Virtual Workshop Series on Stratospheric Aerosol Injection (SAI)

6. – 9. October 2025

The World Climate Research Program (WCRP) Lighthouse Activity *Research on Climate Intervention* and the *Stratospheric Aerosol Activity* of the WCRP Core Project *Atmospheric Processes and their Role in Climate* (APARC) are hosting a series of Virtual Workshops, in which the community can discuss the topic of Stratospheric Aerosol Injection (SAI), a proposed climate intervention that would aim to reduce the impacts of global warming through the injection of reflective particles in the stratosphere. As this topic becomes more widely discussed, it is important that robust scientific discussions are had to better identify potential risks and impacts of SAI across different scenarios, to understand and reduce uncertainties in future projections using Earth System Models, and to understand potential observational strategies to detect and monitor potential deployments. Furthermore, it is important to foster an inclusive, international dialogue where diverse perspectives are heard.

We welcome brief presentations from groups interested in showcasing and discussing their research on SAI. We particularly encourage relevant contributions on stratospheric aerosol detection and monitoring and the parameterization of stratospheric aerosol microphysical and optical properties in climate models. Non-presenting participants, who are interested in learning more and discussing potential future research activities, are also welcome.

Themes:

- Observational strategies: detection, monitoring and attribution
- SAI modeling: processes, capabilities and uncertainties
- Simulation strategies and scenario exploration (emulators)
- Impacts on atmospheric composition, from the stratosphere to air quality
- Global and regional surface climatic impacts, including societal and ecological
- Ethical aspects of studying and testing SAI

Further information and registration:

https://www.wcrp-climate.org/ci-workshop-series-sai

Organizing Committee:

Daniele Visioni, Cornell University, USA; Marc von Hobe, Forschungszentrum Jülich, Germany; Karen Rosenlof, NOAA, USA; Jean-Paul Vernier, NASA/NIA, USA + University of Reims, France; Simone Tilmes, NCAR, USA

The **WCRP Lighthouse Activity *Research on Climate Intervention* (https://www.wcrp-climate.org/ci-overview)** will explore potential future scenarios that include CI implementations and provide an objective overview of expected Earth system risks and opportunities, remaining key uncertainties, and associated knowledge gaps based on the rapidly evolving CI context/scene. By providing an unbiased and objective perspective on proposed climate interventions and identifying and promoting best practices for research, we aim to foster rigorous, transparent, and globally inclusive research to further our understanding of CI and its implications. Only by advancing our understanding of the Earth system's responses to CI, will we be able to provide the basis for well-informed climate policies, potential future CI governance, including litigation.

The ***Stratospheric Aerosol Activity*** **(https://www.aparc-climate.org/activities/stratospheric-aerosol/)** of the ***WCRP Core Project APARC*** **(https://www.aparc-climate.org/)** aims to foster collaboration across observational and modelling groups to better understand the stratospheric aerosol layer and the drivers for its observed variations such as volcanic eruptions, wildfires and changes in natural and anthropogenic sulfur emissions. Observational and modelling capacities developed over the past decades are also relevant in the context of SAI, and the Activity will use its tools and expertise to support the WCRP Lighthouse activity.

Program

Monday, 6 Oct, 18:00 - 21:30 UTC			
Time (UTC)	**First Name**	**Name**	**Title**
Introductory Session			
18:00	Daniele	Visioni	Welcome & Purpose
18:05	Marc	von Hobe	Rules and format (time keeping, changeover, discussions)
Strategies for SAI Detection, Monitoring and Attribution			
18:08	Landon	Rieger	Current and upcoming stratospheric aerosol measurements
18:19	Mahesh	Kovilakam	Long-term Stratospheric Aerosol Observations from GloSSAC and Their Relevance to SRM/SAI Assessments
18:30	Alex	Baron	SAI relevant in situ monitoring of the Stratospheric Aerosol Layer from the NOAA Balloon Baseline Stratospheric Aerosol Profiles (B2SAP) effort
18:34	Jean-Paul	Vernier	The Balloon measurement Network for stratospheric aerosol observations (BalNeO) for SAI monitoring.
18:41	Antonin	Knizek	Stratospheric SO2 in the Earth Observation Data Group
18:52	Anna	Lange	Investigating the ability of satellite occultation instruments to monitor possible geoengineering experiments
18:56	John	Dykema	Bridging the Gap in SAI Monitoring: Design and Trade Studies for a Solar Occultation CubeSat Constellation
19:03	Michael	Höpfner	Observing stratospheric aerosol injection and its impacts using space-borne infrared emission limb sounding
19:10	Frank	Keutsch	Quantifying Stratospheric Aerosol Injection: Observational Requirements from Pre-deployment Baselines to Post-injection Evolution
19:20			Session Discussion
19:32			Mini-Break
Global and Regional Climate Impacts of SAI			
19:35	Andrin	Jörimann	Effects of SAI in the middle atmosphere across models
19:39	Ivy	Glade	Comparing future projections of warm spells and their characteristics under climate change and stratospheric aerosol injection in CESM2 and UKESM1
19:46	Jim	Hurrell	Assessing the impact of solar climate intervention on hazardous convective weather over the contiguous United States
19:57	Mari	Tye	Exploring the effects of deployment targets on extreme precipitation and temperature
20:01	Cameron	Dong	Distinguishing between the Short-Term Climate Responses to Unilateral Stratospheric Aerosol Injection Latitudes with Artificial Intelligence
20:08	Taveen Singh	Kapoor	Rethinking Alumina for Stratospheric Aerosol Injection: New Insights into Shortwave Absorption
20:19	Ewa	Bednarz	SAI impacts on stratospheric ozone, large scale circulation, stratosphere-troposphere coupling and links with surface climate: understanding processes and narrowing uncertainties.
20:25			Session Discussion
20:37			Mini-Break
Ethical Aspects of Studying and Testing SAI			
20:40	James	Fleming	SAI Governance Retrospect and Prospect
20:51	Jennie	Stephens	The Dangers and Injustices of stratospheric aerosol injection
20:58	Ron	Baiman	SAI Deployment and Human Civilization: The Question is No Longer If, but How, When, Where, and by Whom?
21:09	Ryan	O'Loughlin	When Are Small-Scale Field Experiments in Solar Geoengineering Worth Pursuing?
21:19			Session Discussion
21:30			End of Day 1

Tuesday, 7 Oct, 15:00 - 18:05 UTC			
Time (UTC)	**First Name**	**Name**	**Title**
Introductory Session			
15:00			
SAI Simulations: Capabilities, Validation, Process Parameterizations			
15:05	Sebastian	Eastham	Key Gaps in Models' Physical Representation of Stratospheric Aerosol Injection and Its Impacts
15:12	Simone	Tilmes	Uncertainties depending on specifics of the aerosol microphysical models
15:23	Christian	von Savigny	On the importance of the aerosol particle size distribution in the context of SAI
15:30	Ilaria	Quaglia	Developing a simple set of metrics for the evaluation of climate model skills in reproducing the stratospheric behavior after volcanic eruptions
15:41	Johan	Friberg	Simulating stratospheric aerosol injections using SO2 data compiled at sub-kilometer vertical resolution
15:48	Ayse	Koyun	Physicochemical Properties of Solid Aerosol Particles as Alternative SAI Materials
15:59	Kwesi	Quagraine	Enhancing Regional Climate Impact Assessment of Stratospheric Aerosol Injection Using CESM Dynamical Downscaling
16:05			Session Discussion
16:12			Mini-Break
SAI Simulations: Strategies and Scenarios			
16:15	Wake	Smith	Bounding the possibility space for SAI deployment scenarios
16:26	Pete	Irvine	Peak shaving with solar radiation modification would shorten global temperature overshoot
16:33	Patrick	Keys	Designing scenarios for exploring unilateral climate intervention
16:44	Douglas	MacMartin	Managing Uncertainty in SAI through Learning Across Scales
16:51	Jared	Farley	Presenting the Climate Intervention Dynamical EmulatoR (CIDER)
17:02	David	Peterson	Worldwide inventory reveals the frequency and variability of pyrocumulonimbus and stratospheric smoke injections during 2013-2023
17:13	Walker	Lee	Could ARISE-SAI-1.5 have looked different? Exploring diverging stratospheric aerosol injection pathways with G2-SAI
17:19			Session Discussion
17:27			Mini-Break
SAI Impacts on Chemistry, Health and Economy			
17:30	Etienne	Gilgien	Impact on Ozone from Interactions between Sulfate SAI and Potential Future Halogen Sources
17:37	Sandro	Vattioni	Better constraining kinetic parameters of HNO3 and HCl uptake to calcite particles by lab experiments
17:48	Cindy	Wang	Air quality impacts of stratospheric aerosol injections are small and mainly driven by changes in climate, not deposition
17:55	Alice	Wells	An Open-Access Workflow to Assess the Health Impacts of Air Quality under Climate Intervention
18:02	Olivier	Boucher	Optimising PV production under SAI
18:08			Session Discussion
18:15			End of Day 2

Wednesday, 8 Oct, 9:00 - 12:00 UTC			
Time (UTC)	**First Name**	**Name**	**Title**
Introductory Session			
09:00			
SAI Impacts on Global and Regional Climate			
09:05	Alistair	Duffey	Global impacts of high-latitude low-altitude SAI in three earth system models
09:16	Chao	He	Response of Asian summer monsoon rainfall to stratospheric aerosol injections
09:23	Shrabani	Tripathy	Evaluating Polar Climate Risks of Stratospheric Aerosol Injection
09:34	Mohamadou A	Diallo	Stratospheric circulation response to stratospheric aerosol injections remains highly uncertain.
09:45	Xin	Zhou	Increased stratospheric water vapour after volcanic aerosol injection
09:52	Manouk	Geurts	Comparing the hydrological response to stratospheric aerosol injection using solid particles instead of sulfur
10:02			Session Discussion
10:12			Mini-Break
10:15			**Open Discussion on SAI Impacts**
10:55			Mini-Break
Special Session on SAI Assessments and Evaluation			
11:00	Gabriel	Chiodo	Environmental impacts of Stratospheric Aerosol Injections: insights from the upcoming quadrennial report by the Environmental Effects Assessment Panel (EEAP)
11:12	Alistair	Duffey	An Uncertainty Database for Stratospheric Aerosol Injection
11:20			**Open Discussion on SAI Assessments and Evaluation**
12:00			End of Day 3

