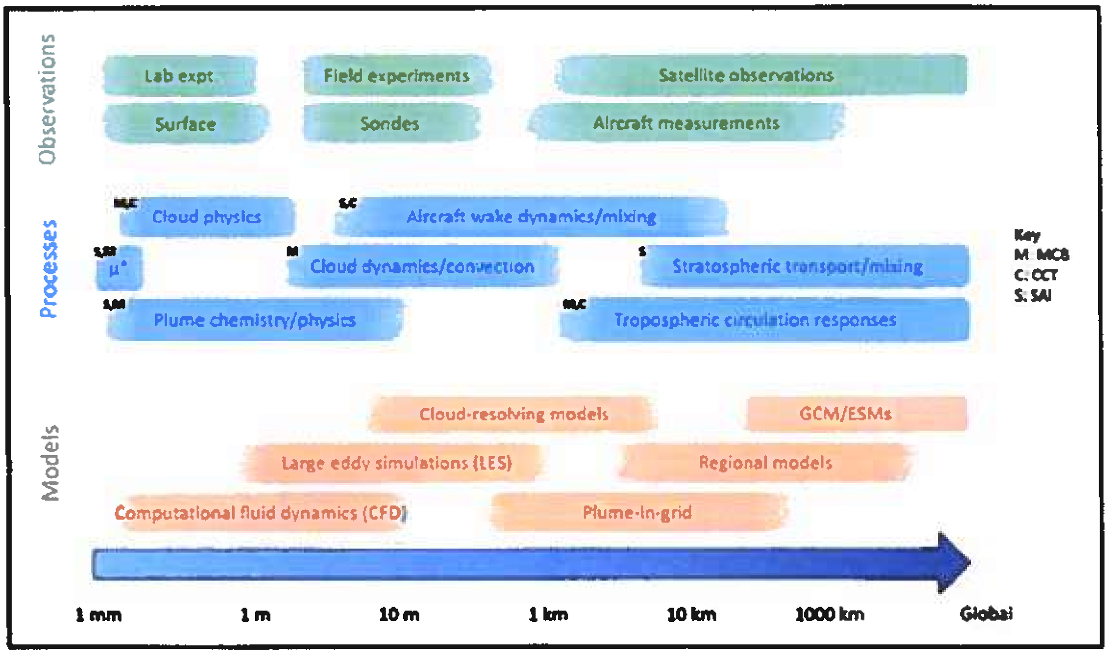


**Figure 2.** Understanding solar radiation modification involves modeling, process understanding, and observational challenges at multiple spatial scales. Light brown bars span the scales explicitly represented by types of models relevant to SRM. (GCM is global climate model; ESM is Earth system model.) Blue bars span scales of distinct sets of physical atmospheric phenomena that pose key challenges for SRM (μ* indicates aerosol chemistry and microphysics). The SRM methods most relevant to each process are noted in black type. Green bars span physical scales that can be directly observed by different approaches. Source: Eastham et al., 2021.

### 1. Assessing Solar Radiation Modification Outcomes with Models

Important objectives of an SRM research program would be improving existing models to enhance assessments of SRM outcomes and developing new modeling capacity applicable to specific aspects of SRM. As shown in **Figure 2**, there is a range of scales associated with SRM processes, and no one model resolves the full range of scales. Global models would be used to assess global radiative impacts, while regional and cloud resolving models would assess changes induced by MCB and CCT methods.

Highly idealized modeling studies[15] show that it may be theoretically possible to use SRM to return the global mean surface air temperature to the preindustrial level, though with some changes in regional temperature and precipitation patterns, as well as possible changes in extremes. A robust result comes from the analysis of multiple-model simulations in which a scenario with CO2 quadrupled relative to the preindustrial value (4 X CO2) is compared with another 4 X CO2 scenario with the solar constant reduced to simulate SAI returning Earth's atmosphere to the preindustrial radiative balance, as well as to a preindustrial climate scenario.

