Developing a Research Agenda for Solar Geoengineering Strategies: Proceedings of a Workshop in Brief (2020)

DETAILS

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Proceedings of a Workshop

IN BRIEF

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Developing a Research Agenda for Solar Geoengineering Strategies

Proceedings of a Workshop—in Brief

INTRODUCTION

On August 7-8, 2019, the National Academies of Sciences, Engineering, and Medicine's Committee on Developing a Research Agenda and Research Governance Approaches for Climate Intervention Strategies That Reflect Sunlight to Cool Earth hosted a workshop on the current status of and future directions for research on solar geoengineering (SG)[1] strategies that influence atmospheric processes: stratospheric aerosol injection (SAI), marine cloud brightening (MCB), and cirrus cloud thinning (CCT). This workshop was followed by a second on September 10-11, 2019, that gathered a broad array of information and perspectives on the governance of research on SG strategies. The workshops were convened to inform the committee as it considered potential research needs and structures for governing that research. This Proceedings of a Workshop—in Brief is a summary of the August workshop on research.

BACKGROUND

As anthropogenic greenhouse gas (GHG) emissions continue to increase globally, reducing climate risks will require a wide range of potential climate response strategies, including emissions reduction, climate adaptation, and carbon dioxide removal and sequestration. SG strategies that reflect sunlight to cool Earth are also considered additions to that portfolio of climate change responses to curb the rise of global temperatures. Of these reflective methods, the strategies with the greatest potential to curb global temperatures are atmosphere-based interventions, including SAI, MCB, and CCT, as described in Box 1. SG strategies are in the early stages of development with respect to research and scientific understanding. Little is known at this point in terms of the effectiveness, costs, and impacts (both positive and negative) of each of the technologies. The five sessions of the workshop were planned to help identify the most critical research questions in SG and what tools are available or still needed to understand them.

SESSION 1: MODELING STUDIES TO UNDERSTAND THE EFFECTS OF ENGINEERED CHANGES IN AEROSOL ON THE CLIMATE SYSTEM

The workshop began with a presentation about how climate models are being used to study SG. Most of the studies completed to date have involved two sorts of modeling experiments. The first involves decreasing the amount of solar radiation in the models (i.e., "solar dimming") as a way to represent an atmosphere that has less solar input. The second involves simulating the addition of aerosols at various locations and times, which would be more similar to a real-world SG strategy. In both cases, scientists examine the impact of these interventions on climate parameters and other systems (e.g., agriculture, ecosystems) represented in the models. Descriptions of current U.S. SG research activities, which all involve modeling activities, are provided in Box 2.

Climate models have the potential to be powerful tools that can be used to explore many research problems relevant to SG and climate change, according to the first panelist, **Phil Rasch** (Pacific Northwest National Laboratory). Even though they are always imperfect approximations of reality, models can be used to simulate potential future climates with and without various SG strategies. Rasch noted that much of the SG modeling research thus far has emphasized idealized scenarios,

[1] The participants of this workshop and the referenced literature use many different terms when referring to climate intervention strategies that reflect sunlight to cool Earth, including solar geoengineering, solar climate intervention, or climate engineering. For the sake of consistency, this Proceedings of a Workshop—in Brief will refer to these activities as solar geoengineering.

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BOX 1 Defining SG Strategies That Influence Atmospheric Processes

Stratospheric Aerosol Injection (SAI) — The intentional introduction of aerosols (solid or liquid particles suspended in the air) into the stratosphere (the layer of the atmosphere at ~10-50 km above the surface) to reflect sunlight to cool Earth.

Marine Cloud Brightening (MCB) — The intentional introduction of aerosols near the ocean surface, by means of ships, to act as cloud condensation nuclei influencing cloud droplet number and cloud reflectivity.

Cirrus Cloud Thinning (CCT) — The intentional introduction of aerosols into the atmosphere that act as ice nuclei, suppressing cirrus cloud formation and their subsequent heat trapping capacity.

but more detailed quantitative and predictive studies are needed to model validation with observations and model inter-comparison studies. This is illustrated by modeling studies that have been conducted to simulate SAI and reproduce observed changes in cloud properties resulting from volcanic eruptions. The subsequent model inter-comparison studies have shown that subtle differences in the models lead to significant differences in cloud response.

When considering the efficacy of MCB strategies, Rasch noted that there is debate about whether global climate models simulate low clouds that are too susceptible to aerosols and as a result overestimate the potential cooling effect of aerosols. However, some studies suggest low clouds do have strong responses to aerosols,[2] and it is possible that climate models are accurately characterizing cloud susceptibility and the aerosol cooling efficacy of low clouds, but for the wrong reasons—they are known to be missing some cloud responses that are important. If climate models are showing a cooling effect from low clouds that is similar to the real world (albeit for the wrong or at least incomplete reasons), it is also possible that climate models are missing some atmospheric mechanisms that warm the climate. It appears to be difficult for climate models to reproduce the historical record of surface temperature change over the past century if they show that aerosol impacts on clouds lead to only cooling. He noted that it is thus important to understand the role of aerosols on mixed-phase, high, and cold clouds too.

In consideration of all SG methods, Rasch also stressed that even high-resolution models have great difficulty in representing some important processes. In particular, the balance among radiative heating, turbulent mixing, and cloud microphysics represents a challenge even for the application of fine-scale simulations, and there are still known deficiencies in their representation.

Rasch suggested that SG research needs to encompass (1) process characterization studies, (2) field studies that involve deliberate small perturbations to induce forcing and examine the primary small-scale cloud (but not climate) responses, and (3) studies of physical consequences of perturbations and their connections with human dimensions and society. He emphasized that small perturbations deliberately introduced in a field study might provide the opportunity to use a "classic science" paradigm (i.e., hypothesis, prediction, experiment, measure, revise, repeat until successful explanation) that would provide a reality check to verify understanding and our ability to model reality. Reproducing observed perturbations could yield an improved quantitative and predictive capability and a better framework for discussing human impacts on climate, including deliberate intervention on the earth system.

As an overview of Rasch's presentation, some of the SG research questions that modeling studies can help address are:

- For only SAI simulations, how much of an aerosol needs to be injected? Where? How much forcing will result? Where?
- What is the anticipated timescale of the response (short versus long)? What is the anticipated spatial scale of the response (local versus far field)?
- What are the local and short-term responses compared to those predicted by detailed process-based models? Compared to observations?
- What is the signal? What is the range of model responses? How long and strong must forcing be to detect a response? Were there unanticipated responses?
- What responses matter to other (human, biological) components of the Earth system?
- Are there "winners" and "losers"? How do we frame an intervention to minimize negative outcomes?
- How do we minimize cost? How do we maximize efficacy?

Isla Simpson (National Center for Atmospheric Research [NCAR]) discussed the potential impact of SG on both the global and regional scales and emphasized that models are the primary tool to advance understanding on this topic. On the global scale, considering energetic constraints and theoretical understanding, evaporation and precipitation should both decline with SG. In contrast, at the regional scale, there are no energetic constraints and there is little theoretical understanding

[2] Rosenfeld, D., Y. Zhu, M. Wang, Y. Zheng, T. Goren, and S. Yu. 2019. Aerosol-Driven Droplet Concentration Dominate Coverage and Water of Oceanic Low-Level Clouds. *Science* 363(6427):eaav0566. DOI: 10.1126/science.aav0566.

BOX 2 Descriptions of Major U.S. SG Research Activities

Geoengineering Model Intercomparison Project (GeoMIP)[a] — This modeling activity develops solar geoengineering (SG) experiments that all participating climate models perform and then compares the results to improve understanding. The first suite of GeoMIP experiments focused on solar dimming while the second suite covered sea spray geoengineering and MCB. More than 80 peer-reviewed publications have been released associated with or using GeoMIP model outputs since 2011.