Thursday, 9 Oct, 6:00 - 9:00 UTC			
Time (UTC)	**First Name**	**Name**	**Title**
Introductory Session			
06:00			
Strategies for SAI Detection, Monitoring and Attribution			
06:05	Kai	Qie	Monitoring Stratospheric Aerosol Changes from Solar Geoengineering Experiments
06:15			**Open Discussion on SAI Detection, Monitoring and Attribution**
06:50			Mini-Break
SAI Simulations			
06:55	Hongwei	Sun	Developing a Plume-in-Grid Model for Plume Evolution in the Stratosphere
07:06	Pengfei	Yu	Injection Near the Stratopause Minimizes the Stratospheric Side Effects of Sulfur-Based Climate Intervention
07:17			**Open Discussion on SAI Simulations**
07:55			Mini-Break
Ethical Aspects of Studying and Testing SAI			
08:00	Xavier	Landes	An Ethics for SAI Mission-Driven Research?
08:07	Timothy	Daly	From Confusion to Confucius: why clarifying language is a priority for ethics of SRM research
08:18	Yvette	Ramos	Governing Solar Radiation Management (SRM): Climate predictability, uncertainties and Policy and governance integration
08:25			**Open Discussion on Ethical Aspects**
09:00			End of Day 4

Abstracts

Current and upcoming stratospheric aerosol measurements

Landon Rieger (1), Ghassan Taha (2), Jean-Paul Vernier (3,4,5), Juan Carlos Antuña-Marerro (6), Corinna Kloss (7), Marc von Hobe (7), Pasquale Sellitto (8)

1. *Environment and Climate Change Canada, Canada*
2. *NASA Goddard Space Flight Center, Greenbelt, MD, USA*
3. *National Institute of Aerospace, USA*
4. *NASA Langley Research Center, USA*
5. *Groupe de Spectroscopie Moléculaire and Atmosphérique, Université de Reims Champagne Ardenne, Reims, France*
6. *Group of Atmospheric Optics (GOA-UVa), Universidad de Valladolid, 47011, Valladolid, Spain*
7. *Forschungszentrum Jülich GmbH, Institute of Climate and Energy Systems (ICE-4): Stratosphere, Jülich, Germany*
8. *Laboratoire Interuniversitaire des Systèmes Atmosphériques, Université Paris-Est Créteil, Université de Paris, Institut Pierre Simon Laplace (IPSL), Créteil, France*

Since the first balloon observations in the 1960s, instruments for measuring stratospheric aerosol have been steadily improving in coverage, resolution, and information content; providing critical data on background conditions and helping quantify the climate impacts of aerosol injections into the stratosphere. Additionally, the application of novel techniques has allowed instruments not originally designed to monitor stratospheric aerosol to investigate injection from extreme events such as the Hunga eruption. Despite these advances, fully quantifying stratospheric aerosols including the size distribution, particle composition, and spatial distribution remains aspirational with different measurements and techniques providing insight into various dimensions of the problem. This talk will provide an overview of the current and planned capabilities for stratospheric aerosol monitoring including ground-based networks and satellite instruments.

Long-term Stratospheric Aerosol Observations from GloSSAC and Their Relevance to SRM/SAI Assessments

Mahesh Kovilakam

ADNET Systems Inc./NASA Langley, USA

The Global Space-based Stratospheric Aerosol Climatology (GloSSAC) provides a unique 45-year record of multi-wavelength stratospheric aerosol extinction profiles derived from a suite of satellite instruments. This long-term dataset has been central to understanding the role of stratospheric aerosols in climate, quantifying radiative forcing, and evaluating models. With growing interest in Stratospheric Aerosol Injection (SAI) and Solar Radiation Modification (SRM) as potential climate interventions, GloSSAC offers an indispensable empirical foundation for assessing feasibility, risks, and uncertainties. In particular, GloSSAC's record of volcanic eruptions and wildfire events provides natural analogs to stratospheric injection scenarios, helping to constrain particle size distributions, transport pathways, and radiative impacts. This presentation highlights recent developments in GloSSAC, its application to SRM/SAI-relevant studies, and the critical need for sustained multi-instrument monitoring to ensure robust assessment of any future intervention strategies.

SAI relevant in situ monitoring of the Stratospheric Aerosol Layer from the NOAA Balloon Baseline Stratospheric Aerosol Profiles (B2SAP) effort

Alex Baron (1,2), Kate Smith (1,2), Elizabeth Asher (1,3), Troy Thornberry (2) and the larger B2SAP team

1. *Cooperative Institute for Environmental Research (CIRES), University of Colorado, Boulder, USA*
2. *NOAA Chemical Sciences Laboratory (CSL), Boulder, USA*
3. *NOAA Global Monitoring Laboratory (GML), Boulder, USA*

Stratospheric aerosols are key components of the climate system, yet substantial uncertainties remain in how their chemical, dynamical, and microphysical processes are represented in models, particularly concerning particle size distributions. The Baseline Balloon Stratospheric Aerosol Profiles (B2SAP) project aims to reduce these uncertainties through regular balloon-borne measurements of aerosol number and size distributions, as well as water vapor, ozone, and meteorological parameters. Since 2019, B2SAP has conducted launches from latitudinally dispersed sites in both hemispheres and, more recently, from tropical locations, building a unique in situ dataset extending into the middle stratosphere. This growing record enhances understanding of the natural stratospheric aerosol burden, its variability, and its response to perturbations. This presentation will detail what B2SAP is all about, as well as how it provides prerequisite knowledge relevant to SAI.

The Balloon measurement Network for stratospheric aerosol Observations (BalNeO) for SAI monitoring

Jean-Paul Vernier (1,2,3); Amit K. Pandit (1); Rubel Das (1); Nicolas Dumelié (3); Lilian Joly (3); Hazel Vernier (3); Giovanni de Souza (4); Eduardo Landulfo (4); Demilson Quintao (5), Bruno Biazon (5); James Flaten (6)

1. National Institute of Aerospace, USA
2. NASA Langley Research Center, USA
3. Groupe de Spectroscopie Moléculaire and Atmosphérique, Université de Reims Champagne Ardenne, Reims, France
4. Instituto de Pesquisas Energéticas e Nucleares Brazil
5. IPMet - Centro de Meteorologia de Bauru - FC/Unesp, Bauru, Brazil
6. University of Minnesota, USA

The Stratospheric aerosol layer is a key component of the climate system with global implications on surface temperature and the hydrological cycle. Being highly variable, regular observations are needed to understand its different sources. Since the era of satellite observations in the late 70's, major and moderate volcanic eruptions affected the total Stratospheric Aerosol Optical Depth. In addition, recent extreme wildfires in Canada and Australia have impacted the stratosphere at levels never observed before. Finally, the Summer Asian Monsoon exports surface pollution into the stratosphere and represents another significant source.

Geoengineering the climate using artificial stratospheric injection of aerosols has been proposed as a temporary solution to reduce the impacts of climate change. Having a network of observations to detect any artificial injection and trace back its origin is critical.

The Balloon Network for stratospheric aerosol Observations (BalNeO) aims to fill those gaps. BalNeo brings together research laboratories from USA (NASA Langley Research Center, The National Insitute of Aerospace), Brazil (IPMet – Centro de Meteorologia de Bauru, Instituto de Pesquisas Energéticas e Nucleares), France (Groupe de Spectroscopie Moléculaire et Atmosphérique-Université de Reims Champagne-Ardenne) and India (Tata Institute of Fundamental Research) in order to profile aerosol concentration from the ground to the stratosphere.

Stratospheric SO_2 in the Earth Observation Data Group

Antonin Knizek, Roy Grainger, Isabelle Taylor, Basudev Swain, Rui Song, Anu Dudhia

Atmospheric Oceanic and Planetary Physics, University of Oxford, UK

The Earth observation data group (EODG) at the University of Oxford uses satellite data to monitor events in the Earth's atmosphere. Large portion of its work is focused on retrievals of sulfur dioxide, sulfuric acid and ash contents in volcanic clouds. Large volcanic eruptions are the single largest perturber of the stratospheric sulfur dioxide content. These events are therefore a direct parallel to stratospheric sulfur dioxide injections as a geoengineering technique to modify solar radiation and offset global warming. In both cases, SO_2 enters the stratosphere and is converted into sulfuric acid, forms secondary aerosols and scatters incoming radiation. A new radiative transfer forward model with rigorous treatment of atmospheric scattering, the Scattering Reference Forward model, is currently under development in the EODG. Along with that, a new retrieval scheme for multispecies retrievals of SO_2, sulfuric acid and ash, called OxHARP, are being developed as well. These tools are tailored to study the fate of volcanic SO_2 and are therefore directly applicable to both research into the impacts of stratospheric aerosol injections and long-term monitoring. Volcanoes are a natural laboratory to study the chemistry and physics of sulfur dioxide in the atmosphere.

At the same time, utilization of climate models within the Climate model intercomparison project (CMIP) in conjunction with satellite data are being used to attribute Artcic warming to volcanic aerosol forcings to past eruptions, such as Agung, El Chichon and Pinatubo. Satellite data retrievals are a critical part of this intercomparison challenge and development of better satellite retrievals helps in model data reanalysis as well as in future climate change prediction.