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[15] See, e.g., Tilmes, S., Richter, J. H., Kravitz, B., MacMartin, D. G., Mills, M. J., and Simpson, I. R. et al. (2018). CESM1(WACCM) stratospheric aerosol geoengineering large ensemble project. *Bulletin of the American Meteorological Society, 99*(11), 2361–2371. https://doi.org/10.1175/BAMS-D-17-0267.1

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The result shows that with SAI, the changes in regional climate and in climate extremes are smaller than for the 4 X CO2 case yet remain significant relative to preindustrial conditions.[16]

It is imperative to understand the potential changes in the frequency, severity, and causes of extreme events under different SRM scenarios, as well as changes in regional-scale climate. Every climate or Earth system model available today has limitations regarding its representation of key processes relevant to SRM scenarios and the quantitative representation of the intended and unintended outcomes of SRM. Hence, further research into model development within a multi-model and multi-ensemble framework, along with model inter-comparison, would further increase confidence in the modeled outcomes of SRM scenarios. Such studies would allow for a systematic effort to first identify and understand relevant small-scale processes, use high-resolution models to represent those processes, and then enable the creation of accurate parameterizations for global models. These studies would also afford an opportunity to evaluate the completeness of the known processes involved in SRM methods and to discover any previously unknown processes of importance. Improvement in the representation of small-scale processes for SRM analysis purposes would improve aerosol process representation overall, which would also likely improve models used for climate change studies.

SRM, and SAI in particular, has been studied using a limited number of global models, none of which were designed initially for SRM evaluation. In particular, the models don't resolve the microphysical and chemical processes that control the formation and distribution of SRM aerosols, nor any cloud–aerosol interactions. These limitations also affect the fidelity of climate system simulations not involving SRM. Dispersal of multiple plumes of injected aerosols, especially important when considering current SAI deployment scenarios, has not been explicitly resolved or parameterized in global models used for SAI studies. MCB has been examined using large-eddy simulation (LES) and cloud resolving models; these would be needed to properly simulate injection of aerosols into low-level marine clouds.[17] CCT has not been established as a viable SRM method and requires more research using realistic ice microphysics relevant to upper tropospheric clouds. More Earth system models with SRM-simulation capability and more evaluation of model results relevant to SRM would be beneficial.

## 2. Assessing and Reducing Uncertainty to Improve Projections

A systematic assessment of uncertainty from SRM model experiments would inform policymakers and prioritize the research activities most likely to improve projections of the outcomes of SRM implementation scenarios. This assessment would involve simulations across a hierarchy of models of varying resolution and complexity, comparing results across models of similar resolution and complexity, and comparing model results with observations. Model assessment would focus on increasing confidence and reducing uncertainty in model simulations. Confidence in models to accurately simulate the impacts of a possible SRM deployment can be increased by demonstrating—through comparison to observations—the model's fidelity in reproducing natural and non-natural analogs to SRM-related physical and chemical processes. These include observations of events which are analogs to SRM, as well as observations of

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[16] Curry, C. L. et al. (2014). A multimodel examination of climate extremes in an idealized geoengineering experiment. *J. Geophys. Res. Atmos.*, *119*(7), 3900–3923. https://doi.org/10.1002/2013JD020648

[17] Wood, R. (2021). Assessing the potential efficacy of marine cloud brightening for cooling Earth using a simple heuristic model. *Atmos. Chem. Phys.*, *21*(19), 14507–14533. https://doi.org/10.5194/acp-21-14507-2021

physical and chemical processes in the climate system that have particular relevance to SRM. In the case of SAI, process understanding is aided by the natural analogs of volcanic eruptions or pyrocumulonimbus (pyroCb) events in which the plumes of large wildfires reach the stratosphere. The analog for MCB is brightening of areas of marine boundary-layer clouds caused by ship emissions in the open ocean (ship tracks). Detailed, process-level observations of these natural analogs can be used to identify and remedy gaps in the representation of key processes, such as the parameterization of cloud–aerosol interactions, to reduce uncertainty and improve projections.