Geoengineering Large Ensemble Project (GLENS)[b] — This modeling activity examines climate impacts in stratospheric aerosol injection geoengineering simulations in which the global mean surface temperature, as well as the interhemispheric and equator-to-pole surface temperature gradients, are maintained at 2020 values under a RCP8.5[c] greenhouse gas scenario. Impacts are compared to control simulations for the time period from 2010 to 2030 and a RCP8.5 scenario without geoengineering. All of the data from these simulations are available to the community online.

Geoengineering Modeling Research Consortium (GMRC)[d] — This program was established in 2019 to bring together the community focused on geoengineering modeling research in the United States. GMRC activities will complement existing research efforts such as GeoMIP to identify and prioritize critical research gaps in climate modeling with specific significance to SG as well as coordinate among U.S. researchers to close those gaps through collaborative model assessment and development efforts.

Harvard University's Solar Geoengineering Research Program (SGRP)[e] — This program was established under the umbrella of the Harvard University Center for the Environment. Specific to modeling research activities, SGRP is developing predictive models of plume evolution using aircraft or balloons in the stratosphere and is also working to understand accumulation mode particle injection using 2D and 3D atmospheric models.

MCB Project[f] — This project is an open, multi-institutional research collaboration within the Atmospheric Intervention Research Program at the University of Washington. In partnership with Pacific Northwest National Laboratory, the MCB Project is working to develop new models and improve existing models of cloud–aerosol interactions and to advance techniques such as machine learning to analyze cloud–aerosol data.

[a] See http://climate.envsci.rutgers.edu/GeoMIP, accessed March 18, 2020.
[b] See http://www.cesm.ucar.edu/projects/community-projects/GLENS, accessed March 18, 2020.
[c] RCP8.5 (Representative Concentration Pathway 8.5) is the highest greenhouse gas emissions scenario developed by the Intergovernmental Panel on Climate Change in its fifth Assessment Report as the theoretical worst case warming scenario. It represents a scenario of radiative forcing reaching 8.5 Watts/meter^2 (W/m^2) by 2100. This scenario would result in more warming than a business-as-usual scenario.
[d] See http://www.cgd.ucar.edu/projects/gmrc, accessed March 18, 2020.
[e] See https://geoengineering.environment.harvard.edu, accessed March 18, 2020.
[f] See http://www.mcbproject.org/index.html, accessed March 18, 2020.

for how hydroclimate would change with SG. Natural analogs in the observational record (e.g., volcanic eruptions) are potentially useful, but there are limitations because internal variability is large for regional-scale hydroclimate.

Simpson continued her presentation by providing an overview of the Geoengineering Large Ensemble Project (GLENS). The results of this modeling exercise indicate that SG may be effective in reducing temperature change relative to a high-emissions scenario. In addition, soil moisture loss in many regions is less severe in the SG scenarios than under continued warming, with some notable exceptions. India is one such example, where there is considerable drying and an increase in the likelihood of monsoon failures (i.e., monsoon seasons could more frequently produce less rain than needed).[3]

Methodology differences among SAI modeling studies make comparisons difficult, said Simpson. The Geoengineering Model Intercomparison Project (GeoMIP) involves a more consistent approach across models and is therefore useful for helping assess the robustness of models. However, the experiments have focused on idealized solar dimming, which does not include the dynamic response of warming the stratosphere. As a next step, Simpson said that scientists should identify realistic SG strategies and perform the same experiment in a number of models.

Better understanding of model behavior would inform assessment of uncertainties and model projections. In particular, Simpson noted that improved understanding is needed on how stratospheric aerosols will behave in practice and whether the precipitation responses to the associated heating are realistic. Other necessary steps forward that she identified include (1) using many ensemble members, (2) thinking about responses in a probabilistic sense, (3) awareness of the irreducible uncertainty arising from internal variability, and (4) framing projected changes in the context of the full probability distribution of outcomes as opposed to the mean change.

[3] Simpson, I. R., S. Tilmes, J. H. Richter, B. Kravitz, D. G. MacMartin, M. J. Mills, J. T. Fasullo, and A. G. Pendergrass. 2019. The Regional Hydroclimate Response to Stratospheric Sulfate Geoengineering and the Role of Stratospheric Heating. *Journal of Geophysical Research: Atmospheres* 124(23):12587-12616. DOI: 10.1029/2019JD031093.

Brian Soden (University of Miami) opened his presentation by noting that there is no SG strategy that can exactly mirror and counteract forcing from CO_2. Rather, SG will inevitably lead to some asymmetries in forcing, and that will generate asymmetries in response. However, if scientists can predict the response to asymmetries in forcing, SG could influence particular spatial patterns of temperature, precipitation, or other climate variables.

Soden explained that the most obvious difference in forcing between SG and CO_2 is in the vertical asymmetries: most CO_2 forcing occurs in the troposphere, but most SG forcing is focused at the surface. This difference affects the hydrological dynamics. Spatial and horizontal asymmetries in forcing can shift large-scale atmospheric circulation and rain belts; this is observed in climate responses to volcanic eruptions and sulfate pollution forcing.

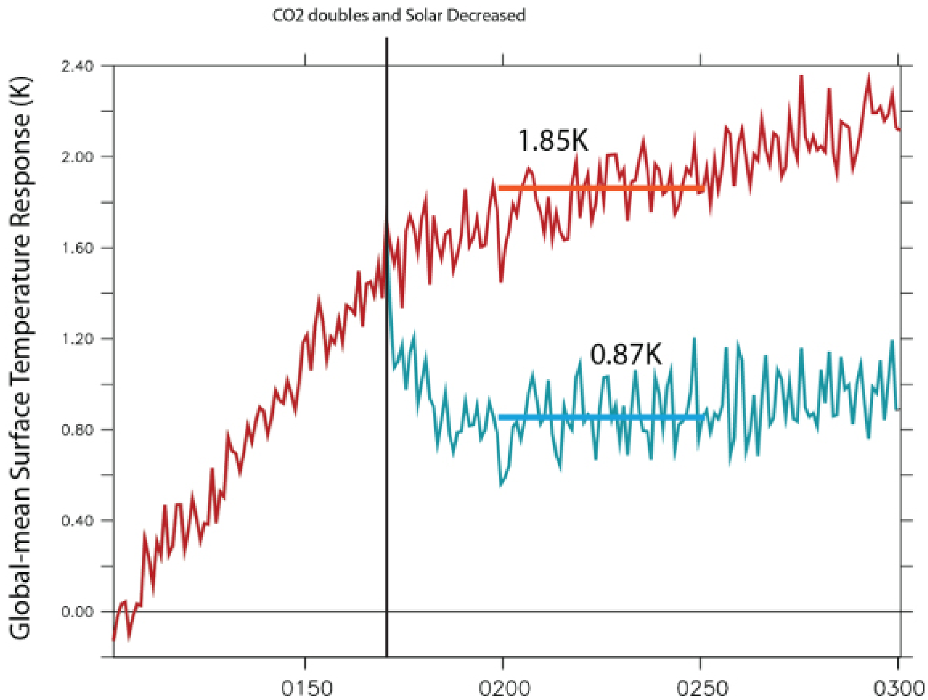

FIGURE 1 Global mean surface temperature responses to doubling of CO_2 (red) and doubling of CO_2 offset by 1% solar reduction simulating SG (blue). SOURCES: Courtesy of Gabe Vecchi; adapted from Irvine et al. (2019).

Soden stated that some modeling work compared impacts of increasing CO_2 to offsetting this increase with 1% solar reduction to simulate SG.[4] It was found that global mean surface temperature increased steadily under the increasing CO_2 scenario, and the SG simulation compensated for roughly half of the CO_2 induced warming as seen in Figure 1. Irvine and colleagues (2019) also examined tropical cyclone activity in both simulations and noted that SG can have a larger impact on decreasing cyclone activity than simply reducing emissions alone due to differences in the vertical heating distribution.

Hemispheric asymmetry in forcing and response also have major significance for the climate system and therefore must be evaluated, said Soden. Aerosol-induced cooling effects will cause asymmetries in circulations, which can cause additional changes and cloud feedbacks, greatly increasing uncertainties and inter-model spread in the projected response of SG.

