documentation.
- A shared radiative-closure pallet with matched broadband SW/LW, spectral radiometry, polarimetry/imaging, high-rate attitude measurement and traceable calibration.
- A shared aerosol/chemistry pallet with configurable particle sizing, composition, scattering/absorption, CCN, trace gases and water-vapor measurements.
- A shared cloud-microphysics pallet with droplet/ice imaging, LWC/IWC, drizzle/precipitation and turbulence, funded primarily by GCM/MCB but available to SAI context campaigns.

- A shared active remote-sensing capability: HSRL/lidar plus W/Ka-band cloud radar where appropriate, with a separate GCM-driven development path for rapid 3-D dual-polarization/phased-array storm radar.

- A common mission computer, aircraft-vessel-ground-satellite data system, quick-look display, calibration archive, spares pool and field-integration team.

## What remains unique to SAI

SAI needs an acid-compatible stratospheric measurement chain and a release aircraft that can carry and meter SO2, concentrated H2SO4/H2O or later C3 materials. It also needs a real-time three-dimensional plume-location/navigation system capable of reacquiring a drifting, dispersing plume over hours to days. The SAI injector should normally remain separate from the clean monitoring fleet because tanks, plumbing, vaporization/atomization hardware and contaminated surfaces complicate background aerosol measurements and independent source verification.

## What remains unique to MCB

MCB does not normally need an aircraft to release the intervention; the source is a ship, autonomous surface vessel or coastal platform. Its unique airborne emphasis is the source-to-cloud-base-to-cloud chain: sea-salt particle survival, CCN activation, droplet response, liquid water, drizzle, entrainment and cloud-field organization. It therefore places unusually high value on agile low-altitude aircraft, external cloud probes, cloud-base vertical velocity and tight real-time coordination with a moving release vessel.

## What remains unique to GCM

GCM needs the widest scientific envelope: mixed-phase ice and INP measurements, polar operations, deep-convection radar, upper-tropospheric humidity, storm organization and rapid-response natural events. These capabilities are not all needed for SAI or MCB experiments, but they make the shared facility more useful because the same instruments test the physical processes that determine how SAI and MCB scale into regional and global climate response.

## Avoiding duplicate spending across the three $1B funds

| Capability | Primary owner / payer | Shared-access rule |
|---|---|---|
| Common racks, timing, data system, metrology and mission software | GCM Area 10 or a jointly governed airborne facility. | All three programs use common standards; campaign-specific integration charged to the campaign. |
| High-altitude radiation and aerosol instruments | Joint GCM/SAI investment. | MCB can use for above-cloud/satellite closure when appropriate. |
| Cloud microphysics, CCN and precipitation suite | Joint GCM/MCB investment. | SAI uses for cloud/context work without buying duplicate suites. |
| SAI release hardware and acid-compatible source system | SAI only. | Not charged to MCB or general GCM observing backbone. |
| MCB sea-salt source/vessel equipment | MCB only. | Aircraft facility receives source data through standard interfaces but does not own the spray fleet. |
| Deep-convection phased-array radar and polar-specific packages | Primarily GCM. | Available to MCB/SAI campaigns when the scientific question justifies use. |

## Recommended shared facility

The three funds should explicitly establish one **Climate Moonshot Airborne Science Facility** rather than three competing aircraft shops. The facility would maintain aircraft-access agreements, reusable payloads, common calibration, integration drawings, airworthiness documentation, instrument readiness, mission software, data standards and spares. Each scientific fund would retain control of its own hypotheses, releases and campaign budget while purchasing shared services from the facility under transparent cost allocation.

Current platform status should be reverified annually. In particular, the former UK FAAM Airborne Laboratory is no longer a current provider; FAAM reports that all operational activity ended on March 31, 2026. Current international alternatives should be verified at the time of each campaign rather than copied forward from older aircraft lists.

The practical conclusion is that most monitoring aircraft and instruments should be shared across SAI, MCB and GCM. The programs differ mainly in altitude and payload emphasis: SAI adds stratospheric plume/release capability, MCB adds intensive marine cloud/CCN capability, and GCM adds the broad cloud, convection, polar and natural-perturbation portfolio. Common infrastructure lowers cost and, more importantly, makes measurements directly comparable across the three research programs.