Investigating the ability of satellite occultation instruments to monitor possible geoengineering experiments

<u>Anna Lange</u> (1), Ulrike Niemeier (2), Alexei Rozanov (3), Christian von Savigny (1)

1. *Institute of Physics, University of Greifswald, Germany*
2. *Max Planck Institute for Meteorology, Hamburg, Germany*
3. *Institute of Environmental Physics, University of Bremen, Germany*

Solar radiation management is a method in the field of geoengineering that aims to modify the Earth's shortwave radiation budget. One idea is to inject sulphur dioxide or sulphuric acid into the stratosphere, where sulphate aerosols are then formed. Such experiments can probably be observed, for example, with satellite occultation instruments like SAGE III/ISS. The aim of the current study is to analyse, using MAECHAM5-HAM simulations and retrievals with the radiative transfer program SCIATRAN, whether it is possible to detect the formed stratospheric aerosols from emissions of 1 and 2 Tg S/y (sulphur per year) with the currently active satellite occultation instruments, taking into account an error estimate that is as realistic as possible. If these smaller amounts of sulphur are detectable, larger amounts will also be detectable. The calculations show that, considering the natural variability and the assumptions made here, the stratospheric aerosols formed from emissions of 1 and 2 Tg S/y in the quasi steady-state phase can be detected, which is not the case in the first month of the two-year initial phase.

Bridging the Gap in SAI Monitoring: Design and Trade Studies for a Solar Occultation CubeSat Constellation

John Dykema (1), Jim Franke (2), and David Keith (2)

1. *Harvard University, School of Engineering and Applied Sciences, USA*
2. *University of Chicago, USA*

As stratospheric aerosol injection (SAI) receives increasing attention from policy and research communities, recognition of the value of robust observational capabilities is becoming more widespread. However, discussions to date lack a quantitatively characterized monitoring system design that can serve as a concrete foundation for both technical and policy considerations. This presentation introduces a new research initiative to develop such a system, leveraging solar occultation CubeSat constellations as a cost-effective, rapidly deployable approach for comprehensive stratospheric aerosol monitoring.

The central objective is to perform engineering trade studies examining the performance and cost of deploying light, low-cost, three-band occultation sensors capable of delivering high-resolution (~1 km) vertical profiles of aerosol optical depth and size distribution. While an individual CubeSat provides only two soundings per orbit, a constellation architecture can significantly enhance temporal and spatial coverage, improving the characterization of stratospheric aerosol perturbations, including those from potential SAI activities.

Our CubeSat-based monitoring system is designed to extend current satellite timeseries, building on SAGE-III/ISS measurements and complementing future missions such as the 2031 HAWCSat-ALI. This approach addresses key observational challenges, including the need for continuous, global coverage and cost-effective, rapid deployment.

We focus on technical considerations such as instrument design, bus architecture, and constellation trade-offs, and are actively seeking industry and academic partners to help advance our collective capability to monitor the stratosphere in the context of potential SAI scenarios.

Observing stratospheric aerosol injection and its impacts using space-borne infrared emission limb sounding

Michael Höpfner (1), P. Sellitto (2), M. Kosary (2), S. Tilmes (3), B. Funke (4), Q. Errera (5), A. Hoffmann (6), B.-M. Sinnhuber (1)

1. Karlsruhe Institute of Technology - IMKASF, Karlsruhe, Germany
2. Laboratoire Interuniversitaire des Systèmes Atmosphériques, Université Paris-Est Créteil, Université de Paris, Institut Pierre Simon Laplace (IPSL), Créteil, France
3. National Center for Atmospheric Research, Boulder, CO, USA
4. Instituto de Astrofísica de Andalucía, CSIC, Granada, Spain
5. Royal Belgian Institute for Space Aeronomy (BIRA-IASB), Brussels, Belgium
6. European Space Research and Technology Centre, European Space Agency (ESA/ESTEC), The Netherlands

As part of the preparatory studies for the CAIRT (Changing-Atmosphere Infra-Red Tomography Explorer) proposal - which advanced to the final selection stage of ESA's Earth Explorer 11 mission - we evaluated the capabilities of an infrared limb-imaging Fourier Transform Infrared (FTIR) instrument for detecting and quantifying the impacts of potential stratospheric sulfur injections. This investigation focused on the instrument's performance through realistic simulations, specifically examining trace gases (including SO_2, NO_2, N_2O_5, HNO_3, $ClONO_2$, and ozone), aerosols (e.g. H_2SO_4), and temperature - key atmospheric parameters likely influenced by geoengineering activities.

Quantifying Stratospheric Aerosol Injection: Observational Requirements from Pre-deployment Baselines to Post-injection Evolution

Frank Keutsch

Harvard University, USA

The development of a robust observational framework is critical for quantifying the impacts of stratospheric aerosol injection (SAI) on atmospheric processes and the Earth system. Effective strategies must integrate aerosol microphysical measurements to constrain nucleation, coagulation, and sedimentation processes that govern aerosol evolution and radiative forcing. Concurrently, high-resolution chemical observations are required to assess heterogeneous reaction rates, halogen activation, and perturbations to reactive nitrogen and hydrogen cycles that directly influence stratospheric ozone. Dynamical measurements must capture modifications to stratospheric circulation as well as potential teleconnections influencing surface climate. A multi-platform observational architecture that combines in situ profiling with remote sensing is necessary to characterize both localized injection plumes and their subsequent large-scale dispersion. Crucially, sustained observational records must be established prior to any deployment to define pre-perturbation baselines, enabling separation of SAI-induced signals from natural variability and volcanic analogs. Such early, continuous, and multi-scale measurements will provide the empirical foundation to evaluate SAI efficacy, attribute unintended consequences, and improve predictive capability in coupled Earth system models.

Monitoring Stratospheric Aerosol Changes from Solar Geoengineering Experiments

Kai Qui, Chao He, Zhixuan Bai, Yifeng Peng, Jianchun Bian, Pengfei Yu

Laboratory of Middle Atmosphere and Global Environment Observation, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

Stratospheric Aerosol Injection (SAI), a proposed climate intervention strategy to mitigate global warming by reflecting sunlight, demonstrates for reducing global temperatures and modulating weather patterns. While large-scale deployment of SAI remains both technically and morally challenging, small-scale SAI experiments are increasingly likely to happen in the near future. Monitoring such experiments are crucial in international regulations of SAI activities. While the tropospheric signals from small-scale experiments are almost impossible to detect, stratospheric aerosol properties prove significantly more detectable, highlighting a relative advantage for monitoring such activities. This study uses climate model simulations constrained by the multiyear (2019-2022) balloon-borne aerosol measurements over the Tibetan Plateau and Boulder, Colorado to diagnose the detectability of SAI-induced changes in stratospheric aerosol properties against the natural variability. In the absence of volcanic or wildfire perturbations, a pulse injection of 0.1 Tg at 15 °S and 15 °N produced globally persistent detectable signals for over 1.5 years. However, under atmospheric background conditions perturbed by the wildfire and volcanoes between 2019-2022, a pulse injection of 0.5 Tg failed to produce sustained discernible signals at Southern Hemispheric mid-latitudes. These findings elucidate the complex interplay between SAI and natural atmospheric variability, providing critical guidance for designing robust monitoring frameworks in anticipation of potential SAI deployment.

Uncertainties depending on specifics of the aerosol microphysical models

Simone Tilmes (1), Sebastian D. Eastham (2), Amy H. Butler (3), Ewa M. Bednarz (3), Gabriel Chiodo (4), Daniele Visioni (5), Lili Xia (6), and Pengfei Yu (7)

1. *NSF National Center for Atmospheric Research, Boulder, CO, USA*
2. *Imperial College London, UK*
3. *NOAA Chemical Sciences Laboratory, Boulder, USA*
4. *Spanish National Research Council – CSIC*
5. *Department of Earth and Atmospheric Sciences, Cornell University, USA*
6. *Rutgers University, USA*
7. *Jinan University, China*

I will give an overview on the different outcomes of SAI injections using different aerosol microphysical models, with implications for the impacts of SAI on radiation and ozone.

Key Gaps in Models' Physical Representation of Stratospheric Aerosol Injection and Its Impacts

Sebastian D. Eastham (1), *Daniele Visioni (2,3), Simone Tilmes (2), Ewa Bednarz (4,5)*

1. *Imperial College London, UK*
2. *NSF National Center for Atmospheric Research, Boulder, CO, USA*
3. *Department of Earth and Atmospheric Sciences, Cornell University, USA*
4. *Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, Boulder, USA*
5. *NOAA Chemical Sciences Laboratory, Boulder, USA*

Stratospheric aerosol injection (SAI) is a proposed solar radiation modification strategy to mitigate the negative effects of climate change. However, significant uncertainties exist in climate model simulations of the Earth system's response to SAI. Drawing on a recent expert working group assessment, we identify and prioritize key modeling gaps that are most reducible through targeted observations and/or model development efforts. For SAI, the assessment specifically highlights three critical areas for model evaluation and improvement: aerosol microphysics, aerosol-radiation interactions, and aerosol-chemistry interactions. We argue that progress in these areas would be largely accelerated by new, dedicated satellite and in-situ observations to better constrain model processes. Furthermore, existing model capabilities could be leveraged - such as by working to harmonize models which operate at different spatial and temporal scales and cover different ranges of complexity - to bridge these gaps, offering a clear path forward for advancing the simulation of SAI and its potential impacts. This work provides a framework for directing future research and observational campaigns to reduce key uncertainties in simulations of SAI.

As an aside: atmospheric chemists and air-quality folks seem eager to learn more about SAI and SRM in general… which is why they invited me to give a talk about SAI at the last GRC on Atmospheric Chemistry. I ended my talk with your schematic on the key gaps in models… and it was really well received. I made the point that improvements in CMIP7 in terms of modeling and observations of aerosol-radiation interactions and aerosol-cloud interactions will definitely help the future generation of models in terms of the accuracy of their SAI results. Also, new work on wildfire aerosols and heterogeneous chemistry on them may help too.