Realistic SG scenarios (rather than idealized) are needed to understand the sensitivity to the spatial structure of forcing, Soden said. He also noted that careful evaluation of forcings is required when comparing across models because some recent inter-comparison studies found a large spread in instantaneous forcing across models, even for identical emission scenarios.

To briefly add to what the previous speakers had discussed regarding SAI strategies, the final session panelist, **Ulrike Lohmann** (ETH Zürich), stated that models are capable of reproducing radiative forcing and temperature changes after the Mount Pinatubo eruptions, which suggests these models are useful for SG research. However, SAI has an inherent limitation: the more particles emitted, the more likely they are to coagulate, grow larger, and sediment out more quickly, and thus the efficiency is reduced. In MCB research, models seem to largely agree regarding the temperature changes resulting from MCB, but there is much less agreement on whether MCB will lead to decreases or increases in precipitation.

Lohmann then provided an overview of CCT. Cirrus are the only clouds that lead to net warming at the surface because they absorb outgoing longwave radiation that would otherwise escape to space. The net forcing of cirrus is about 5 W/m^2 and is dominated by longwave warming with a smaller shortwave contribution. Thus, if cirrus clouds could be thinned, there would be cooling with the escape of more heat from the surface.

Lohmann explained further that practical deployment of CCT would be extremely challenging, because it requires targeting cirrus clouds that are about to form and then seeding them with suitable ice nucleating particles (INPs) so that the clouds might have fewer but larger ice crystals. Storelvmo and Herger (2014)[5] suggest that there is a "sweet spot" where a cirrus cloud formed in the presence of INPs has a net cooling effect of ~2 W/m^2. However, seeding cirrus with too many INPs creates an optically thick cloud, which would result in net warming rather than cooling. Other studies (e.g., Penner et al.,

[4] Irvine, P., K. Emanuel, J. He, L. W. Horowitz, G. Vecchi, and D. Keith. 2019. Halving Warming with Idealized Solar Geoengineering Moderates Key Climate Hazards. *Nature Climate Change* 9(4):295-299. DOI: 10.1038/s41558-019-0398-8.

[5] Storelvmo, T., and N. Herger. 2014. Cirrus Cloud Susceptibility to the Injection of Ice Nuclei in the Upper Troposphere. *Journal of Geophysical Research: Atmospheres* 119(5):2375-2389. DOI: 10.1002/2013JD020816.

2015;[6] Gasparini and Lohmann, 2016;[7] Gasparini et al., 2017[8]) found only minor cooling because regions where cirrus clouds form rival those regions where cirrus clouds become thinner, indicating CCT methods may not be feasible. Lohmann noted that controlled inter-comparisons are needed because all CCT studies to date were conducted slightly differently.

SESSION 2: OBSERVATION-BASED STUDIES TO UNDERSTAND THE EFFECTS OF ENGINEERED CHANGES IN AEROSOL ON THE CLIMATE SYSTEM

The second session of the workshop delved into observation-based studies related to SG, including lab, in situ, and remote-sensing observations. Lab experiments allow for the testing of different atmospheric processes and chemical reactions in a closed, small-scale environment. In situ observations come from the deployment of sensors detecting various atmospheric properties in their immediate vicinity, for example, at a ground-based station, on a tower, or attached to a balloon. Remote-sensing observations are collected from various ground- or space-based instruments. These instruments can be used to observe natural processes, such as volcanic eruptions and impacts of current pollution sources on the atmosphere, and they can be used to observe in situ experiments that involve the release of material into the atmosphere.

David Fahey (National Oceanic and Atmospheric Administration's [NOAA's] Earth System Research Laboratories) identified the many stratospheric chemical and physical processes relevant to SAI. Such processes include (1) chemical reactions in the gas-phase and aerosol surfaces; (2) microphysical processes that form aerosol particles; (3) solar and infrared radiative transfer and heating; (4) air transport into, around, and out of the stratosphere; and (5) formation of upper tropospheric clouds. Baseline conditions of stratospheric aerosols (size, number, composition, and distribution), ozone, water vapor, and other GHGs are also critical for understanding the potential impacts of SAI.

Stratospheric chemistry and transport processes are highly coupled and in constant flux, and thus detailed observations are needed over time, working together with atmospheric models, to understand processes and project future states, Fahey continued. According to Fahey, options for collecting baseline and experimental observations in the stratosphere include:

- airborne platforms, which can fly up to 20 km above the surface of the Earth;
- small balloons, which can be outfitted with small instrumental payloads and fly directly through volcanic plumes; and
- satellite observations, which are highly complementary to the in situ observations; but current satellite instruments may not be sufficient to address SG research needs.

Fahey noted several lines of stratospheric chemistry research that could help improve understanding of SG and its potential impacts. The sulfur cycle is a complex system with natural and anthropogenically driven elements, along with poorly quantified fluxes into and out of the stratosphere. Aerosols must be critically evaluated both in the laboratory and in the real atmosphere to better understand their microphysics (e.g., multi-phase chemical processes, growth and coagulation processes, radiative properties), Fahey explained. Microphysical modeling and measurements of aerosol evolution from point-source to steady-state distribution (e.g., time-dependent size distribution) could provide a foundation for understanding the impacts of SAI, said Fahey.

Allison McComiskey (Brookhaven National Laboratory) discussed ground-based measurements that can contribute to SG research. For example, high-quality, ground-based observations of aerosol extinction (or attenuation) from Mauna Loa eruptions have been used since the 1960s to understand stratospheric aerosol variability. Additional ground-based records can be used to understand spatial variability. Potential resources are the U.S. Department of Energy's Atmospheric Radiation Measurement Climate Research Facility Southern Great Plains Site[9] and NOAA's Surface Radiation Monitoring Network,[10] which provides a record of annual average aerosol optical depth minima across the continental United States. These ground-based observations can complement satellite sensors such as Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), which provides observations of stratospheric aerosol variability.

In studying MCB, McComiskey stated that better integration of observations with modeling efforts would help to address the limitations of current models. General circulation models cannot simulate many processes that need to be resolved and better understood (e.g., cloud liquid water path and radiative responses to aerosol). Likewise, process models find contradictory outcomes due to differing forcing, environmental conditions represented in the model, and physics representations. Microphysical aerosol and cloud measurements are traditionally examined separately from dynamical and thermodynamical regimes, radiative fluxes, and cloud radiative properties. More integrated measurements of the aerosol–cloud–atmosphere system are needed to confirm the radiative impact of aerosol on clouds that result from microphysical and macrophysical adjustments and to help bridge scales in the measurements (i.e., from scales relevant to process models

[6] Penner, J. E., C. Zhou, and X. Liu. 2015. Can Cirrus Cloud Seeding Be Used For Geoengineering? *Geophysical Research Letters* 42(20):8775-8782. DOI: 10.1002/2015GL065992.

[7] Gasparini, B., and U. Lohmann. 2016. Why Cirrus Cloud Seeding Cannot Substantially Cool the Planet. *Journal of Geophysical Research: Atmospheres* 121(9):4877-4893. DOI: 10.1002/2015JD024666.

[8] Gasparini, B., S. Münch, L. Poncet, M. Feldmann, and U. Lohmann. 2017. Is Increasing Ice Crystal Sedimentation Velocity in Geoengineering Simulations a Good Proxy for Cirrus Cloud Seeding? *Atmospheric Chemistry and Physics* 17(7):4871-4885. DOI: 10.5194/acp-17-4871-2017.

[9] See https://www.evs.anl.gov/user-facilities/sgp, accessed March 18, 2020.

[10] See https://www.esrl.noaa.gov/gmd/grad/surfrad/index.html, accessed March 18, 2020.

to scales relevant to global models). Addressing these problems requires advancing multi-scale modeling frameworks and conducting comprehensive field campaigns that are purposefully designed to meet the needs of these modeling frameworks, she added.