Confidence in projections of the future can be inferred by comparing results across a suite of models of similar resolution and complexity. Vetting models for accurate representation of processes important for SRM simulations would improve the comparison process. If all models include accurate representations of the key physical and chemical processes, higher levels of inter-model consensus provide higher confidence in the accuracy of the simulations. Among the suite of models being compared, greater weight might be assigned to the models that more accurately represent the relevant processes for the SRM strategy being considered, and thus reproduce relevant observations relatively better. This type of model weighting would need to be done carefully in order to yield improved projections of the future.[18]

Each model would include a host of parameterizations representing, among other things, cloud–aerosol processes that are fundamental to accurately projecting the climate impacts of an SRM deployment. Each of the multiple parameters has a range of possible values that is consistent with observations and theory. Model performance and the range of SRM climate outcomes can be assessed by measuring the sensitivity of model results to changing values of key parameters. These sensitivity studies not only provide an estimate of uncertainty but can also aid in determining combinations of parameter values to improve model projections. Distinct from sensitivity studies, the intrinsic uncertainty of SRM outcomes can be assessed through modeling studies in which the initial conditions of the Earth system simulation are changed slightly to allow various realizations of natural variability to develop.

It is important to point out that additional research does not lead linearly to increasing certainty. In many cases, new discoveries, or more sophisticated representations of physical processes in climate models, lead initially to increased uncertainty. Dramatic enhancement in the certainty of our ability to simulate Earth system processes is a long-range challenge.

### 3. Observations for Model Validation, Process Understanding, and Monitoring

Model evaluation and improvement involve observations and experiments, as noted above. A focus of the current ERB project is making the observations to allow for model evaluation and improvement. These and related studies and observations are fundamental to improve understanding of the present state of the atmosphere that would be perturbed by SRM methods. Uncertainties associated with aerosol and aerosol–cloud processes and the implications for

[18] E.g., Wootten, A., Massoud, E., Waliser, D., and Lee, H. (2022). To weight or not to weight: assessing sensitivities of climate model weighting to multiple methods, variables, and domains. *Earth Syst. Dynam. Discuss.* [Preprint]. https://doi.org/10.5194/esd-2022-15; Knutti, R., Sedláček, J., Sanderson, B. M., Lorenz, R., Fischer, E. M., and Eyring, V. (2017). A climate model projection weighting scheme accounting for performance and interdependence. *Geophys. Res. Lett.*, *44*(4), 1909–1918. https://doi.org/10.1002/2016GL072012

radiative forcing are still large.[19] In the case of SAI, there are significant differences across models in simulated radiative forcing from aerosol injections that are due to differences in the microphysical models used to represent aerosol processes. There are still significant uncertainties concerning how anthropogenic sulfur emissions at Earth's surface influence the background aerosol layer in the stratosphere.[20] An expansion of stratospheric and tropospheric observations related to key model parameters would be required, especially those related to composition (gases and aerosols), aerosol–cloud interactions, chemistry, dynamics, radiation, short-term and long-term trends, and seasonal variability. In the event of an SRM deployment, sustained regular observations would allow the monitoring of the evolution of the SRM material and its effectiveness.

Ground-based, airborne, and spaceborne platforms and associated instruments would be part of understanding SRM processes and possible deployments. Both types of platforms have made large contributions to Earth science in the troposphere and stratosphere over many decades and can be expected to make large contributions to SRM research going forward (**Figure 3**). Aircraft platforms afford instrument payloads direct access (i.e., *in situ* sampling) to the atmosphere from Earth's surface to the lower stratosphere, which is essential to diagnose and monitor atmospheric composition and the chemical and dynamical processes that control composition. Instruments orbiting in space have the advantage of continuous monitoring of Earth's atmosphere using a variety of remote-sensing methods. To date, instruments on both types of platforms have provided essential data to describe the background atmosphere and associated events and trends and thereby help document the changes brought about by climate change. Aircraft and spaceborne instrumented platforms would likely be essential tools for diagnosing, verifying, and monitoring outdoor experiments and any subsequent implementation of SRM methods.