On the importance of the aerosol particle size distribution in the context of SAI

Christian von Savigny (1), Anna Lange (1), Felix Wrana (1), Alexei Rozanov (2) and Ulrike Niemeier (3)

1. *Institute of Physics, University of Greifswald, Germany*
2. *Institute of Environmental Physics, University of Bremen, Germany*
3. *Max-Planck-Institute for Meteorology, Hamburg, Germany*

The size distribution of stratospheric sulfate particles is obviously of crucial importance for many reasons, but several important questions exist regarding measurements and simulations of the size distribution. This contribution will briefly discuss three different aspects. First, uncertainties in aerosol size retrievals from remote sensing measurements in the visible/NIR spectral range. Second, how to compare measured and simulated particle size distributions. Third, how the particle size distribution affects alterations of the sky colours associated with SAI experiments.

Simulating stratospheric aerosol injections using SO_2 data compiled at sub-kilometer vertical resolution

Johan Friberg, Christine Pohl, Moa K. Sporre

Lund University, Sweden

Our ability to simulate the climate cooling from deliberate stratospheric aerosol injections relies on the knowledge of prior stratospheric injections by explosive volcanic eruptions and their impact on the stratospheric aerosol load and climate impact. The extent and duration of cooling is strongly dependent on the injection altitude and mass of the SO_2.
We have developed a method to produce vertical profiles of volcanic SO_2 layers at more than one order of magnitude higher resolution than the vertical resolution in today's climate models [1]. Simulations with our SO_2 vertical profiles align well with satellite observations of the stratospheric aerosol load after the June 2009 eruptions of the Sarychev volcano [2]. Here, we will discuss our present and near-future effort to produce high-vertical resolution SO_2 profiles for all stratospheric volcanic injections in the past ~20 years.

References

[1] Sandvik, O. S., Friberg, J., Sporre, M. K., and Martinsson, B. G., doi: 10.5194/amt-14-7153-2021, 2021.
[2] Axebrink, E., Sporre, M. K., Friberg, J., doi: 10.5194/acp-25-2047-2025, 2025.

Physicochemical Properties of Solid Aerosol Particles as Alternative SAI Materials

Ayse N. Koyun (1), David Verbart (2), John Dykema (1), Frank Keutsch (1,2,3)

1. John A. Paulson School of Engineering and Applied Sciences, Harvard University, MA, USA
2. Department of Chemistry and Chemical Biology, Harvard University, MA, USA
3. Department of Earth and Planetary Sciences, Harvard University, MA, USA

Alternative stratospheric aerosol injection materials (ASAIMs) such as diamond (C), calcite $CaCO_3$ and alumina Al_2O_3 have been proposed. However, fundamental knowledge gaps exist regarding their physicochemical properties under stratospheric conditions.

We investigate ASAIM optical properties and morphology following ageing by UV and HCl exposure. Beyond previously studied diamond, calcite and alumina we examine Earth-abundant carbonate minerals: smithsonite ($ZnCO_3$), dolomite [$CaMg(CO_3)_2$] and magnesite ($MgCO_3$). Our experimental approach combines controlled aging in a photochemical reaction cell with characterization of complex refractive index using s-SNOM, FTIR and Ellipsometry. Quantitative gas monitoring during reactions provides insights into reaction pathways and material stability. Preliminary results reveal distinct reactivity patterns among carbonate materials under HCl exposure, with varying degrees of surface modification and stability. These findings provide critical data for climate-chemistry models and inform selection criteria for viable SAI materials.

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Developing a Plume-in-Grid Model for Plume Evolution in the Stratosphere

Hongwei Sun (1), Sebastian Eastham (2), and David Keith (3)

1. *University of Hawaii at Manoa*
2. *Imperial College London, UK*
3. *University of Chicago, USA*

Small-radius high-aspect-ratio aerosol plumes from stratospheric aerosol injection (SAI) are smaller than global Eulerian models' grid cells. To help global Eulerian models resolve subgrid aerosol plumes in the stratosphere, a Lagrangian plume model, comprising a Lagrangian trajectory model and an adaptive-grid plume model with a sequence of plume cross-section representations (from a highly resolved 2-D grid to a simplified 1-D grid based on a tradeoff between the accuracy and computational cost), is created and embedded into a global Eulerian (i.e., GEOS-Chem) model to establish a multiscale Plume-in-Grid (PiG) model.

Could ARISE-SAI-1.5 have looked different? Exploring diverging stratospheric aerosol injection pathways with G2-SAI

Walker Lee (1), Simone Tilmes (1), Ewa M. Bednarz (2,3)

1. *NSF National Center for Atmospheric Research, Boulder, CO, USA*
2. *Cooperative Institute for Research in Environmental Sciences (CIRES), Univ. of Colorado, Boulder, USA*
3. *NOAA Chemical Sciences Laboratory, Boulder, USA*

Simulations of stratospheric aerosol injection (SAI) are usually short relative to climatic timescales and are often simulated against a backdrop of global warming. As a result, it can be difficult to disentangle the impacts of the intervention from ongoing changes in the climate, especially for parts of the Earth system that vary and change on timescales longer than the typical SAI experiment; one such example is the Atlantic Meridional Overturning Circulation (AMOC). To address these challenges, we use the Community Earth System Model (CESM2) to revisit the Geoengineering Model Intercomparison Project's G2 experiment, which simulates SAI against a pre-industrial control background with annual 1% increases in atmospheric CO_2 concentrations. We design our simulations to mirror other contemporary SAI experiments, and we run the model for 150 years at a time. Two of our simulations, which use the 'three degree-of-freedom controller' strategy used by past experiments such as GLENS and ARISE-SAI-1.5, diverge sharply: they meet the same temperature targets, but after 150 years, one simulation injects mostly in the southern hemisphere and slows the decline of AMOC but does not stop it; the other injects more in the northern hemisphere subtropics and halts the decline of AMOC entirely. Using this knowledge, we revisit the ARISE-SAI-1.5 simulations and design a new injection strategy which shifts a significant portion of the injection to the NH without changing the temperature targets. Our results suggest that the impacts of ARISE-SAI-1.5 could have looked noticeably different, especially in the long term.

Designing scenarios for exploring unilateral climate intervention

Patrick Keys (1), Curtis Bell (2); Elizabeth Barnes (1); James Hurrell (3); ChenRui Diao (3)

1. *Boston University, USA*
2. *US Naval War College, USA*
3. *Colorado State University*

Climate change is causing increasingly severe global and regional impacts, such as rising temperatures and more frequent extreme rainfall events. Despite this, current global policies to systematically reduce greenhouse gas emissions are incommensurate with the scale of the problem. This raises the possibility that an individual actor (or actors) will find present and future climate changes intolerable, and may seek to individually respond to these changes through deliberate intervention in the climate for their own benefit. In this study, we specifically aim to identify which actor would be the most likely to pursue unilateral climate intervention in the form of stratospheric aerosol injection (SAI), an approach to disperse reflective particles in the stratosphere to reflect a small percentage of the sun's energy back to space. First, we use a formal, two-player model to identify strategic interactions among actors. Second, we design a framework of geopolitically-relevant filters that progressively reduces the number of candidate actors (in this case, nation states), with the aim of identifying a single unilateral initiator. These filters consider the state's capacity to deploy SAI, their motivation, the confidence that a deployment could be sustained, and the state's insensitivity to economic sanctions. We begin with sixteen candidates for the unilateral initiator, and eventually identify a single initiator. Third, we design and implement a simulation of this unilateral deployment scenario based on the single initiator using the Community Earth System Model 2 (CESM2), and additional two branching simulations based on two different subsequent respondents. We find that certain unilateral actors may entrain certain types of geostrategic outcomes. We will discuss how this type of geopolitical scenario development can be further expanded to explore other geopolitically plausible climate intervention scenarios.

Peak shaving with solar radiation modification would shorten global temperature overshoot

Linus Boselius (1), Alistair Duffey (2), Peter J. Irvine (3)

1. *SRM360*
2. *University College London, UK*
3. *University of Chicago, USA*

Projected rates of emissions reductions are unlikely to keep global temperatures from crossing the Paris Agreement temperature targets. Large-scale carbon dioxide removal (CDR) could help recover a target temperature after it has been exceeded, producing an overshoot scenario. Solar radiation modification (SRM) is the idea to cool the planet by increasing the reflection of incoming solar radiation. SRM could be used in an overshoot scenario for ‘peak shaving’, where SRM is deployed to maintain a temperature target during the overshoot. Here, we quantify the effect of SRM peak shaving on the duration of the overshoot using an adapted extension of the SSP2-4.5 scenario and an ensemble of variants of the FaIR simple climate model. We find a substantial reduction in overshoot duration, which ranges from approximately 5% for multi-decade overshoots up to approximately 20% for multi-century overshoots. The shortening is predominantly driven by the ocean response to peak shaving. Peak shaving results in lower ocean temperatures relative to the overshoot scenario, inducing a stronger surface temperature response to decreasing and negative emissions, driving overshoot shortening. Thus, SRM, when deployed as a complement to emissions reductions and CDR, could end overshoot decades earlier than otherwise.

Enhancing Regional Climate Impact Assessment of Stratospheric Aerosol Injection Using CESM Dynamical Downscaling

Kuwesi Quagraine, *Simone Tilmes*

NSF National Center for Atmospheric Research, Boulder, CO, USA

Imagine trying to understand the intricate details of a painting from a hundred meters away. This is analogous to the challenge faced by current geoengineering models, which often rely on climate models with coarse spatial resolutions. With grid sizes around 100 kilometers, these models struggle to capture the nuanced regional dynamics and localized impacts of Stratospheric Aerosol Injection (SAI). To overcome this limitation, we apply dynamical downscaling through CESM regional refinement, a technique that significantly enhances both spatial and vertical resolution in climate modeling. By refining these models, we can more accurately assess the regional-scale impacts of climate interventions such as SAI. This approach not only advances our understanding of how geoengineering might affect local climates but also supports more informed and responsible decision-making in the field. In this study, we explore how dynamical downscaling of CESM-SAI datasets could transform the assessment of climate interventions.

