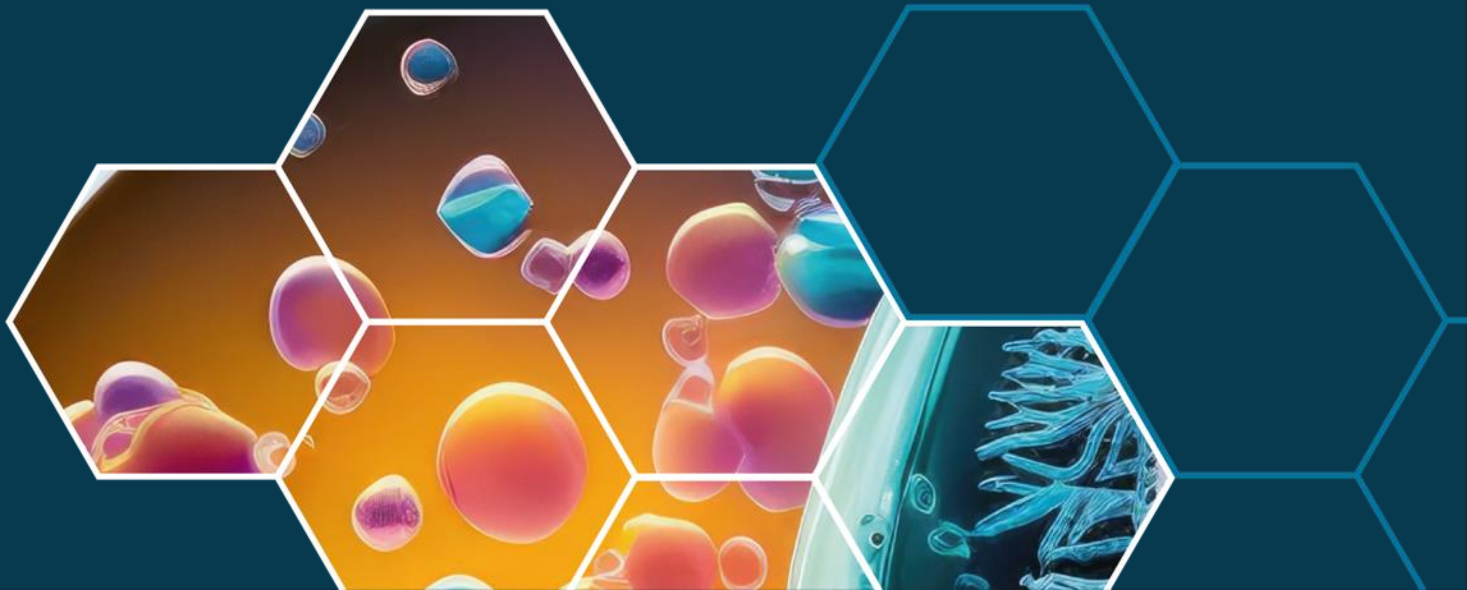
Scientific Advice Mechanism
to the European Commission

Solar radiation modification: What are the technologies, and what are the risks?

11th March 2025



ACADEMIA EUROPAEA

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CARDIFF

***Director*: Ole Petersen CBE FRS ML MAE; *Hub Manager*: Louise Edwards**

SAPEA:

Science **A**dvice for **P**olicy by **E**uropean **A**cademies

provides scientific evidence for

SAM: The European Commission's

Scientific **A**dvice **M**echanism

Academia Europaea (AE)

- **Founded in 1988**
- **Now has more than 5000 members, including more than 80 Nobel laureates**
- **Members are leading scientists and scholars, elected by their peers**
- **Operates through a network of hubs across Europe, including Cardiff**
- **Is a partner in SAPEA together with several other European academic networks**
- **The AE Hub in Cardiff co-ordinates AE's work for SAPEA**

SRM webinar series

- Solar radiation modification: What are the technologies, and what are the risks?
  - 11th March, 14:00 hours CET
- Solar radiation modification: What's at stake for society?
  - 3rd February, recording and slides
- Solar radiation modification: What should Europe's strategy be?
  - 23rd January, recording and slides

Our speakers

- Simone Tilmes, Member of the SAPEA Working Group on SRM
- Gabriel Chiodo, Member of the SAPEA Working Group on SRM
- Johannes Quaas, Co-Chair of SAPEA Working Group on SRM
- Nebojsa Nakicenovic , Deputy Chair, Group of Chief Scientific Advisors
- Dušan Chrenek, Principal Adviser, Directorate-General for Climate Action, European Commission