Satellite measurements have provided stratospheric gas and aerosol measurements with high-altitude resolution for over 40 years. Certain measurement wavelengths, such as in the microwave region, have the advantage that enhancements in stratospheric aerosols from volcanos, wildfires, or SRM deployment do not interfere in the retrieval of trace gases. From U.S. satellites, vertically resolved stratospheric aerosol and ozone measurements with near-global coverage will continue in the foreseeable future from the Ozone Mapping and Profiler Suite (OMPS)-Limb instruments on board the NOAA operational polar-orbiting satellites. The Stratospheric Aerosol and Gas Experiment (SAGE) III/ISS instrument provides water vapor with limited spatial sampling and is expected to continue through the life of the International Space Station (ISS).

[19] Lee, L. A., Reddington, C. L., and Carslaw, K. S. (2016). On the relationship between aerosol model uncertainty and radiative forcing uncertainty. *Proceedings of the National Academy of Sciences, 113*(21), 5820-7. https://doi.org/10.1073/pnas.1507050113

[20] Lelieveld J., et al. (2018). The South Asian monsoon—pollution pump and purifier. *Science, 361*(6399), 270-273. https://doi.org/10.1126/science.aar2501

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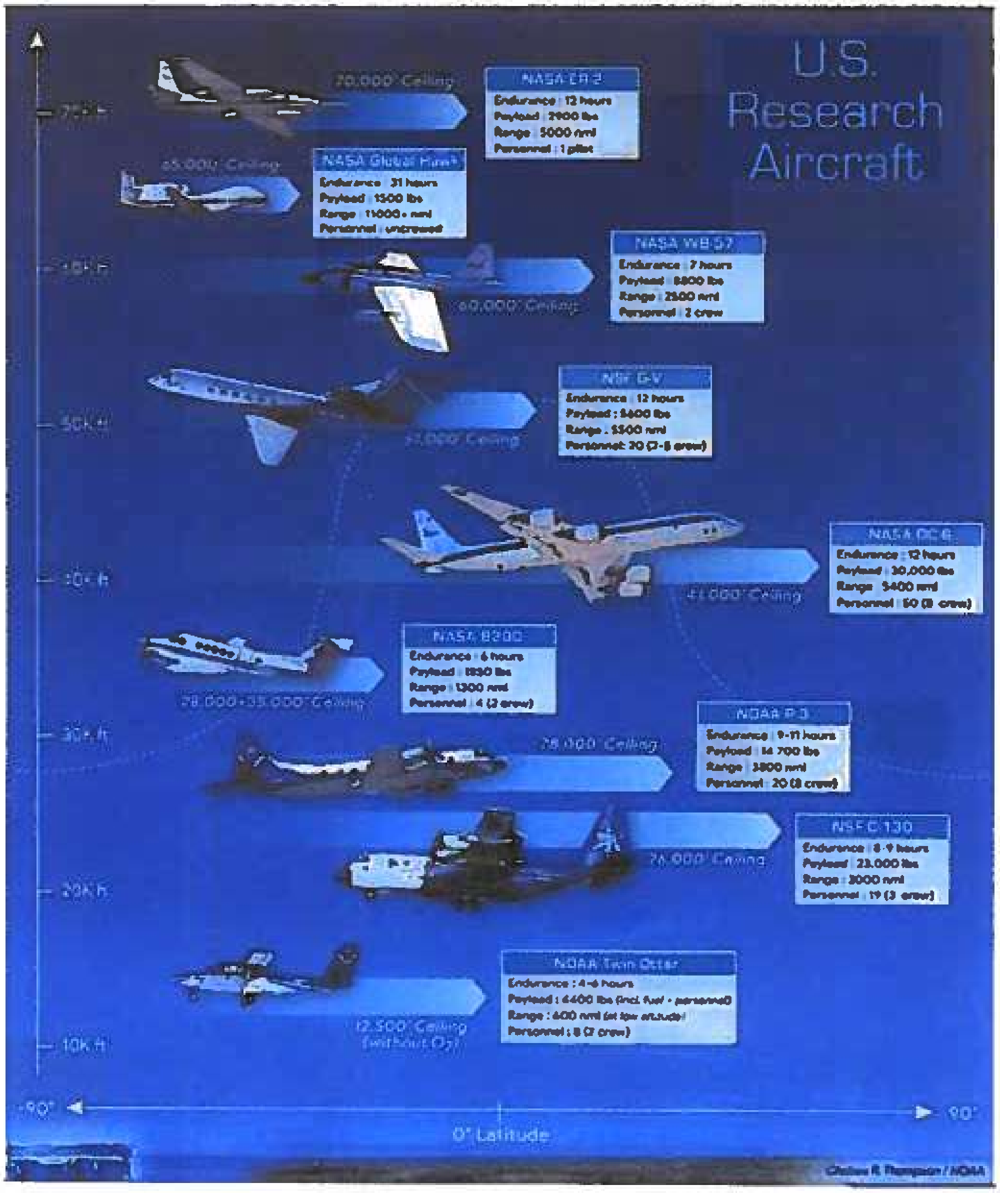