Managing Uncertainty in SAI through Learning Across Scales

Douglas MacMartin, *Daniele Visioni*

Department of Earth and Atmospheric Sciences, Cornell University, USA

Stratospheric Aerosol Injection (SAI) could be used to cool the climate, and while it is certain that a deployment would lead to global cooling, the regional responses that would occur are somewhat uncertain, influencing the perceived risks of deployment. However, making a choice about whether to begin deploying SAI in the presence of uncertainty is quite un-like jumping out of an airplane and hoping that your parachute works – you can't un-jump from an airplane. But for SAI, you can constantly learn as the scale of activity grows, and revise strategies, or the desired cooling, including potentially phasing out deployment altogether. Some of the current uncertainty in model projections would be substantially reduced at scales much smaller than the scales at which they matter: uncertainty in aerosol microphysics and aerosol spatial distribution are clear examples. Understanding what scale of material release into the stratosphere is needed to resolve different uncertainties is essential for assessing risks, for design of responsible research, and for designing governance of research.

We argue that there are three main questions and corresponding scales. A small experiment that released one plane-load (10-100 tons) of SO_2 could resolve many uncertainties in aerosol microphysics, given the proper observational system is in place. To meaningfully reduce uncertainty in aerosol transport and the resulting spatial distribution, we estimate that it would require continued injection over a season, perhaps of around 50-100 kt; this is still too small to have detectable surface climate effects. Finally, while much could be learned during the early decade(s) of a gradually-ramped-up deployment, where global mean cooling is less than 0.5 °C, changes in many regional climate metrics will still be small enough that they would be difficult to detect and attribute. While this also implies that uncertainty in these outcomes will have more limited impact, it is less clear whether the scale at which one could learn about any particular uncertainty and adjust the deployment strategy in response is larger or smaller than the scale at which it matters. Uncertainties in the regional climate response will thus need to continue to be assessed through climate modeling and a deeper understanding of the underlying climatic features.

Presenting the Climate Intervention Dynamical EmulatoR (CIDER)

Jared Farley (1), Douglas MacMartin (1), Daniele Visioni (1), Ben Kravitz (2), Ewa Bednarz (3,4), Alistair Duffey (5), Matthew Henry (6)

1. *Department of Earth and Atmospheric Sciences, Cornell University, USA*
2. *Indiana University, USA*
3. *Cooperative Institute for Research in Environmental Sciences (CIRES), Univ. of Colorado, Boulder, USA*
4. *NOAA Chemical Sciences Laboratory, Boulder, USA*
5. *University College London, UK*
6. *University of Exeter, UK*

The range of stratospheric aerosol injection (SAI) scenarios is complex and extensive. It encompasses many different factors including various climate targets, various strategies of achieving climate targets, and multi-actor deployments in which various actors use various strategies to achieve (or attempt to achieve) various climate targets. To explore this range of scenarios, we have designed a simple dynamical climate emulator that can take in a combination of different injection locations and amounts, has dynamics that model the timescale of starting and stopping injection, and can estimate regional effects by outputting regional temperature, precipitation, and evaporation. We have used this emulator to facilitate games and workshops exploring SAI, aid in SAI deployment algorithm design, and estimate the consequences of a non-cooperative deployment of SAI.

Worldwide inventory reveals the frequency and variability of pyrocumulo-nimbus and stratospheric smoke injections during 2013-2023

David A. Peterson (1), Melinda T. Berman (2), Michael D. Fromm (3), René Servranckx (4), William J. Julstrom (5), Edward J. Hyer (1), James R. Campbell (1), Theodore M. McHardy (1), Andrew Lambert (7)

1. US Naval Research Laboratory, Monterey, California
2. University of Illinois Urbana-Champaign
3. US Naval Research Laboratory, Washington, DC
4. Retired Meteorologist, PyroCb Community Member, Dorval, Quebec
5. University of Iowa
6. General Dynamics Information Technology

An inventory of 761 confirmed pyrocumulonimbus (pyroCb) events observed worldwide during 2013-2023 answers many open questions on the inter-annual, seasonal, sub-daily, and regional variability of this natural source of stratospheric aerosol injection (SAI), along with potential controlling factors. This pyroCb inventory is critical for understanding how wildfire smoke may interact with other sources of SAIs and improving aerosol plume transport forecasts. Smoke injection altitudes range from the mid-troposphere to the lower stratosphere (8-18 km), with 414 pyroCb events (55%) linked to smoke injection within one kilometer of the tropopause or higher. Estimated aerosol mass in these plumes spans four orders of magnitude, which has significant implications for climate-scale radiative effects. The cumulative aerosol particle mass injected near the tropopause over an active fire season can rival that of recent extreme pyroCb events and significant volcanic eruptions. The 2023 fire season in Canada set new records for total pyroCb activity regionally (142 events) and worldwide (169 events). This inventory sets a foundation for an Earth System Data Record that can be used to identify longer-term trends in pyroCb activity and consequent impacts.

Injection Near the Stratopause Minimizes the Stratospheric Side Effects of Sulfur-Based Climate Intervention

Pengfei Yu

Jinan University, China

Stratospheric aerosol injection (SAI) using sulfur cools the planet by reflecting sunlight back to space. Traditional SAI, with sulfur dioxide injection rate of 10 Tg/year at 25 km, accumulates aerosols in the tropical lower stratosphere, causing a 6 K warming of the tropical lower stratosphere that impact the entry value of stratospheric water vapor and jet positions. This approach could also delay October Antarctic total column ozone (TCO) recovery to 1980s values by 25â€“55 years. We propose a novel SAI approach of injecting sulfur at 50 km (SAI50) that substantially reduces these negative impacts. In SAI50, the mean meridional overturning circulation near the stratopause rapidly transports aerosols to mid-high latitudes, preventing their accumulation in the tropical lower stratosphere. This approach reduces tropical stratospheric warming to 3 K and shortens the Antarctic ozone recovery delay to 5 years. Furthermore, SAI50 demonstrates greater cooling efficiency, enhancing global and polar surface cooling by 22 % and 40 % respectively. Consequently, SAI50 preserves 20 % more Arctic September sea ice compared to lower-altitude SAI. These findings suggest that SAI50 could offer a more effective and less disruptive approach to climate intervention.

Bounding the possibility space for SAI deployment scenarios

Wake Smith

Yale University, USA

Stratospheric Aerosol Injection deployment scenarios may vary across a variety of dimensions, but those dimensions are not unlimited and are instead constrained by both by physics and technology. This talk will explore the boundaries of the deployment scenario possibility space in respect of several distinct dimensions. These include pre-start time requirements, speed of ramp up of deployed mass, prospective latitudes and longitudes of deployment bases, deployment altitudes, lofting platform requirements, target coverage areas, duration of deployment, and termination dynamics. This talk will not seek to advocate for any particular form of deployment or any preferred outcomes in respect of these dimensions, but will seek to help policy makers understand their degrees of freedom in choosing deployment scenarios.

Effects of SAI in the middle atmosphere across models

Andrin Jörimann (1), Timofei Sukhodolov (1), Gabriel Chiodo (2), Sandro Vattioni (1), Simone Tilmes (3), Daniele Visioni (4),David Plummer (5),Shingo Watanabe (6),Hideharu Akiyoshi (7)

1. *PMOD/WRC, ETH Zürich, Switzerland*
2. *CSIC, Spain*
3. *NSF National Center for Atmospheric Research, Boulder, CO, USA*
4. *Department of Earth and Atmospheric Sciences, Cornell University, USA*
5. *ECCC, Canada*
6. *JAMSTEC, Japan*
7. *NIES, Japan*

We use CCMI-2022 data to extract SAI signals in five models that arise from uniformly prescribed aerosol optical and physical properties in all models. The simulated aerosol cools the surface up to some 1.5 K by the end of the century compared to reference simulations that follow a moderate climate change scenario. We identify key changes in the middle atmosphere that result from SAI in this scenario. Our analysis shows that models largely agree on whether dynamical or chemical processes dominate in different regions. However, we also point out inter-model differences, encountered notably in the lower Arctic stratosphere.

Comparing future projections of warm spells and their characteristics under climate change and stratospheric aerosol injection in CESM2 and UKESM1

Ivy Glade (1), James W. Hurrell (1), Danica L. Lombardozzi (2)

1. *Department of Atmospheric Science, Colorado State University, USA*
2. *Department Ecosystem Science & Sustainability, Colorado State University, USA*

Extreme heat events have increased in frequency, intensity and duration over the last several decades as a result of anthropogenic climate change. Extreme heat events impact human and natural systems including human mortality and morbidity, agricultural and livestock yields, ecosystem vulnerability and water resource management. Increasing risks from climate change has prompted an increase in research into the potential impacts “both good and bad“ of climate intervention. Stratospheric aerosol injection (SAI) is one of the most studied methods of climate intervention and could quickly cool or stabilize global temperatures by injecting reflective aerosols into the stratosphere. We investigate future projections of a type of extreme heat event, called a warm spell, in the context of a policy relevant and moderate emissions scenario (SSP2-4.5) and SAI deployment simulated in two Earth-system models: CESM2 and UKESM1. Warm spells are prolonged periods of anomalously high temperature that can occur at any time of the year. Under SSP2-4.5 warm spells are projected to become increasingly frequent, intense and longer in both models. SAI deployment is able to effectively mitigate many of these changes; however, differences in future projections of warm spells between CESM2 and UKESM1, regardless of whether or not SAI is deployed, highlight the importance of inter-model comparisons in assessments of future climates.

Assessing the impact of solar climate intervention on hazardous convective weather over the contiguous United States

James W. Hurrel, Lantao Sun, Kristen Rasmussen, Bali Summers

Colorado State University, USA

We have produced an ensemble of convection-permitting regional simulations over the contiguous United States (CONUS) driven by large ensembles of climate model simulations in order to achieve three goals: (1) determine how the impacts of Solar Climate Intervention (SCI) might influence the occurrence, frequency, and structure of convective storms; (2) quantify the range of uncertainties associated with internal variability and different forcing scenarios on the environments supporting convective storms; and (3) provide a thoroughly tested and evaluated high-resolution convection-permitting future climate ensemble dataset with and without SCI for the atmospheric science community. Specifically, existing Community Earth System Model (CESM) climate change and SAI large ensemble simulations have been used to drive high-resolution convection-permitting (4-km) ensemble Weather Research and Forecasting (WRF) model simulations to explicitly resolve convection over the CONUS. Our hypothesis is that SCI can effectively offset the greenhouse gas effect by suppressing incoming solar radiation and the production of positive buoyancy associated with daytime heating, resulting in a decrease in the hazardous convective weather that would otherwise increase in a future climate. To address this hypothesis, we have evaluated the thermodynamic and dynamic environments that favor severe convective storms, examined the characteristics of populations of convective storms, and assessed their changes in future climate with and without SCI.