# Further Reading

**Prompt to AI:** Provide links to the principal source documents and related climate-moonshot research materials.

**Response From AI:**

## Primary source documents supplied for this proposal

Proposed Experiments Measure Sunlight Reflecting off Pollution (47-pg PDF)

https://drive.google.com/drive/folders/1X6PBoXXu-VhMOtQ5JOzlt29oW3qjzGhY

Proposed $250M Cloud Experimental Research Fund (13-page PDF)

https://drive.google.com/drive/folders/1apa-sQ4fyz-k6e5cnyvsyO1QKQ8r_ICB

Proposed $2B Atmospheric Experimental Research Fund (400-page PDF)

https://drive.google.com/drive/folders/1e5jvAmJUfBLCpkQVKwR0dS_Ur2UtFLkG

## Related sunlight-reflection research funds

### Stratospheric Aerosol Injection (SAI)

SAI Reflectivity Plan (7-page PDF)

https://drive.google.com/drive/folders/1Jf8jmP38b2P-vj9XTWRLGGMuahuLwxB6

Proposed $1B SAI Experimental Research Fund

https://drive.google.com/drive/folders/1KRtdfFEjKmzV5XaxiyzRL4JckPzrF_sM

Proposed $1B SAI Equipment Development Fund

https://drive.google.com/drive/folders/1B0Sko2M2cl_V-_uZcPozD-s0cF8bjV-_

### Marine Cloud Brightening (MCB)

MCB Reflectivity Plan (7-page PDF)

https://drive.google.com/drive/folders/1Aoz9vLxKLF4qBw1xnjlCfYGXERhTY3rI

Proposed $1B MCB Experimental Research Fund

https://drive.google.com/drive/folders/1ItaJh7OQMeZMInUkArcShi-SGVFmzvD0

Proposed $1B MCB Equipment Development Fund

https://drive.google.com/drive/folders/1Leivbra4GXj5VlPg_jFZfPN1UQyHgR-S

## Climate Moonshot Related Materials

### Climate Laboratory

Climate Moonshot Business Plan (90-page PDF)

https://drive.google.com/drive/folders/1EMb-Tqw49ewj16UeGhR7UOc9HY6POpKC

### Climate Moonshot Conference

Climate Moonshot Conference (3-page PDF)

https://drive.google.com/drive/folders/114b_lLPTVhBuBQ4ZFpTQsjlh29_rKaB7

### Climate Moonshot Film

The Climate Kids (docudrama film)

https://drive.google.com/drive/folders/1UyEyyGock43PQpnMMcEmq_94gy4m3GHI

## Selected scientific programs and observing systems

**DOE Atmospheric Radiation Measurement (ARM) user facility**
https://www.arm.gov/

**Coupled Model Intercomparison Project (CMIP)**
https://wcrp-cmip.org/

**Cloud Feedback Model Intercomparison Project (CFMIP)**
https://cfmip.github.io/

**Geoengineering Model Intercomparison Project (GeoMIP)**
https://climate.envsci.rutgers.edu/GeoMIP/

**Argo global ocean observing program**
https://argo.ucsd.edu/

**OSNAP overturning observations**
https://www.o-snap.org/

**RAPID AMOC observing project**
https://rapid.ac.uk/

## Important caution

This document is a research-program concept and uses order-of-magnitude planning estimates. It is not an engineering design, deployment authorization, environmental assessment, legal opinion or substitute for independent scientific review. Any controlled atmospheric perturbation would require its own scientific justification, governance process, environmental analysis, permits and public consultation.

# Initial Prompt to AI

**Prompt to AI:** To bend the global warming curve, we need to reflect sunlight back into outer space. Before we do this, we need calculate to how much sunlight needs to be reflected, from where, and when. This requires climate models. However, existing models do not accurately predict observations (e.g. average global temperature, global warming rate, rate of change of albedo, etc.). Therefore, a surge of funding is needed to improve them. More specifically, we need to improve our understanding of clouds, our understanding of how much sunlight reflects off air pollution (i.e. measure anthropogenic aerosol radiative forcing), etc.

Enclosed is file "sai_experiments_research_fund_ai, v1j.docx." This describes a Proposed $1B research fund for Stratospheric Aerosol Injection (SAI) experiments. I would like a similar file that describes a $1B 5-year fund for experiments that improve the accuracy of global climate models. We need this to calculate how much sunlight needs to reflected back into outer space (e.g. via SAI or MCB), from where, and when. Our goal is to bend the global warming curve, prevent the collapse of Atlantic Ocean currents (AMOC), etc.

With the new .docx file that you create, use File “Instructions for file formating.docx” for information on how to format it. Also enclosed is file “gsw_research_fund_template_v4.dotx” for reference on fonts. After you format the final .docx file, allow me to download it.

For references on potential experiments, see:

> Proposed Experiments that Measure How Much Sunlight Reflects off Pollution (47-page PDF)
> https://ma2life.org/g/eet/eetcs_plan/decarb_plan/measure_aerosol_reflection_experiment.pdf
>
> Proposed $250M Cloud Experimental Research Fund (13-page PDF)
> https://ma2life.org/g/eet/eetcs_plan/decarb_plan/cloud_science_surge_ChatGPT.pdf
>
> Proposed $2B Atmospheric Experimental Research Fund (400-page PDF)
> https://ma2life.org/g/eet/eetcs_plan/decarb_plan/Atmospheric_Experiments.pdf

**Response From AI:**

Created this file.