The largest lever on cloud reflectivity comes from the adjustment to liquid water content, but the response of cloud water to aerosols is highly dependent on the environmental regime (e.g., on cloud height and whether air is dry or moist above the cloud). These meteorological influences are illustrated by the fact that visible ship tracks form a small percentage of the time that ships are present. In examining the effect of aerosols on clouds, all components of the meteorological environment should be considered, said McComiskey. Large-scale systematic climate drivers will likely have larger impacts on cloud liquid water than the addition of aerosols. A continuum of conditions involving aerosol and atmospheric states are possible at any place and time. Rather than continuing to focus on untangling each component, McComiskey argued that scientists should instead embrace the complexity and design experiments and multi-scale modeling frameworks that examine the holistic system with this complexity in mind.

The next session panelist, **Robert Wood** (University of Washington), provided an overview of the MCB Project. The basic concept behind MCB is that adding submicron-sized salt particles to a low cloud over the ocean results in an increase in droplet number and a decrease in cloud droplet size, which drives a higher albedo assuming that the amount of cloud liquid water in the cloud remains fixed. The method proposed by the MCB Project uses sea salt, which is environmentally benign. The effects are localized and temporary; marine aerosols tend to last only a few days at most, said Wood.

Significant questions remain regarding how cloud liquid water, which is maintained by complex and turbulent processes, responds to this intervention, Wood continued. In addition, it is unknown what quantity and size of salt particles will lead to the optimal albedo increase. Wood stated that controlled field experiments could be used to test multi-scale models. Such models are needed to determine the potential cooling that can be obtained using MCB if applied at regional and global scales. The overall extent to which MCB can offset GHG warming remains an open question. Early modeling studies indicate that if applied to 10-30% of marine clouds, MCB might be able to temporarily offset a doubling of CO_2 globally.[11] Wood also noted that MCB could possibly be used on smaller scales (i.e., to cool regions where hurricanes form or to protect coral reefs).

MCB research could also advance understanding in climate science. Wood explained that sulfate aerosol particles derived from anthropogenic emissions are already cooling the planet via direct and indirect forcing, partially offsetting warming from GHGs. Quantifying this cooling effect is challenging and remains the largest uncertainty in human-induced forcing of the climate system. MCB field experiments with controlled, well-defined aerosol injections into the marine boundary layer can both provide scientific insight into aerosol–cloud interactions and help quantify the cloud responses to aerosol increases. Advancing models of aerosol and cloud processes and their interactions can improve the representation of these processes in climate models, which would be a critical advance in climate science, Wood said.

In order to move forward, Wood argued that nozzles need to be developed that can generate and disperse the aerosol particles. In addition, he stated that new multi-scale modeling and multi-platform observations are needed for (1) scaling up from single-plume to multiple-plume studies, (2) assessing the efficacy of MCB in different low cloud regimes, and (3) optimizing the size and rate at which particles are injected.

Steve Platnick (National Aeronautics and Space Administration's [NASA's] Goddard Space Flight Center) offered a snapshot of some key space-based observations that can contribute to SG research: stratospheric aerosol detection and extinction retrievals that would be applicable to SAI research and tropospheric cloud and aerosol observations and retrieved properties that would be applicable to MCB and CCT research. He emphasized satellite instruments that are expected to be available in the coming decades, as detailed in Table 1.

High-fidelity global satellite stratospheric aerosol retrieval profiles can be obtained with limb measurements[12] of scattered light. Such passive ultraviolet (UV)/visible light observations are currently collected by the Ozone Mapping and Profiler Suite Limb Profiler (OMPS-L) on NASA's SNPP satellite and will be available on future U.S. operational satellites JPSS (-2,-3,-4). The OMPS-L products include stratospheric aerosol extinction profiles, stratospheric O3 profiles, cloud height detection, and cloud temperature (research product). NASA's Stratosphere Aerosol and Gas Experiment (SAGE)-III on the International Space Station (ISS), launched in 2017, provides stratospheric profiles from solar occultation observations, allowing for direct extinction measurements, but there is no follow-on instrument currently planned. However, the Royal Belgian Institute for Space Aeronomy plans to launch a limb observing spectrometer (ALTIUS) in 2023 as part of the European Space Agency (ESA) Earth Watch Programme to monitor ozone and aerosol changes.

One constraint in the aerosol extinction retrieval, Platnick explained, is that the composition and size distribution must be assumed; this is likely a reasonable assumption for background sulfate but not during stratospheric injection from recent volcanic eruptions or major wildfires. The accuracy of limb scattering aerosol retrievals is evaluated by comparison against SAGE III/ISS products. Active stratospheric observations and climatologies have been collected by NASA's CALIOP backscatter lidar on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation and are expected from the Atmospheric Lidar on the ESA/Japan Aerospace Exploration Agency Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) mission.

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[11] Wood, R., T. Ackerman, P. Rasch, and K. Wanser. 2017. Could Geoengineering Research Help Answer One of the Biggest Questions in Climate Science? *Earth's Future* 5(7):659-663. DOI: 10.1002/2017EF000601.

[12] Limb measurements are satellite observations that look "edge on" through the atmosphere rather than down toward the surface.

TABLE 1 Overview of Several Sensors and Their Platforms Relevant to SG Research

Sensor	Type	Relevant Measurements	Current Platform	Future Platform
STRATOSPHERIC AEROSOLS SATELLITE OBSERVATIONS				
OMPS-L	Passive	O_3 – total column + vertical profile	SNPP (NASA)	JPSS-2 (NASA) (2022) JPSS-3 (NASA) (2026) JPSS-4 (NASA) (2031)
SAGE-III	Passive	Vertical distribution of aerosols + O_3 stratospheric temperature + trace gas profiles (water vapor + NO_2)	ISS	—
ALTIUS	Passive	Vertical distribution of O_3 measures aerosols + greenhouse gases	—	PROBA (BIRA-IASB) ESA Earth Watch Programme (2023)
CALIOP	Active	Vertical profiles of clouds/aerosols	CALIPSO (NASA)	—
ATLID	Active	Vertical profiles of clouds/aerosols	—	EarthCARE (ESA/JAXA) (2022)
MARINE BOUNDARY LAYER CLOUDS AND TROPOSPHERIC AEROSOL SATELLITE OBSERVATIONS				
MODIS	Passive	Cloud/aerosol optical properties	Aqua (NASA) Terra (NASA)	—
VIIRS	Passive	Cloud/aerosol optical properties	SNPP (NASA)	—
MISR	Passive	Cloud/aerosol optical properties	Terra (NASA)	—
GMI	Passive	Liquid water path	GPM (NASA)	—
CPR	Active	Cloud properties	CloudSat (NASA)	EarthCARE (ESA/JAXA) (2022)
3MI	Passive	Cloud/aerosol characteristics	—	EPS-SG (EUMETSAT) (2022)
SPEXOne	Passive	Degree of Linear Polarization (DoLP) + Angle of Linear Polarization (AoLP) of sunlight reflected from Earth	—	PACE (NASA) (2022)
HARP-2	Passive	Clouds/aerosol particle measurements + land/water surface properties	—	PACE (NASA) (2022)
TEMPO	Passive	Major air pollutants (North America)	—	NASA (2022)
GEMS	Passive	Major air pollutants (Asia)	—	KARI (2020)
Sentinel 4	Passive	Major air pollutants (Europe)	—	ESA (2021)

NOTE: The supporting space program for the data is provided with the platform.

A variety of passive satellite observations are relevant to marine boundary layer clouds and tropospheric aerosols, for example, VNIR (visible/near infrared)/SWIR (shortwave infrared)/IR (infrared) imagers to study optical and physical properties, new-generation operational geosynchronous Earth orbit (GEO) imagers, and microwave imagers for determining water path. Newer developments include multi-angle/multi-spectral polarimeters and GEO imagers designed for atmospheric composition studies, as well as the CALIOP and future EarthCARE lidars and instruments that may be part of NASA's Aerosol and Cloud, Convection and Precipitation Decadal Survey mission, which Platnick noted was in the early stages of conducting a study plan at the time of the workshop.