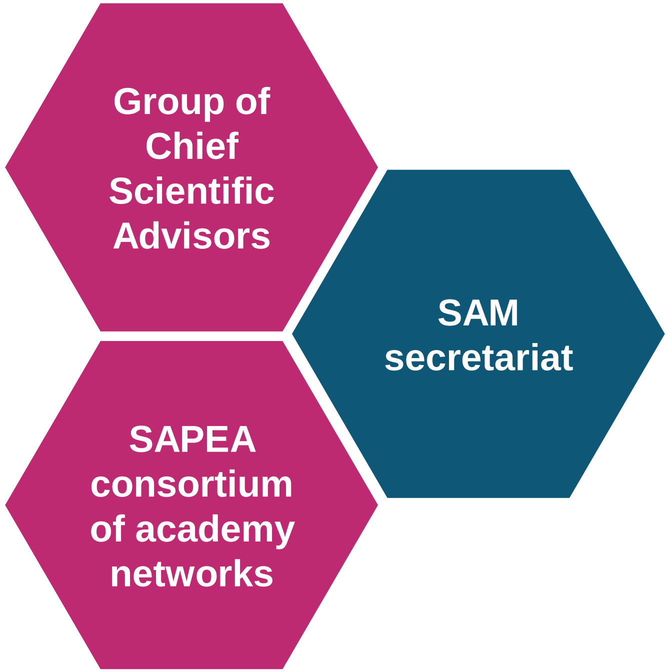
Format of webinar

- Background
- Opening 8-minute presentations from 4 speakers
- Brief comments from Dušan Chrenek (DG CLIMA, European Commission)
- Audience interaction – please use Q&A box to ask questions to the panel

Who we are

The SAM provides **independent scientific evidence and policy recommendations** to the College of European Commissioners on any subject, including on issues that the European Parliament and the Council consider to be of major importance.

The three parts of the SAM



About the Advisors

- **Seven highly qualified experts**
  Backgrounds in various disciplines, both social and natural sciences

- **Make policy recommendations**
  in response to requests for advice

About SAPEA (Science Advice by European Academies)

- Brings together some 120 academies from 40 countries across Europe
- Provides independent evidence reviews on request
- Informs the Advisors' policy recommendations

How we work

We receive a request

European Commissioners can ask us for advice on any topic

We review the evidence

A SAPEA working group writes an evidence review report

We make recommendations

The Advisors write a Scientific Opinion based on the evidence

We deliver our advice

Our evidence and recommendations are both handed to the Commission

Request for scientifc advice

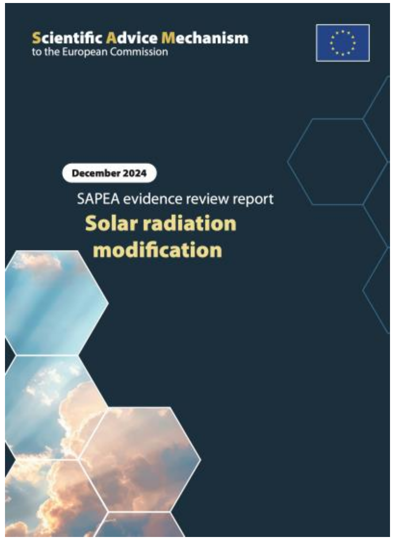
- In 2023, **former EVP Timmermans** asked the European Group of Chief Scientific Advisors (GCSA) to assess the **risks and opportunities associated with research on SRM** and its potential deployment

1. *How can we address the risks and opportunities associated with research on solar radiation modification and with its potential deployment?*

2. *What are the options for a governance system for research and potential deployment considering different solar radiation modification technologies and their scale?*

SAPEA Evidence Review Report

- Working group
  - 20 experts from different disciplines, countries, career stage, stance on SRM etc
- Structure of report
  - Introduction
  - 3 chapters on science and technology background and issues
  - 3 chapters on social science-related background and issues
  - Policy options