**Figure 3.** Examples of U.S. research aircraft with nominal performance specifications shown in order of maximum operating altitude vertically and nominal payload horizontally. The dashed line illustrates the approximate tropopause dependence on latitude. The U.S. and international fleet of research aircraft is far larger than shown here. Not shown are a variety of uncrewed low-altitude aircraft that are of potential value to MCB studies. NASA is operating Global Hawk Uncrewed Aircraft Systems (UAS) platforms that are not presently available for atmospheric research. Credit: Chelsea Thompson, NOAA.

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**Figure 4.** Example launch of a small (weather) balloon launch with a payload of *in situ* instruments for ozone, water vapor, and aerosol measurements. These balloons reach a maximum altitude of 30 km (100,000 ft) and telemeter data to the ground during flight since many payloads are not recovered. Source: NOAA Chemical Sciences Laboratory.

## 4. Advancing Understanding of Solar Radiation Modification Methods with Small-Scale Outdoor Experiments

For understanding the effectiveness and outcomes of potential SRM deployment, small-scale outdoor experiments would be of value in combination with model and laboratory studies.[21] While improved atmospheric models and expanded observations as described above would improve modeling of SRM deployments, small-scale outdoor experiments would serve to test the completeness and accuracy of SRM modeling. By affording comparisons of observations and modeling of real-world aerosol perturbations, outdoor experiments could provide important new knowledge that cannot be obtained by any other means, despite governance challenges. Observations in small-scale outdoor experiments would be critical for validating and advancing key chemical transport and microphysical aspects of SRM modeling. Of importance for SAI and MCB are, for example, aerosol microphysical processes, plume dispersion mechanics, atmospheric chemistry, atmospheric transport, albedo response, and delivery mechanisms.

While small-scale experiments improve our understanding of the effectiveness and outcomes of SRM deployments, further research and analysis would be needed to understand how a global- or

[21] National Academies of Sciences, Engineering, and Medicine. (2021b). *Airborne Platforms to Advance NASA Earth System Science Priorities: Assessing the Future Need for a Large Aircraft*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26079

regional-scale deployment would be conducted. For example, different platforms and technology could be required for a large-scale deployment. These activities are outside of the scope of this Research Plan.

Instrumented aircraft platforms and aerosol or aerosol-precursor injection systems would be needed in both SAI and MCB small-scale outdoor experiments. The effort to design, plan, coordinate, and execute these outdoor experiments is a multi-disciplinary, multi-year activity involving scientists, engineers, and technicians and one that spans multiple institutions and agencies.

For SAI experiments, of interest is how aerosols are formed and evolve in the real stratosphere in response to the injection of aerosols or aerosol-precursor gases (e.g., sulfur dioxide). A variety of aerosol materials could be examined. Detecting the radiative signature of the enhanced aerosol population is fundamental to understanding SAI.

For MCB, of interest is how marine boundary-layer clouds respond to injected aerosol(s) over a range of background aerosol and meteorological conditions. Systematically conducting controlled perturbation experiments would allow for building statistical relationships between aerosol perturbations, meteorological conditions, and cloud responses over a range of timescales. Measurement of radiative fluxes inside and outside of the perturbed region under a range of marine stratocumulus conditions would demonstrate the effectiveness of MCB.