The MOderate Resolution Imaging Spectroradiometer (MODIS)/Visible Infrared Imaging Radiometer Suite (VIIRS) imagers provide pixel-level aerosol/cloud optical properties that are needed, in part, to make radiative calculations of observed scenes. However, the standard cloud products do not provide cloud droplet or ice particle concentrations, which are essential parameters helpful in linking aerosol–cloud processes, while imager aerosol retrievals require particle absorption assumptions. The community has used MODIS cloud products (optical thickness, effective radius) to infer droplet number concentration, but those products require several cloud parameter assumptions. MODIS observations of ship tracks illustrate the current retrieval capabilities. Ship tracks often show a microphysical signature without a noticeable change in the visible spectrum (related to optical thickness), indicating complexities in the radiative response to aerosol modification, Platnick explained.

Regarding validation, a quantitative understanding of aerosol column optical depth uncertainties for MODIS/VIIRS are available because ground-based measurement sites allow ground truthing. Independent truth for cloud retrievals is more problematic. Retrieval artifacts related to 3D radiative transfer are issues for heterogeneous cloud retrievals and (to a lesser extent) aerosol retrievals in the vicinity of nearby clouds. In the future, new-generation operational GEO imagers with better spatial and temporal resolution could open up new possibilities for cloud and aerosol products and process understanding.

Platnick concluded by stating that for cirrus clouds, challenges in imager observations of optical thickness and effective particle size include an inherent sensitivity to ice particle habit/scattering assumptions. The lidar ratio is a significant error source for optical thickness from backscatter lidars that are unable to measure cirrus layer extinction directly (e.g., majority of CALIOP daytime observations). Earlier disagreements in estimates of cirrus cloud optical thickness between MODIS and CALIOP have converged with the help of independent constraints on lidar ratio and particle habit. Retrieving ice effective particle size remains difficult due to a lack of independent information.

SESSION 3: RESEARCH TO ESTIMATE THE IMPACTS AND RISKS, POSITIVE AND NEGATIVE, OF SOLAR CLIMATE INTERVENTIONS ON HUMAN AND ENVIRONMENTAL SYSTEMS

The third session of the workshop included presentations on some impacts and risks that have been considered for both research and potential deployment of SG. Some questions on risks and impacts can be explored with modeling and observation-based studies like those described in the first two sessions. Other questions, such as potential cascading effects, are not yet understood by the scientific community and will emerge as SG research proceeds.

Alan Robock (Rutgers University) outlined a number of scientific questions and uncertainties that need to be resolved before making an informed decision on SG deployment, especially with respect to understanding the impacts of both starting and stopping SG. Some possible risks (e.g., increased drought, ozone depletion, ice melt) and benefits (e.g., reduction in surface air temperatures, increased plant productivity) of SG could be studied with GeoMIP, other climate models, or volcanic eruptions.

Robock discussed some key questions yet to be answered or understood, including:

- What temperature would we want to reduce to? This question also raises the issue of how to maintain a given desirable temperature, especially once SG could no longer be deployed. Modeling studies have shown that rapid termination would cause the temperature to increase more quickly than it has in the recent past or as projected in RCP4.5.[13]
- What might SG do to precipitation? Modeling studies suggest that many locations would have extreme drying at SG implementation and termination.[14]
- Is it technically feasible to create a stratospheric aerosol cloud with the desired properties and inject it into the stratosphere? Would direct emission of H_2SO_4 (sulfuric acid) create the desired size distribution? Niemeier and Timmreck (2015) showed that SO_2 (sulfur dioxide) injections equivalent to five to seven times the 1991 Mount Pinatubo eruption each year would be required by the end of the 21st century to keep temperatures constant at the 2020 level if maintaining business-as-usual emissions. Robock said that currently planes and other methods for injecting particles into the stratosphere are not yet ready but, in theory, could be invented, tested, and deployed in a decade or so.[15]

In addition to these concerns, there is little research in the area of SG impacts on, for example, agriculture, natural ecosystems, and human populations.

Cheryl Harrison (The University of Texas Rio Grande Valley) discussed the potential impacts of SG on ocean ecosystems and biogeochemistry. Climate change studies have shown that ocean warming is correlated with deoxygenation, acidification, and declines/shifts in productivity. One critical limitation of SG is that it does not stem the increase of CO_2 in the atmosphere, and therefore does not address ocean acidification. A global temperature reduction that would result from SG could impact oceanic systems in both positive and negative ways with cascading effects that scientists may not be able to predict. Because temperature reductions would not be homogeneous, it would be important to understand how the oceans would stabilize and on what timescale.

Fisheries in particular may be impacted by an SG-induced temperature reduction. Climate model studies have estimated that on average, every 1°C of warming results in a 5% reduction in fisheries biomass.[16] Thus, it is possible that using SG to limit warming could maintain fisheries populations; however, it is unclear exactly where and by how much SG would mitigate loss in fisheries biomass. Likewise, the UV implications of SG, particularly on the plankton population, is still an unanswered question, said Harrison.

In her concluding remarks, Harrison emphasized the importance of incorporating ocean ecosystems and biogeochemical models in SG research in order to advance understanding of ocean dynamics and its systems under different scenarios. As this research moves forward, she noted that it is also important to engage the fisheries modeling community, as well as managers for policy, governance, and planning on regional and global scales.

[13] Robock, A., L. Oman, and G. L. Stenchikov. 2008. Regional Climate Responses to Geoengineering with Tropical and Arctic SO_2 Injections. *Journal of Geophysical Research: Atmospheres* 113(D16). DOI: 10.1029/2008JD010050.

[14] Rasch, P. J., S. Tilmes, R. P. Turco, A. Robock, L. Oman, C.-C. Chen, G. L. Stenchikov, and R. R. Garcia. 2008. An Overview of Geoengineering of Climate Using Stratospheric Sulphate Aerosols. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 366(1882):4007-4037. DOI: 10.1098/rsta.2008.0131.

[15] Niemeier, U., and C. Timmreck. 2015. What Is the Limit of Climate Engineering by Stratospheric Injection of SO_2? *Atmospheric Chemistry and Physics* 15(16):9129-9141. DOI: 10.5194/acp-15-9129-2015.

[16] Lotze, H. K., D. P. Tittensor, A. Bryndum-Buchholz, T. D. Eddy, W. W. L. Cheung, E. D. Galbraith, M. Barange, N. Barrier, D. Bianchi, J. L. Blanchard, L. Bopp, M. Büchner, C. M. Bulman, D. A. Carozza, V. Christensen, M. Coll, J. P. Dunne, E. A. Fulton, S. Jennings, M. C. Jones, S. Mackinson, O. Maury, S. Niiranen, R. Oliveros-Ramos, T. Roy, J. A. Fernandes, J. Schewe, Y.-J. Shin, T. A. M. Silva, J. Steenbeek, C. A. Stock, P. Verley, J. Volkholz, N. D. Walker, and B. Worm. 2019. Global Ensemble Projections Reveal Trophic Amplification of Ocean Biomass Declines with Climate Change. *Proceedings of the National Academy of Sciences* 116(26):12907. DOI: 10.1073/pnas.1900194116.

Colin Carlson (Georgetown University) presented the human health perspective of SG research. He pointed out that research related to potential health impacts of SG is not robust. A number of areas would benefit from more study by both the SG community and the public health community. According to Carlson, research priorities should be focused around the question "How do we save lives?" and health concerns with the greatest global burden. For example, some past studies have considered the health implications of stratospheric ozone depletion associated with SAI, which could lead to more UV-B radiation and potential cases of skin cancer.[17] However, Carlson pointed out these adverse health outcomes may be less significant than the potential for SG to reduce the projected impact of vector-borne diseases such as malaria, which could be exacerbated as temperatures increase and precipitation patterns change.

Waleed Abdalati (Cooperative Institute for Research in Environmental Sciences) discussed potential polar impacts of SG. He noted that in general there is deep uncertainty in our current understanding of polar change and feedbacks. For example, observations of sea ice loss have been greater than what the models have predicted. Even without the added forcing of SG, models are not capturing the effects of the current climate on sea ice because the internal mechanisms of sea ice are difficult to understand and model. Cryospheric responses to SG could have the potential to be a huge factor in unknown impacts regardless of the location of deployment. There are several questions yet to be addressed regarding SG impacts on sea ice, ice sheets, and permafrost that have broader implications for concerns such as sea level rise and methane release. Abdalati noted that research should consider these questions in the context of both the deployment and rapid termination of SG. Impacts and feedbacks in the poles have broader global implications that should be considered before informed decisions can be made.