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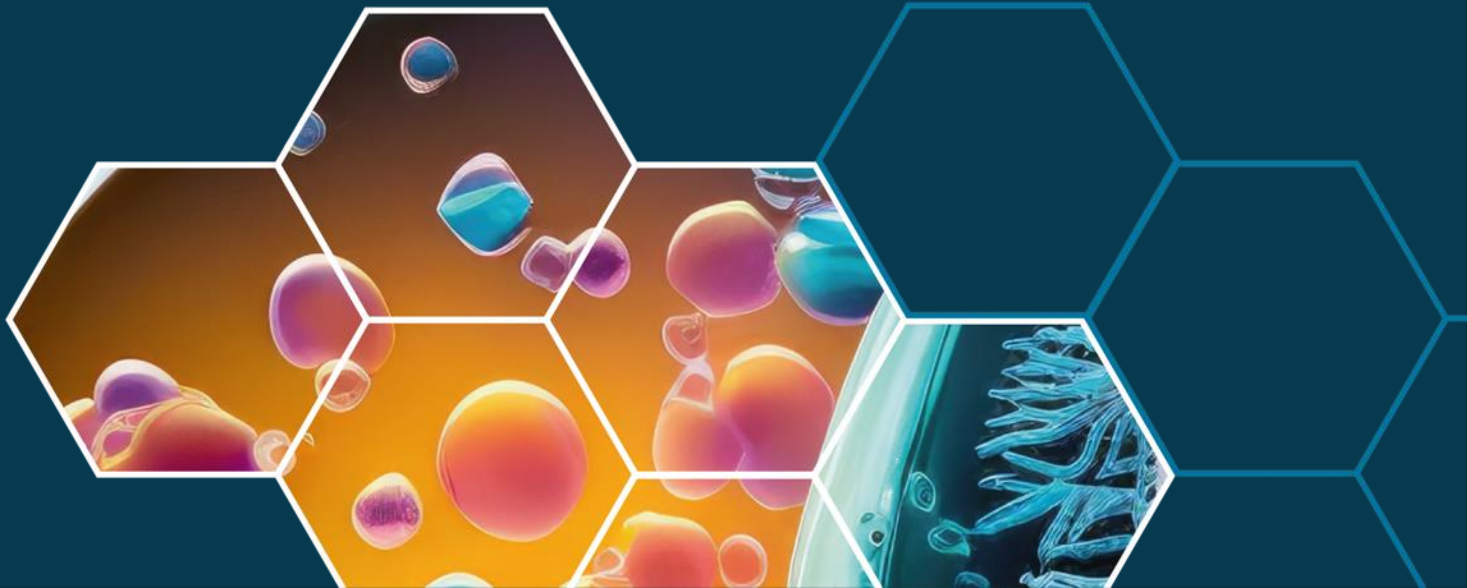
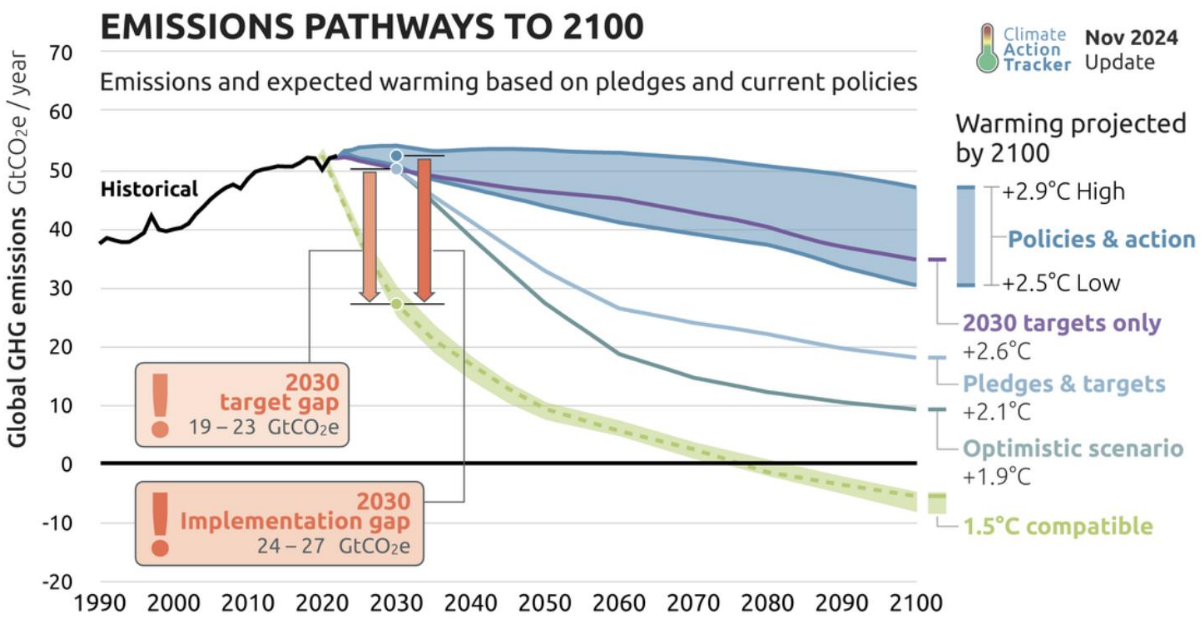
Solar radiation modification – background and technology options

Simone Tilmes



Solar Radiation Modification: Motivation for Research

Lack of ambition to meet required emission targets



- Continued warming with growing impacts on vulnerable societies and ecosystems until net-zero is reached
- Increasing risks of reaching climatic tipping points

Should we consider Solar Radiation Modification as one of the Climate Responses to help reduce some of the projected future climate impacts?