The results of SAI and MCB small-scale outdoor experiments would provide dual benefits by substantially accelerating improvements in climate model representations of stratospheric aerosol and cloud-aerosol effects, thereby reducing the uncertainties in estimated aerosol climate forcings. A further benefit might come from enhanced preparedness and capabilities to sample analog events in the troposphere and stratosphere as discussed above.

### 5. Verifying and Monitoring Potential Solar Radiation Modification Deployment

It would be important to verify and monitor any SRM deployment over the short- and long-term by measuring and monitoring the characteristics of the deployment, and assessing the intended and unintended physical, environmental, and societal outcomes.

Detection of SRM implementation of SAI or MCB methods would require coordination of new and existing atmospheric observations and other information. For SAI, material injected into the stratosphere reflects sunlight, while remaining in the stratosphere for several years on average and spreading over the globe. Routine observations of stratospheric composition and detailed knowledge of stratospheric transport dynamics could allow early detection of large injections of aerosol and identification of injection locations. Hence, high-sensitivity baseline observations of key ranges of aerosol size, altitudes, and latitudes would be required for optimal early detection. Instruments in the United States and other regions operating on the ground, on board research aircraft, and on satellites have capabilities for this targeted detection. Orbiting remote-sensing instruments are especially important in early detection because of their continuous global observations of aerosols and key radiative species in the middle atmosphere (i.e., stratosphere and mesosphere). Observing instruments would also be valuable on short-duration and long-duration uncrewed (UAS) platforms operating in the stratosphere. Atmospheric aerosol and trajectory models would be required to assess the magnitude, location of injection, and future climate impact associated with anomalous aerosol observations in the stratosphere.

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Accurate and globally representative measurements and models of global or regional radiative flux through the atmosphere could also potentially detect an unanticipated, non-public SAI implementation.

Improving the ability to detect these relatively small changes in radiative flux driven by stratospheric composition would also aid in diagnosing and monitoring any publicly announced implementation of SRM.

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# Section B. Development of Scenarios for Solar Radiation Modification

## Summary

Development of a standard set of SRM scenarios would be an important integrating aspect of a comprehensive research program. A set of scenarios should include those carefully designed to produce specific climate outcomes (e.g., "peak-shaving" or cooling the Arctic and/or other regions), as well as those that might be implemented without having been carefully designed. SRM scenario development is an iterative process where scenarios are periodically revised based on updated policy choices, new observations, and improved process-based understanding.

Since SRM is intended to reduce risks associated with climate change, a research program would most usefully assess risks and benefits associated with SRM scenarios in comparison to risks associated with plausible climate change scenarios not involving SRM.

## Context

An important aspect of an SRM research program would be developing a suite of SRM scenarios. Collectively, the scenarios would span the climate intervention scenarios that the international community might choose to analyze in the future. Key aspects of an SRM research program would be assessment of both the climatic and environmental impacts, as well as feasibility of implementation strategies, of specific SRM scenarios. The development of SRM scenarios would provide a process for the physical, biological, environmental, socioeconomic, ethical, and geopolitical aspects of SRM implementation to be considered within a holistic framework. The exploration of a set of scenarios would serve to coordinate and integrate activities across all aspects of SRM research, while ensuring that the knowledge gained improves the assessment of the most relevant intervention scenarios.

The outcomes of an SRM scenario depend on the background climate, level of warming being offset, and the implementation strategy—namely, the type of SRM deployed; the location, scale, and rate of deployment; duration; and other factors.[22]

A well-chosen set of scenarios would span the range of situations that decision-makers might need to consider. Insights gained through examination of a representative set of scenarios would provide improved understanding, which would be helpful in deciding whether and when to implement SRM and in reacting to contingencies. Contingencies that arise during the planning or implementation stages could lead to changes in the scenario objectives and associated strategies, and may require significant analysis to reassess benefits, costs, risks, and uncertainties. Performing research into a well-chosen set of scenarios would necessitate the development of tools and understanding which later might be quickly adapted to assess scenario contingencies.