SESSION 4: RESEARCH QUESTIONS FOR SOLAR CLIMATE INTERVENTION: ENGINEERING AND IMPLEMENTATION CHALLENGES

In the fourth session the presenters were asked to address engineering and design issues related to SG. These ranged from questions regarding technological feasibility and estimates of cost to considerations of moral hazard. Experiences of the research community in developing two potential in situ experiments (SCoPEx and the MCB Project) were considered in detail, as they are actively working through these design issues.

Frank Keutsch (Harvard University) described the plan for SCoPEx (Stratospheric Controlled Perturbation Experiment), a process-level, small-scale field experiment proposed in the context of geoengineering to better understand the interaction of the stratosphere and solid aerosols. As planned, SCoPEx will introduce ~1kg of material at 20 km altitude and make a plume, and the team will study the behavior of the atmosphere and the material. The goal is to improve large-scale models used for predicting the risks and efficacy of SG. Keutsch explained that they established a governance advisory committee for SCoPEx to help weigh the broader implications of this experiment.

Currently, the size distribution of any aerosol is not well understood by scientists, and there are modeling uncertainties moving from plume- to grid-scale. Keutsch noted that there is a need to model and observe atmospheric parameters, aerosol composition, and size distributions as well as the aging process of solid aerosols. SCoPEx aims to address some of these observational needs and uncertainties.

The SCoPEx team is also exploring options for aerosols other than SO_2 in hopes of finding an alternate material that is less risky. SO_2 causes stratospheric heating, depletion of stratospheric ozone, particulate matter pollution, and reduced efficacy at higher loading. Furthermore, the mass of aerosol needed could be reduced by using materials with more effective scattering.

It is not yet well known what type of chemical reactions will take place within the stratosphere when the solid particles being considered for the SCoPEx experiments are injected. These reactions will vary depending on stratospheric state and location. It is also not known how the materials will behave after injection and what the impacts will be as the materials age in the atmosphere and descend to the surface. Because of these unknowns, Keutsch noted, before scaling up the research priorities, such questions as these should be answered:

- How will the aerosols behave in the atmosphere?
- How will these aerosols impact stratospheric composition, ozone, and dynamics and what will the feedbacks be?
- What are the correct observations and models to test our understanding of the stratosphere?
- What will the tropospheric impacts be?
- What would the diffuse/direct radiation impact be on ecosystems?
- Can materials used in laboratory experiments be manufactured to scale up?
- Can the same properties be guaranteed to ensure the laboratory experiment results remain true?
- How might other materials introduced with the aerosol affect the plume?
- Is there a concern for contamination, impurities, or the introduction of other materials with any given method of deployment?

[17] Eastham, S. D., D. K. Weisenstein, D. W. Keith, and S. R. H. Barrett. 2018. Quantifying the Impact of Sulfate Geoengineering on Mortality from Air Quality and UV-B Exposure. *Atmospheric Environment* 187:424-434. https://doi.org/10.1016/j.atmosenv.2018.05.047.

Simone Tilmes (NCAR) made the point that modeling is the only method available to both design and test the global effects of SG applications. In past studies, SG has been simulated by solar dimming or sulfur injections at one location. Scientists then examine the impacts on the climate (e.g., temperature, precipitation) or other systems (e.g., agriculture productivity). Tilmes described a new approach, "design experiments," that involves reversing the process to set the goals of geoengineering first, and designing an approach in a model experiment to achieve those climate goals.

This can be done with a "feedback controller" that selects the characteristics of geoengineering (such as the location and strength of stratospheric injections) to match the desired climate goals, based on prior simulations that linked characteristics of injections to their effects on those goals. This is done to reduce earlier identified side effects of SG in each model experiment. These injections may be varied annually or on shorter timescales to reach the desired results.

This systematic, design-oriented approach begins with clearly articulated objectives intended to be met through the experiment. Then, Tilmes explained, degrees of freedom in the climate system should be identified that will affect the objectives selected. Next, a strategy for meeting the objectives in the presence of uncertainty should be developed. Once the experiment is designed, one can perform the model experiment, verify the results, assess the impacts, and understand the benefits and risks associated and the underlying processes resulting in more or different side effects. Iterations between improving the design and evaluation of the outcome are needed until side effects are limited as much as possible, she said. This experiment is intended to simulate a real-world scenario in which potential SG strategies are adjusted each year to meet climate targets.

In order for this process to be more reflective of the real world, Tilmes stated that there is a need for more complex models to simulate SO_2 injections. Solar dimming experiments are not realistic and do not accurately capture impacts and feedbacks. Furthermore, Tilmes noted, an expanded observational network is necessary for global temperatures and atmospheric composition so these data can be incorporated in the models and help evaluate and improve models.

Running large-scale simulations (such as those conducted in the GLENS project) has demonstrated that control of surface temperature is possible with SG, Tilmes noted. These multi-model comparisons are necessary in order to understand the uncertainties and side effects of SG. Making small corrections in the design of new experiments by changing the injection location(s) or timing or by using different aerosols can help determine what is responsible for changes and how impacts are connected.

Sean Garner (Palo Alto Research Center) discussed the engineering and design elements of the MCB Project that Wood presented in the first session. The current understanding, based on assumptions that require further research and validation, Garner explained, is that a modest increase (5-7%) in the reflectivity of 15-25% of marine clouds representing about 3-5% of the ocean's surface could be enough to significantly reduce global temperatures and possibly even offset anthropogenic climate forcing.[18,19] This would require ~1,500 ships,[20] each spraying about 10^{15}-10^{16} droplets per second.[21] These are rough estimates, and the MCB Project has proposed small-scale experiments at sea coupled with modeling to improve them. Garner pointed out that the proposed experiments are low risk because they would be spraying sea salt aerosol generated from seawater, and the aerosols would last a few days at most, affecting only tens of kilometers spatially.

In order to carry out these proposed MCB experiments, said Garner, nozzles capable of spraying seawater in a manner that creates aerosol of the right size and concentrations are needed, and they would also need to be developed and tested for any larger-scale implementation. For experimentation and implementation, the design of the sprayer system would initially be modeled after snowmaking equipment and would need a few hundred nozzles, pumps, filters, a fan, possibly a heater (to offset the cooling from evaporation at the nozzles), and a control system. Currently, a nozzle sufficient for MCB testing purposes exists, but its efficiency is not optimal beyond experimentation. Garner presented three components of the proposed MCB research program: (1) to scale up and test with the available nozzle; (2) to continue nozzle and spray system modeling efforts; and (3) to continue the research and design of an optimal nozzle that would produce the desired droplet size and spray with less energy. The first two are necessary to improve the state of scientific knowledge of MCB and ideally should be performed simultaneously and collaboratively. The third would address the ultimate feasibility of performing MCB on a global scale, Garner explained. If the path of scaling up to small-scale experiments is desired, the approach to testing would be to load a sprayer system onto a boat and measure the effects on clouds with measurement platforms. These experiments would both be guided by and inform parallel modeling efforts.

Garner continued by noting several questions that could be addressed through these experiments should they be executed, including:

- Are the current predictions of the response of clouds to the addition of an aerosol optimized for MCB accurate?