Exploring the effects of deployment targets on extreme precipitation and temperature

Mari Tye, Kwesi A. Quagraine

NSF National Center for Atmospheric Research, Boulder, CO, USA

Humans experience the impacts of Earth system changes primarily through extreme events and their immediate environmental consequences. To broaden public discourse around solar radiation management (SRM), it is essential that research is contextualized within lived experiences such as the devastating megafloods and droughts of recent years. In this study, we leverage a counterfactual analysis to explore the probability of widespread regional hydrometeorological extremes in the recent past and under different scenarios of stratospheric aerosol injection. Specifically, we utilize the Assessing Responses and Impacts of Solar Climate Intervention of the Earth System-SAI (ARISE-SAI) simulations with 1.0 ℃, 1.5 ℃ and 1.5 ℃ with a 10 year delay (respectively SAI-1.0, SAI-1.5, SAI-Delay) as well as Shared Socio-economic Pathways 2.45 (SSP2-4.5) to compare the likely changes in the distribution of extreme precipitation metrics such as the longest number of Consecutive Dry Days (CDD) or Consecutive Wet Days (CWD), annual maximum 5-day rainfall (Rx5Day), or annual maximum daily maximum and minimum temperatures (TXx, TNx). Applying extreme value theory, we examine whether the statistical distributions of these extreme events differ significantly across scenarios, and whether robust differences emerge due to perturbations in the global water cycle.

Distinguishing between the Short-Term Climate Responses to Unilateral Stratospheric Aerosol Injection Latitudes with Artificial Intelligence

Cameron Dong (1), Elizabeth Barnes (1,2), Charlotte Connolly (1)

1. *Colorado State University, USA*
2. *Boston University, USA*

Stratospheric aerosol injection (SAI), whereby reflective particles are released into the stratosphere to induce cooling, is one possible tool to counteract global warming and its associated risks. While most previous research has focused on characterizing the long-term climate response to SAI, we instead analyze the short-term response to unilateral injections, within two years of deployment, using an explainable artificial intelligence (XAI) framework. Specifically, we train neural networks to predict the latitude of injection in climate simulations with continuous 2-year cycles of unilateral SAI, using seasonal or annual composites of global 2m-temperature or precipitation. The network is able to skillfully determine the latitude of SAI, indicating that there would be distinguishable differences in impacts depending on SAI injection latitude within 2 years of deployment. XAI methods indicate that while distinctive temperature impacts could be identified in both the tropics and midlatitudes, distinguishable precipitation impacts are largely restricted to the tropics.

Rethinking Alumina for Stratospheric Aerosol Injection: New Insights into Shortwave Absorption

Taveen Singh Kapoor, Prabhav Upadhyay, Jian Huang, Guodong Ren, John Cavin, Dhruv Mitroo, Joshin Kumar, Jordan A. Hachtel, Lu Xu, Rohan Mishra, Rajan K. Chakrabarty

Washington University in St Louis, USA

Alumina is proposed as a promising solid particle material for stratospheric aerosol injection (SAI). Model studies suggest it could be more effective than sulphate aerosols due to its strong shortwave scattering and negligible absorption properties, which would enhance tropospheric cooling while minimizing stratospheric heating. However, the presumed negligible shortwave absorption stems from the lack of reliable absorption data, which are weak and hence difficult to detect. In this presentation, we report new measurements of alumina absorption using sensitive, first-principles based techniques: photoacoustic spectroscopy and electron energy loss spectroscopy. From these, we derive the imaginary refractive index (k), the intrinsic property that governs absorption strength, and find values ranging from $1.4 \times 10^{-4} – 1.2 \times 10^{-3}$. The non-negligible absorption appears to originate from oxygen vacancy defects, which introduce mid-band-gap states into alumina's wide-bandgap crystal structure. Such defects are expected to be ubiquitous in Alumina nanoparticles from entropy considerations. Preliminary radiative transfer calculations indicate that the non-negligible absorption would reduce the radiative efficacy of alumina-based SAI by up to 10%. These findings call for revisiting SAI efficacy calculations with alumina and reassessing the optical properties reported for other candidate materials.

Global impacts of high-latitude low-altitude SAI in three earth system models

Alistair Duffey (1), Walker Lee (2), Lauren Wheeler (3), Benj Wagman (3), Matthew Henry (4), Daniele Visioni (5), Michel Tsamados (1), Peter Irvine (6), Doug MacMartin (5)

1. *University College London, UK*
2. *NSF National Center for Atmospheric Research, Boulder, CO, USA*
3. *Sandia National Laboratory*
4. *University of Exeter, UK*
5. *Department of Earth and Atmospheric Sciences, Cornell University, USA*
6. *University of Chicago, USA*

High-latitude low-altitude (HiLLA) SAI may face lower logistical barriers relative to conventional SAI, because it could use repurposed existing large aircraft for deployment. However, it is expected to have strongly reduced global cooling efficiency, and the more polar forcing profile it produces would result in many differences in the surface climate response relative to subtropical high-altitude SAI. Here, we present the first multi-model simulations of HiLLA-SAI. All three models show similar global cooling efficiency for seasonal injections at 60 °N/S and 13km (HiLLA-13), of around 0.6 °C global temperature change per 12 MtSO2 per year. Raising the injection height by 2 km to 15 km increases this cooling efficiency by around 50%. The impacts of HiLLA-SAI are polar focused, with only weak cooling in the tropics, particularly for the 13 km injection case.

Response of Asian summer monsoon rainfall to stratospheric aerosol injections

Chao He (1), Yifeng Peng (1), Pengfei Yu (2)

1. *Lanzhou University, China*
2. *Jinan University, China*

Stratospheric aerosol injection (SAI) has been proposed as a potential approach to limit global mean surface temperature (GMST) increases below critical thresholds, thereby providing additional time to reduce atmospheric greenhouse gas (GHG) concentrations. However, its effects on Asian summer monsoon (ASM) rainfall remain uncertain. Using idealized simulations from six climate models participating in the Geoengineering Model Intercomparison Project Phase 6 (GeoMIP6), we show that both GHG reduction and equatorial SAI lead to an overall decrease in ASM rainfall alongside GMST cooling, primarily due to thermodynamic effects associated with reduced atmospheric moisture content. For an equivalent GMST decrease, however, the amplitude of SAI-induced rainfall reduction does not exceed that under GHG reduction. Relative to a baseline with the same GMST, two of the six models simulate a substantial SAI-induced increase in ASM rainfall beyond internal variability, while the remaining four models show responses within internal variability. The inter-model spread is closely connected to changes in the meridional gradient of net incoming shortwave radiation across the tropical Northern Hemisphere, which is shaped by the spatial distribution of aerosols. A lighter (heavier) aerosol load over the ASM region relative to the equatorial region favors increased (decreased) ASM rainfall, and this relationship is corroborated by single-model experiments with aerosol injections at multiple latitudes. These results highlight the importance of baseline selection and suggest that carefully tailored SAI deployment strategies could reduce the risk of monsoon failure.

Evaluating Polar Climate Risks of Stratospheric Aerosol Injection

Shrabani S. Tripathy and Rajan K. Chakrabarty

Department of Energy, Environmental & Chemical Engineering, Washington University in St. Louis, Missouri, USA

Stratospheric Aerosol Injection (SAI) is proposed as a solar radiation modification (SRM) strategy to counteract global warming. The approach involves injecting reflective aerosol into the lower stratosphere to reduce incoming solar radiation from reaching the lower atmosphere, thereby cooling the surface. While theoretically SAI has the potential to limit earth's rising temperature, it also raises serious concerns about unforeseen regional effects, particularly in polar regions, where climate model projections remain highly uncertain. This is concerning given the critical role of polar ice in regulating Earth's climate and the relative lack of understanding of polar climate systems.

This study employs a risk analysis framework to assess the potential climatological impacts of SAI deployment on Earth's polar ice melts. The framework enables direct comparison of both the likelihood and magnitude of negative impacts reported under SAI and non-SAI scenarios, allowing for more informed evaluation of trade-offs. Additionally, this allows us to compare different SAI strategies as a function of particle type, latitude and altitude of injection, ramp-up rates, and delivery mechanisms. A key area of concern in the polar region is the interaction between SAI and the stratospheric polar vortex. As atmospheric models results show, the heating of the tropical stratosphere from aerosol absorption can increase the pole-to-equator temperature gradient for SO_2 but may not be true for AL_2O_3. This change in the polar vortex can alter tropospheric circulation patterns, potentially influencing the Northern Annular Mode and Southern Annular Mode. The interaction also includes uncertainties regarding residual Arctic warming, insufficient cooling in ice shelf regions, warm-water upwelling, and suppression of the global hydrological cycle, potentially reducing snowfall and ice accumulation. By systematically cataloguing the potential benefits and harms of various SAI strategies, this presentation summarises scenario-based risk profiles to support a more robust and nuanced understanding of SAI's implications.

Stratospheric circulation response to stratospheric aerosol injections remains highly uncertain.