The development and updating of SRM scenarios would be an integrating activity of a U.S. SRM research program and would support international cooperation and dialogue on SRM matters.

[22] As stated in NASEM (2021a), "The [SRM] literature frequently describes the impacts of a particular strategy as if they applied to all possible strategies, but the magnitude and spatial/temporal *patterns* of many impacts would depend upon details of how an intervention is implemented—that is, the specific approach used (SAI, MCB, or CCT), how that approach is deployed, and how much cooling is pursued."

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Within the United States, the scenarios would help identify the most pressing research questions related to the physical, biological, environmental, socioeconomic, and geopolitical aspects of SRM methods. Internationally, the scenarios convey the motivation for undertaking research in a transparent and easy-to-understand manner. The scenarios would also serve as a vehicle to engage international partners who might wish to contribute to both the development and understanding of the scenarios.

Ideally, an SRM research program would periodically update the set of scenarios. In practice, therefore, the scenario design process and the broader research program would proceed as a coupled, iterative process in which each activity informs the other. Current understanding would inform the development of an initial set of scenarios; new understanding developed as a result of researching the diverse aspects of these scenarios would then inform the definition of new scenarios, and so on. As understanding and technology matures—and as international conditions evolve—entirely new scenarios might be developed. The cycle of scenario revision and research would allow the SRM research program to evolve while remaining focused and integrated.

All scenarios would be studied and evaluated using the risk vs. risk framework where costs, benefits, risks, and uncertainties of SRM deployment are measured in relation to a non-intervention baseline scenario.

## Solar Radiation Modification Research Priorities for Scenario Development

The development and refinement of a suite of SRM scenarios is an important research priority to gain a comprehensive understanding of how SRM might affect the physical environment, as well as human and natural systems, and to maintain a cohesive SRM research program over the long term. At the same time, the design characteristics of SRM scenarios depend—in an iterative process—on the knowledge gained through this research. Specifically, the design of scenarios intended to produce specific climatic or environmental outcomes would require substantial understanding of the functional relationships between SRM strategies and the environmental responses.

An initial research priority for SRM scenario development would be assessing the existing scenarios used in the research community to simulate SRM deployments in contemporary models. A group of experts could be convened to define what constitutes an SRM scenario and conduct workshops and other community activities to ultimately propose a suite of SRM scenarios that takes relevant physical, biological, and socioeconomic research aspects of SRM into consideration, as well as identifying relevant non-intervention baseline scenarios. This SRM Scenario Development Group ideally would involve a dedicated and inter-disciplinary group of scientists and decision-makers with a range of expertise. Given the potential global nature of SRM deployment and its effects, an international process would be preferable to ensure global representativeness of the scenarios. An international process would also reinforce and exemplify the value of international cooperation and transparency on issues related to SRM. A portfolio of scenarios that is developed jointly by the global community as a shared investment would be an aid to SRM policy decisions.

The range of physical science expertise needed for SRM scenario development and refinement would include multiple disciplines in atmospheric and Earth system sciences, such as atmospheric composition, tropospheric and stratospheric chemistry, radiation, dynamics, aerosol composition and microphysics, the global carbon budget, climate system modeling and observation, and integrated assessment models (IAMs). Expertise in possible deployment technologies and strategies would also be needed to avoid wasting effort developing and studying scenarios that are not viable for implementation. At a higher level, understanding the potential long-term implications of SRM deployment requires input from experts in ecosystems, economics, decision processes, public health, social sciences, governance, history, ethics, environmental justice, and political science. Involving a wide range of experts in the scenario development and refinement process would accelerate the evaluation and use of the scenarios in IAMs that are used to develop scenarios of energy, land, emissions, and climate, and in impact models that use information from climate models to assess the implications for people and ecosystems. These IAM and impact model results would provide feedback into the scenario development process.

In accordance with the initial Governance Framework above, an SRM Scenario Development Group would be expected to be transparent in how the scenarios are developed and to solicit public and stakeholder comments on the provisional suite of scenarios and their associated strategies.