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[18] Jones, A., J. Haywood, and O. Boucher. 2009. Climate Impacts of Geoengineering Marine Stratocumulus Clouds. *Journal of Geophysical Research D: Atmospheres* 114(10). DOI: 10.1029/2008JD011450.
[19] Slingo, A. 1990. Sensitivity of the Earth's Radiation Budget to Changes in Low Clouds. *Nature* 343(6253):49-51. DOI: 10.1038/343049a0.
[20] Latham, J., K. Bower, T. Choularton, H. Coe, P. Connolly, G. Cooper, T. Craft, J. Foster, A. Gadian, L. Galbraith, H. Iacovides, D. Johnston, B. Launder, B. Leslie, J. Meyer, A. Neukermans, B. Ormond, B. Parkes, P. Rasch, J. Rush, S. Salter, T. Stevenson, H. Wang, Q. Wang, and R. Wood. 2012. Marine Cloud Brightening. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 370(1974):4217-4262. DOI: 10.1098/rsta.2012.0086.
[21] Salter, S., G. Sortino, and J. Latham. 2008. Sea-Going Hardware for the Cloud Albedo Method of Reversing Global Warming. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 366(1882):3989-4006. DOI: 10.1098/rsta.2008.0136.

- Are the predictions about the size of the effect on specific cloud properties (e.g., cloud droplet number concentration, liquid water path, cloud fraction) in both perturbed and adjacent clouds accurate?
- What measurement tools are needed to determine target locations?
- Can we measure any other effects on the ocean surface?
- Can the system be run open loop? Can the sprayer system be operated without human intervention?
- What measurements are required for control systems?

When considering large-scale implementation, Garner provided other questions that should be considered:

- What sensors would need to be on board the vessels versus be remote?
- Will there be unintended consequences, and if so, how can they be mitigated?
- How can responsibility for a certain weather outcome be attributed to a given MCB action?
- How would ship schedules and measurements be integrated into large-scale weather and climate models in a predictive fashion?

Currently there are several logistical and operational concerns that will determine the readiness of a large-scale effort, according to Garner. For instance, weather observation data would be needed from multiple sources and multiple governments. Fleet control and scheduling would require oversight, possibly from an intergovernmental authority. Feasibility will depend on the efficiency of sprayer systems and how difficult it is to place ships in the right locations at the right times. Garner concluded by emphasizing that climate and weather modeling is vital to improve understanding the risks of unintended consequences.

The final panelist, **Gernot Wagner** (New York University), began by discussing an estimate for the cost of implementation of SAI through a bottom-up approach. Wagner posed the question, "If we wanted to deploy SG in 15 years time, in order to halve the increase in radiative forcing, could we do it, and what would it cost?" To answer this question, Wagner assumed that the research had been conducted and the decision to deploy had been made. For SAI, lofting technologies exist and can be relatively inexpensive at ~$1,500/ton (~$2.5B/year for the first 15 years of this scenario).[22] Considering this, Wagner argued that the cost of high-altitude aircraft would not be the limiting factor in the deployment of SAI. Smaller-scale platforms, such as balloons, would be too costly for large-scale deployment, but they could be enticing to hobbyists or influence a small group of covert interveners.[23] Currently, platforms for deployment are technically possible and economically feasible for different groups, but governance must play a role in decision-making before this deployment is used, Wagner stated.

Wagner also discussed others ways that researchers have examined factors involved in implementation. He noted that many researchers have looked at the moral hazard, or mitigation avoidance.[24] He emphasized that it is not as simple as having an active research program in place and trusting that informed decisions will be made. Wagner noted that there are trade-offs to consider: introducing SG may reduce mitigation efforts, therefore decreasing welfare, but it may also reduce climate impacts, therefore increasing welfare.

Wagner concluded by recommending an approach that would consider risks and uncertainties, both known and unknown, to identify potential courses of action. Such an approach would enable one to consider the broader system trade-offs associated with various different climate response strategies.

SESSION 5: SOCIAL SCIENCE PERSPECTIVES ON SOLAR CLIMATE INTERVENTION RESEARCH, INCLUDING PUBLIC PERCEPTION, PUBLIC ENGAGEMENT, AND APPROACHES TO RISK AND UNCERTAINTY

In the final session of the workshop, the presenters described the existing social science studies accompanying SG research and the directions they think studies on public perception, engagement, and framings could go moving forward. There are few investments in social science related to SG, and much of the funding is private rather than public. The United States saw a spike in funding levels after 2016 with the start of Harvard's SGRP (see Box 2), as well as the Carnegie Climate Geoengineering Governance Initiative.[25]

Jane Flegal (Arizona State University) provided the context for this session and reviewed current social science research on SG. According to Flegal, the dilemma for social science researchers in this field is that a socio-technical system[26] for SG capable of delivering desirable global outcomes through deployment is not yet understood. In this context, social scientists

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[22] Smith, W., and G. Wagner. 2018. Stratospheric Aerosol Injection Tactics and Costs in the First 15 Years of Deployment. *Environmental Research Letters* 13(12):124001. DOI: 10.1088/1748-9326/aae98d.

[23] Reynolds, J. L., and G. Wagner. 2019. Highly Decentralized Solar Geoengineering. *Environmental Politics*. DOI: 10.1080/09644016.2019.1648169.

[24] Merk, C., G. Pönitzsch, and K. Rehdanz. 2016. Knowledge About Aerosol Injection Does Not Reduce Individual Mitigation Efforts. *Environmental Research Letters* 11(5):054009. DOI: 10.1088/1748-9326/11/5/054009.

[25] See https://www.c2g2.net, accessed March 18, 2020.

[26] A sociotechnical system is an approach to understanding a complex process that involves both technical and human behavioral elements.

are faced with challenges around "upstream engagement," or studying technological systems that do not yet exist. Due to a lack of specificity, social scientists find it difficult to conduct assessments based on hypothetical SG systems. With technologists waiting for evidence from the social scientists to justify proceeding with research and development (R&D), and social scientists waiting for more concrete technological ideas and physical research to analyze, the field has reached what has been labeled "the research impasse," Flegal argued.

Flegal noted several challenges for the social science research that has been conducted in SG so far. Low familiarity of the subject of SG allows different framings to sway survey responses, producing mixed results. Also, the studies conducted thus far on public views have been primarily conducted in the United States and have focused on the general public rather than policy makers or other decision makers. This bias in participants has implications for the studies of moral hazard, which have seen mixed results depending on the participants and framing. This raises the question of whether moral hazard is only an issue for policy makers rather than more general or mixed populations.

Flegal then spoke about how to deliberately govern research. She stressed the point that by steering research directions, the choice to fund a research project or not is a form of governance in and of itself. This point highlights the importance of defining and governing the role of private funding, which she noted has not received significant attention in the literature to date.

Karen Parkhill (University of York) explored the role of publics in the Stratospheric Particle Injection for Climate Engineering (SPICE) project in 2011. After the project had gotten under way, and upon recognizing the contentious nature of the issue, funders retrospectively added requirements for "stage-gates" (e.g., scientists would need to provide more evidence before the funding would be granted for field testing). Before the SPICE project could advance to field testing, the research team was required to conduct research on public attitudes about the field test. Parkhill noted that the research team was not equipped to conduct such research within the given time.

Parkhill identified ways that the process undertaken to regulate the SPICE project could be improved. She said that funders need to have clear processes and procedures outlined in advance of funding for researchers to follow. This planning will allow for more realistic timelines and the ability for teams to embed social science work from trained social scientists at the beginning of the process.

Research on social science and public attitudes is important, said Parkhill, because it is generally good practice in a democratic society to have wider representation in decision-making, and it can help foster trust and public acceptance of unknown topics. She emphasized that dialogues among affected parties and stakeholders should start early in the R&D process before significant applications or social controversy may arise. In addition, most engagement and social science research thus far has taken place in the Global North, and this work should start to shift to the Global South, where innovations in environment and energy justice work are developing.

According to Parkhill, public engagement research during the SPICE project revealed a few key findings about public attitudes toward SG:[27]

- Mitigation should always be prioritized, and carbon dioxide removal is preferred to SG.
- There is a strong trust in scientists and innovators in this space, but there is a concern that their good intentions might be ignored by politicians, businesses, or due to a lack of resources.
- Outdoor SG experiments should only proceed if it is safe for both local inhabitants and the local environment.
- All information regarding safety and impacts of such experiments should be made publicly available.