Mohamadou A. Diallo (1), Mr Nils Dunker (2), Dr Roland Eichinger (3), Dr Felix Ploeger (1), Hella Garny (3), Dr Manfred Ern (1), Dr William Ball (4), Dr Andrea Stenke (5), Dr Laura Revell (6), Dr Valentina Aquila (7), Dr Simone Tilmes (8), Dr Douglas Kinnison (8), Professor Theodore Shepherd (9), Professor Michaela Hegglin (1)

1. *Forschungszentrum Jülich GmbH, Institute of Climate and Energy Systems (ICE-4) – Stratosphere, Jülich, Germany*
2. *University of Duisburg, Germany*
3. *Deutsches Zentrum für Luft- und Raumfahrt, Inst. für Physik der Atmosphäre, Oberpfaffenhofen, Germany*
4. *TU Delft, Netherlands*
5. *ETH Zürich, Switzerland*
6. *University of Canterbury*
7. *American University*
8. *NSF National Center for Atmospheric Research, Boulder, CO, USA*
9. *University of Reading, UK*

Mitigating global warming through stratospheric aerosol injection (SAI), which aims to reproduce the cooling effects of tropical volcanoes on surface climate, is emerging as a potential strategy for limiting near-surface global warming to around 1.5 – 2 °C above pre-industrial levels. However, knowledge of how the stratospheric circulation will respond to SAI, and the resulting feedback on surface climate and weather, remain highly uncertain. Here, we quantify the stratospheric circulation response to the 1991 Mount Pinatubo eruption and compare its response to a future global warming scenario with and without tropical SAI. We show that the shallow branch of the stratospheric circulation slows down in climate models and observations following tropical aerosol perturbations due to reduced lower stratospheric planetary and gravity wave breaking. However, the depth and strength of the deep branch response is highly uncertain. Climate models show a strengthening of the deep branch due to enhanced middle/upper stratospheric planetary and gravity wave breaking, contrasting with the observed weakening of the deep branch induced by reduced planetary and gravity wave forcing. As interest in SAI continues to grow, our results demonstrate the urgent need to study the gravity/planetary uncertainty in the circulation response to SAI, which impacts ozone recovery, tropospheric circulation, and surface climate and weather through two-way stratosphere-troposphere coupling.

Increased stratospheric water vapour after volcanic aerosol injection

Xin Zhou, Graham Mann, Martyn Chipperfield

University of Leeds, UK

Volcanic eruptions inject vast amounts of aerosols into the stratosphere, driving well-known cooling effects by scattering solar radiation. However, their role in modulating stratospheric water vapor—a potent greenhouse gas—has been largely overlooked. In this talk, I present results from simulations of a Pinatubo-like explosive tropical eruption, revealing that aerosol heating significantly enhances the entry of water vapor into the stratosphere. This moistening effect is further amplified one year after the eruption due to aerosol-radiation-dynamical feedbacks, a process that has likely been underestimated in previous assessments.

These findings have critical implications for our understanding of volcanic climate forcing and stratospheric aerosol injection (SAI) geoengineering. The same aerosol-radiation-dynamical feedbacks that amplify volcanic moistening are expected to operate under SAI, where sustained aerosol enhancements could similarly increase stratospheric water vapour (e.g., Krishnamohan et al., 2019; Visioni et al., 2021; Bednarz et al., 2023). Such moistening may partially offset the intended cooling effect of SAI and introduce complex feedbacks that must be accounted for in climate models.

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Comparing the hydrological response to stratospheric aerosol injection using solid particles instead of sulfur

Manouk Geurts (1), Timofei Sukhodolov (2), Jan Sedlacek (2), Sandro Vattioni (3), Gabriel Chiodo (4), Ayantika Dey Choudhury (5)

1. *Wageningen University Metereology and Air Quality, Netherlands*
2. *PMOD/WRC, Switzerland*
3. *ETH Zürich, Switzerland*
4. *CSIC, Sapin*
5. *Indian Institute of Tropical Meteorology, Pune, India*

Stratospheric aerosol injection (SAI) has been proposed as a temporary measure to limit global warming. Sulfur-based SAI can effectively cool surface climate by scattering solar radiation. However, it absorbs terrestrial longwave (LW) radiation, causing stratospheric heating that has been linked to reductions in global mean precipitation and circulation changes. Using alternative materials may reduce these undesirable side-effects of SAI.

Impact on Ozone from Interactions between Sulfate SAI and Potential Future Halogen Sources

Etienne Gilgien (1), Timofei Sukhodolov (2), Gabriel Chiodo (3), Jan Sedlacek (2), Sandro Vattioni (1), Andrin Jörimann (1,2), Laura Revell (4)

1. *ETH Zurich, Switzerland*
2. *PMOD, Davos, Switzerland*
3. *CSIC-UCM Madrid, Spain*
4. *University of Canterbury, Whitechurch*

As the climate is warming, sulfate SAI has been proposed as a way of cooling down the planet's surface. One of the drawbacks of this method is the ozone destruction that it causes. At the same time, an increase in rocket launches is leading to higher halogen concentrations in the atmosphere, which is also known to destroy the ozone layer. In this study, we research the interactions of sulfate SAI with future potential halogen sources, specifically rocket emissions and volcanic eruptions. SAI and reference scenarios were simulated in a 30-year time-slice experiment and the resulting ozone destruction compared. We demonstrate that sulfate SAI will strengthen the ozone-destroying properties of halogens, leading to an even worse ozone balance especially in the southern hemisphere. In the case of volcanic eruptions, the slightly positive effect in the northern hemisphere even gets fully negated by the presence of sulfate SAI in the atmosphere.

Better constraining kinetic parameters of HNO_3 and HCl uptake to calcite particles by lab experiments

Sandro Vattioni (1,2,3), Pantanassa Telliou (1), Oliver Klaus (1), Christof Vockenhuber (4), Max Däbeli (4), Luca Longetti (2), Luca Artiglia (2), Thorsten Bartels-Rausch (2), Huanyu Yang (2), Yanisha Manoharan (2), Jérôme Philippe Gabathuler (2), Arnold Müller (2), Célia Paolucci (2), Beiping Luo (1), Ulrich K. Krieger (1), Timofei Sukhodolov (3), Frank N. Keutsch (5,6,7), Markus Ammann (2), Gabriel Chiodo (1,8), and Thomas Peter (1)

1. *Institute for Atmospheric and Climate Science, ETH Zurich, Switzerland*
2. *PSI Center for Energy and Environmental Sciences, Paul Scherrer Institute, Villigen PSI, Switzerland*
3. *Physical Meteorological Observatory Davos/World Radiation Center, Davos, Switzerland*
4. *Laboratory of Ion Beam Physics, ETH Zurich, Switzerland*
5. *John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, USA*
6. *Dept. of Chemistry and Chemical Biology, Harvard University, Cambridge, MA, USA*
7. *Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA*
8. *Instituto de Geociencias (IGEO), CSIC-UCM, Madrid, Spain*

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Air quality impacts of stratospheric aerosol injections are small and mainly driven by changes in climate, not deposition

Cindy Wang (1), Daniele Visioni (1), Glen Chua (2), Ewa M. Bednarz (3,4)

1. *Department of Earth and Atmospheric Sciences, Cornell University, USA*
2. *NASA Goddard Institute for Space Sciences, USA*
3. *NOAA Chemical Sciences Laboratory, Boulder, USA*
4. *Cooperative Institute for Research in Environmental Sciences (CIRES), Univ. of Colorado, Boulder, USA*

Stratospheric aerosol injection (SAI) is a proposed climate intervention that could potentially reduce future global warming, but its broader environmental and public health implications are yet to be thoroughly explored. Here, we assess changes in mortality attributable to fine particulate matter (PM2.5) and ozone (O3) using three large ensembles of fully coupled CESM2-WACCM6 simulations from the ARISE-SAI-1.5, ARISE-SAI-1.0 and SSP2-4.5 scenarios. In the ARISE-SAI-1.5 scenario, the ensemble mean indicates that maintaining temperatures at 1.5 C above preindustrial levels through SAI would result in a 0.4% (ensemble range: -1.9% to +1.5%) reduction in pollution-related mortality during 2060 – 2069 relative to SSP2-4.5, driven by a 1.3% (-2.3% to -0.6%) decrease in ozone-related deaths and a 0.9% (-0.4% to +2.1%) increase in PM2.5-related deaths. The spread among ensemble members underscores the influence of internal variability and highlights the importance of ensemble-based analyses when assessing the potential health impacts of climate intervention strategies. PM2.5 mortality changes exhibit almost no sensitivity to injected sulfate amounts, with the most variability driven by precipitation-mediated changes in non-sulfate PM2.5 species (e.g., dust and secondary organic aerosols), whereas ozone-related mortality would be primarily driven by surface cooling and hemispheric asymmetries in stratospheric-tropospheric exchange and ozone transport. Overall, SAI impacts on pollution-related mortality are modest, regionally heterogeneous, and much smaller in magnitude compared to improvements expected from air quality policies planned or implemented within the same time frame. Our finding that air quality mortality impacts do not directly scale with SO2 injection rates underscores the nonlinear and complex nature of atmospheric responses to SAI.

An Open-Access Workflow to Assess the Health Impacts of Air Quality under Climate Intervention

Alice Wells, Jim Hurrell and Brooke Anderson

Colorado State University, USA

Stratospheric aerosol injection (SAI) has been proposed as a potential method to reduce global warming, however its implications for human health remain poorly understood. Surface-level air pollutants, including ozone and particulate matter, are strongly linked to increased mortality. Understanding how different SAI strategies - such as variations in injection altitude or latitude - might influence air pollution and related mortality outcomes is important to assess the overall benefits and risks of an intervention relative to climate change itself.

SAI Governance Retrospect and Prospect

James Fleming

Colby College, USA

A review of legal precedents, current challenges, and pressing needs involving the governance, testing, and potential implementation of climate engineering.

The Dangers and Injustices of stratospheric aerosol injection

Jennie Stephens

National University of Ireland Maynooth, Ireland

The societal dangers of advancing stratospheric aerosol injection (SAI) are disregarded by many SAI researchers and SAI advocates. Feminist decolonial and indigenous perspectives are ignored and dismissed. This contribution argues that the financial backing of SAI by tech billionaires and the multiple efforts by entrepreneurs to profit from SAI reflects the inherent injustices of SAI technology, i.e the power dynamics of developing SAI are inherently patriarchal, racist and colonial. The presentation calls for a transformation away from the current approach.

SAI Deployment and Human Civilization: The Question is No Longer If, but How, When, Where, and by Whom?

Ron Baiman (1), Michael MacCracken (1,2) and Gregory Slater (1)

1. *Healthy Planet Action Coalition, Benedictine University, USA*
2. *The Climate Institute, USA*

Recent data suggests that excluding exogenous factors, the per decade rate of increase annual surface average temperature (GSAT) has approximately doubled in 2015-2024 relative to the decades of 1980-2000. This suggests that without climate intervention, on the current pathway, even with realistic acceleration of global GHG emissions reduction and removal, annual warming of 2.0 C is likely to be crossed in the 2035 - 2044 decade or earlier.

A number of Solar Radiation Modification (SRM) methods described in the peer-reviewed literature are capable of exerting a significant cooling influence before 2050. Method comparison matrices offer a means for comparing potential approaches capable of exerting significant climate cooling influences within the next two decades. A step-wise ordering prioritization methodology identifies SAI as the most likely to be successful to: 1) reduce the near-term risk of crossing climate-tipping point(s), 2) provide substantial global-scale cooling with at-scale deployment over the next 20 years, and 3) ensure low likelihood of triggering adverse impacts. While sharp reductions in emissions of short-lived GHGs like methane are essential to slow the pace of global warming, only SAI offers the realistic near-term potential for reducing GSAT increase above pre-industrial to < 1 °C.

At least three differently motivated near-term deployment governance scenarios seem plausible:

1) An effort organized by a coalition of willing mid- and high-latitude nations, perhaps through the Arctic Council, motivated by desires to restore the low temperatures of the polar regions and thereby reduce the likelihood of extreme weather in mid-latitudes; 2) A collaborative international effort under the auspices of the relevant UN bodies to ensure that climatic conditions remain suitable for the fulfillment of the Sustainable Development Goals; or 3) A self- interested action by a “geopolitical power” such as the US, China or a consortium of nations, motivated by the goal of reducing near-term national security risks stemming from the failure of climate change policies that do not include intervention. All three scenarios would likely start modestly and be increased over time as confidence is gained that global-scale SAI deployment would be both largely beneficial and essential to return GSAT to < 1 °C by 2050.

When Are Small-Scale Field Experiments in Solar Geoengineering Worth Pursuing?

Ryan O'Loughlin (1), Daniele Visioni (2)

1. *Queens College City University of New York, USA*
2. *Department of Earth and Atmospheric Sciences, Cornell University, USA*

We propose a set of heuristic ”scientific rigor, safety, usefulness, and transparency” for assessing the pursuitworthiness of small-scale field experiments in solar geoengineering research. Rather than offering a fixed logic of pursuit, we emphasize that these heuristics should operate as part of a dynamic and iterative evaluative process within the solar geoengineering research community, responsive to changing modeling priorities, new data, and shifting ethical and political landscapes. We argue that such experiments must be understood within the broader context of climate modeling research, where their primary role is to improve model components and identify further uncertainties. As debates about “moonshot” research and urgent science continue to evolve, our heuristics offer a way for the community, and for potential funders, to evaluate field experiments without abandoning the standards that guide responsible inquiry. Although our heuristics presuppose the pursuitworthiness of solar geoengineering research as a whole, they provide a structured framework for evaluating which field experiments are worth undertaking and why.

An Ethics for SAI Mission-Driven Research?

Xavier Landes

Stockholm School of Economics in Riga, Latvia

The presentation will be exploratory. The idea is to collect thoughts from the SAI research community.

A simple question will be introduced: is mission-driven SAI research subject to specific ethical norms and practices in comparison to traditional curiosity-driven approaches? Or should it be subject to specific norms?

Existing guidelines (Oxford, Tollgate, American Geophysical Union) do not explicitly discriminate between project types. But differences are significant. At their core, mission-driven projects seem to directly challenge scientific independence. The mounting pressure from runaway climate change and political authorities may further weaken academic practices.

The presentation will not provide a full-fledged analysis of the ethics for mission-driven SAI research. Instead, it will highlight key points that could serve as a basis for a more ambitious collaborative project and collect insights from the SAI community.

From Confusion to Confucius: Why clarifying language is a priority for ethics of SRM research

Timothy Daly, Ignacio Mastroleo

Bioethics Program, FLACSO Argentina, Argentina

When ancient philosopher Confucius was asked the first thing he would do if he were to govern, he said he would "rectify names" to make words correspond to reality, because failure to call things by their proper names sows confusion and impedes effective action, which ultimately leads to harm and injustice. First, we argue that ethics and governance of Solar Radiation Modification (SRM) research currently suffer from unrectified names—a technology or intervention, if defined as a thing and not as a use, has no ethics and cannot be governed. Only human actions with aims can, so we favor use-based definitions of SRM technology and interventions. Second, we draw on the history of research ethics with human participants to show that the distinction between "research", "validated practice" and "non-validated practice" in the Belmont Report can provide a conceptual foundation for ethics and governance of SRM research and non-research experimentation based on their distinct primary aims and contributions to an ultimate goal or purpose. We thus present SCoPEx and Make Sunsets as exemplary cases of an SRM research experiment and non-research experiment respectively, and propose a novel definition of an SRM experiment to reduce confusion in the ethics and governance of SRM research.

Governing Solar Radiation Management (SRM): Climate predictability, uncertainties and Policy and governance integration

Yvette Ramos

University of Lisbon, Portugal

Solar Radiation Management (SRM) refers to a class of climate intervention techniques aimed at reflecting a portion of incoming solar radiation to temporarily reduce global temperatures. While SRM may offer a potential mechanism to moderate near-term climate risks, it also presents significant challenges regarding its impacts on climate variability and predictability, particularly in relation to ocean-atmosphere dynamics. As such, SRM governance is not only a political and ethical challenge but a pressing scientific one – requiring a deeper understanding of how SRM might affect the energy and carbon cycles central to climate system behavior.

Recent modeling and scenario-based studies (e.g., IPCC, 2023; WCRP, 2021) have indicated SRM's potential to alter global hydrological cycles, monsoon systems, ocean heat transport, and regional climates – particularly in the tropics and polar regions. Uncertainties remain concerning its feedback loops, temporal persistence, and unintended consequences on ecosystems, particularly marine systems. Moreover, SRM scenarios – when integrated into global climate models – pose new challenges for decadal and multidecadal climate predictability and risk assessments.

Despite growing scientific interest, SRM the topic remains marginal in formal UNFCCC negotiations, including the Conference of the Parties (COPs). The lack of consensus and the political sensitivity surrounding geoengineering require a robust, evidence-based approach that can inform future multilateral deliberations. This Research Focus aims to contribute to these processes by generating policy-relevant knowledge capable of supporting informed dialogue under the UNFCCC, proposing mechanisms to guide its research, potential deployment, or monitoring. This governance vacuum is particularly concerning for vulnerable regions, including Least Developed Countries (LDCs) and Small Island Developing States (SIDS), which may be disproportionately affected by SRM-related climate shifts.

Environmental impacts of Stratospheric Aerosol Injections: insights from the upcoming quadrennial report by the Environmental Effects Assessment Panel (EEAP)

Gabriel Chiodo (1), Laura Revell (2), Anna Harper (3), Sasha Madronich (4), Kelsey Roberts (5), Sharon Robinson (6), Simone Tilmes (4)

1. *CSIC-UCM, Madrid, Spain*
2. *University of Canterbury*
3. *University of Georgia, USA*
4. *NSF National Center for Atmospheric Research, Boulder, CO, USA*
5. *Louisiana State University*
6. *University of Wollongong, Wollongong, Australia*

Various solar radiation modification (SRM) schemes have been proposed to counteract the warming effects of greenhouse gases. One of the most-studied approaches is stratospheric aerosol injection (SAI). SAI involves continuously injecting reflective particles or their precursors into the lower stratosphere to form an aerosol layer; this in turn increases the Earth's albedo. This idea is inspired by large volcanic eruptions which can inject sulfate aerosols into the stratosphere and cause temporary global cooling (Crutzen, 2006). While SAI could offset some warming from greenhouse gases, environmental side effects could occur depending on implementation details. In this presentation, we will provide an overview of the work being done in the Environmental Effects Assessment Panel (EEAP) report concerning the assessment of environmental effects of SAI.

We will review ozone changes and in particular, the expected changes in UV-B radiation at the surface as a result of these ozone changes, and scattering. Potential changes of stratospheric temperature and dynamics could lead to unintended changes in surface climate. Finally, changes in the ratio of direct to diffuse radiation could impact plant growth and may also have environmental impacts. We will assess these aspects as well as other broader potential environmental consequences on terrestrial and marine ecosystems, as well as air quality.

An Uncertainty Database for Stratospheric Aerosol Injection

Alistair Duffey (1,2), Douglas MacMartin (3), Daniele Visioni (3) and Kion Yaghoobzadeh (2)

1. *Univeristy College London, United Kingdom*
2. *Reflective*
3. *Department of Earth and Atmospheric Sciences, Cornell University, USA*

Stratospheric aerosol injection (SAI) has been the subject of much study, but a comprehensive assessment of uncertainties related to its implementation and impacts is lacking. This assessment is necessary in order to prioritize the research efforts needed to inform a future decision on deployment. Here we present a framework and methodology for producing this assessment as a living database with community input. We describe an initial list of the uncertainties across four categories (engineering, aerosol evolution, climate response, earth system response), prioritized according to the consequence level and the degree of uncertainty. These uncertainties are then mapped onto relevant impacts, and we then suggest which research activities would be required to resolve or reduce them. We specifically focus on near-term deployment, which we define as cooling of 0.5 °C at least within a decade from the start of the large-scale deployment. The database is intended to be used by a diverse set of users, including both researchers and decision-makers. Populating the database has primarily relied on literature review and feedback from an initial set of experts. We are actively seeking input from experts across the physical sciences and engineering disciplines relevant to the study of SAI, to refine this list and our assessed prioritization of uncertainties.