It is also worth noting that there was conditional acceptance of outdoor SG experiments by many, but there were still significant concerns regarding large-scale deployment, including justification, efficacy, equity, ethics, and governance concerns.

Parkhill concluded by noting that publics understand that they are not well equipped to be decision makers in this space, but nonetheless, they feel as though they should be engaged on a continual basis. When publics are asked to engage, it should be clear why, and their concerns should be heard and addressed, said Parkhill. Engagement should not be done simply to check a box for public voice.

Jack Stilgoe (University College London) argued against the urgency of deployment and expressed that decisions about SG should not be taken lightly. Stilgoe worked on the SPICE project as a social scientist. In working with the stage-gate process, he developed a model known as "Responsible Innovation" in the context of SG.[28] Responsible Innovation is "collective care for the future through the stewardship of innovation in the present." This model asks researchers to act within four basic principles: anticipate potential concerns, include new and varied voices, reflect on intended/unintended consequences, and be responsive in order to change course as necessary.

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[27] Pidgeon, N., K. Parkhill, A. Corner, and N. Vaughan. 2013. Deliberating Stratospheric Aerosols for Climate Geoengineering and the SPICE Project. *Nature Climate Change* 3(5):451-457. DOI: 10.1038/nclimate1807.

[28] Stilgoe, J., R. Owen, and P. Macnaghten. 2013. Developing a Framework for Responsible Innovation. *Research Policy* 42(9):1568-1580. https://doi.org/10.1016/j.respol.2013.05.008.

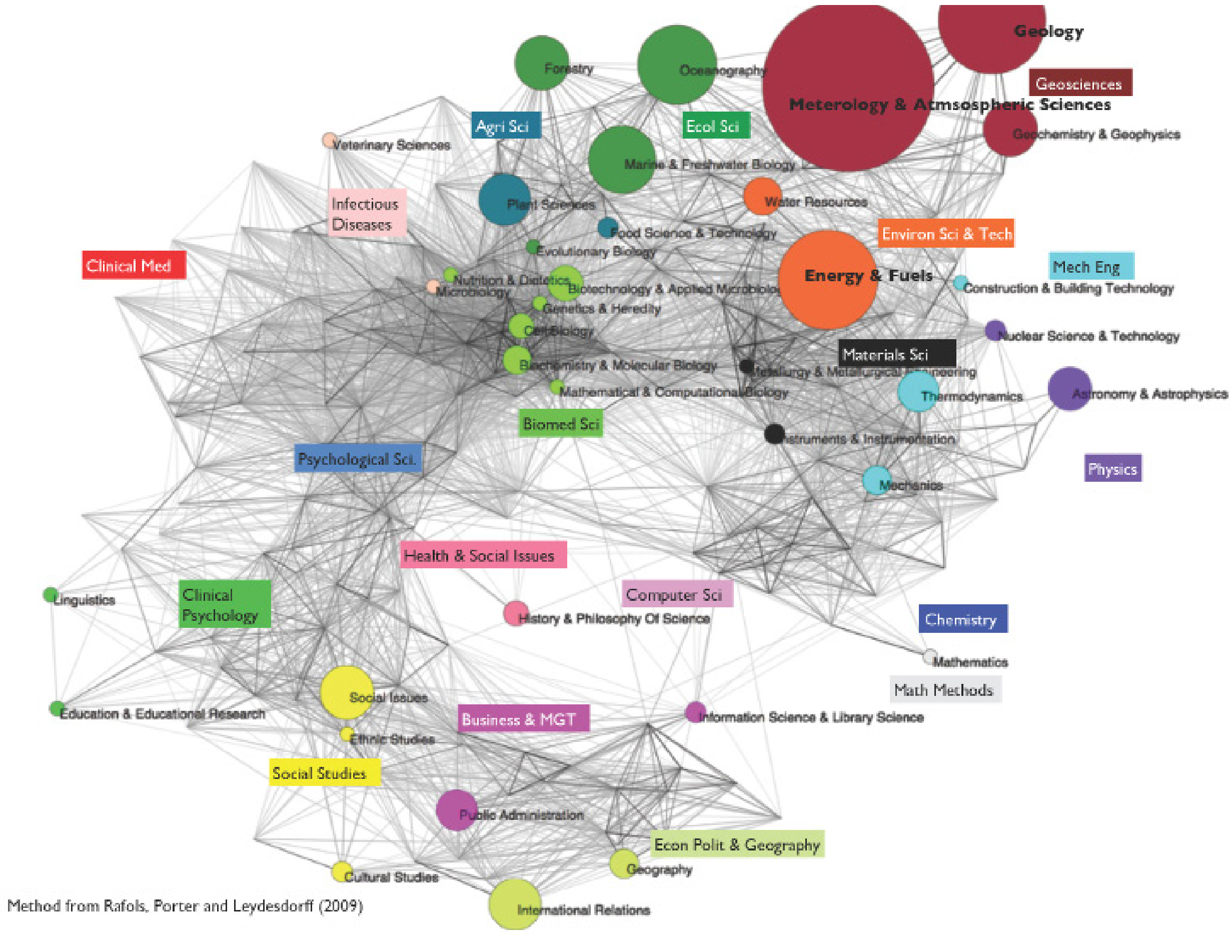

FIGURE 2 Science overlay map presented by Jack Stilgoe on SG research literature. The larger the circle, the more literature that exists in that area in the context of SG. Most of the literature and research focuses on the geosciences in dark red, but the research involving the engineering, impacts, and social science of SG are thinner. Method to create overlay map from Rafols, I., A. L. Porter, and L. Leydesdorff. 2010. Science Overlay Maps: A New Tool for Research Policy and Library Management. *Journal of the American Society for Information Science and Technology* 61(9):1871-1887. DOI: 10.1002/asi.21368.

Stilgoe noted that SG is a highly interdisciplinary problem, but most research completed to date falls heavily in the physical sciences and is much sparser in social sciences as well as in engineering itself. Figure 2 shows the current nature of SG research across disciplines reflected in the current literature.

With the diversity of issues, and lack of diverse research, Stilgoe argued that governance approaches could be deployed to create multi-disciplinary research opportunities.

Rob Bellamy (University of Manchester) provided an overview of the importance of framing in fields like SG that are susceptible to multiple frames because the R&D plans are still in progress. Framings are influential ways people inadvertently, deliberately, or implicitly choose to organize and communicate ideas. Bellamy stated that framings in SG research thus far have marginalized adaptation or mitigation alternatives, focused on SAI at the expense of other ideas, employed exclusive specialist methods at the expense of inclusive participatory ones, mobilized predominately narrow technical criteria without broader social ones, and have not fully represented uncertainties and subjectivities in the communication of outcomes. Bellamy argued that opening up appraisals of research proposals using multi-criteria mapping can assist in overcoming these narrow framings. He also argued that participatory research is equally susceptible to framing effects and that efforts to “unframe” them have begun, involving:

- deliberative workshops rather than opinion surveys and focus groups,
- a smaller role for scientific experts in guiding the participation,
- treating SG research as proposals or ideas rather than tangible technologies or techniques to deploy, and
- framing the scope broadly in the context of mitigation and adaptation rather than a narrow view of the climate “emergency” and “natural” solutions.

DISCLAIMER: This Proceedings of a Workshop—in Brief was prepared by **Erin Markovich** and **Laurie Geller** as a factual summary of what occurred at the workshop. The committee's role was limited to planning the event. The statements made are those of the individual workshop participants and do not necessarily represent the views of all participants; the planning committee; the Board on Atmospheric Sciences and Climate; the Committee on Science, Technology, and Law; or the National Academies.

REVIEWERS: To ensure that it meets institutional standards for quality and objectivity, this Proceedings of a Workshop—in Brief was reviewed in draft form by **Waleed Abdalati,** University of Colorado Boulder; **Ulrike Lohmann,** ETH Zürich; **Jadwiga (Yaga) Richter,** National Center for Atmospheric Research; **Lynn Russell,** Scripps Institution of Oceanography; and **Jack Stilgoe,** University College London. The review comments and draft manuscript remain confidential to protect the integrity of the process.

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