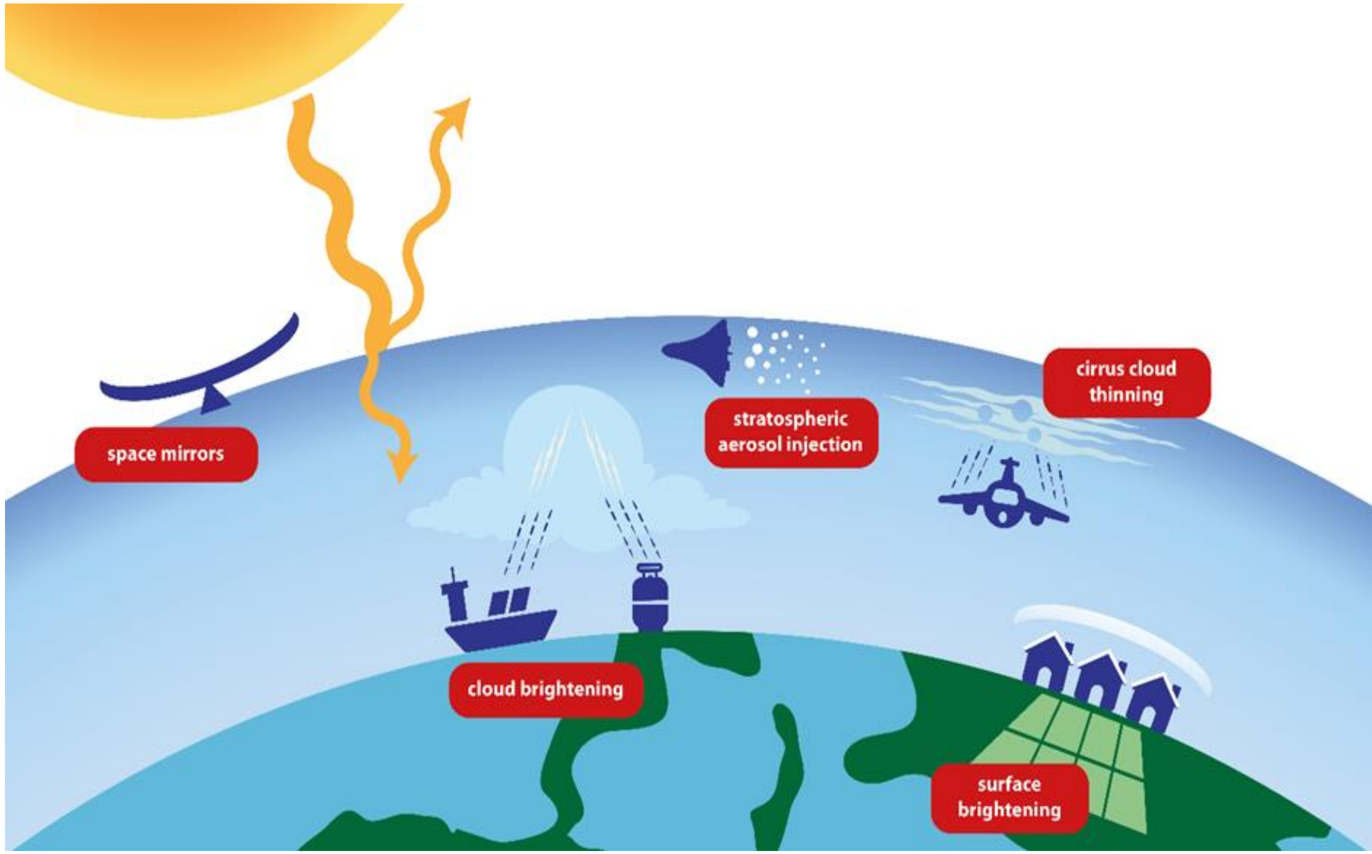
What are the benefits, side effects and risks?

Solar Radiation Modification – Proposed Technologies

Definition: SRM is the deliberate intervention into the Climate System through modifications to the Earth Radiation Budget in order to reduce some of impacts of global warming.

- Stratospheric aerosol injection (SAI)
- Marine Cloud Brightening (MBC)
- Cirrus (mixed-phase) cloud thinning
- Surface brightening
- Space mirrors

Non of these technologies can perfectly counter the effects of increases GHG concentrations in the atmosphere



Solar Radiation Modification – Why consider it?

- *Global SRM could reduce global mean surface temperatures, slow the rate of warming, or maintain global mean temperatures*
  -> Potentially reduces increasing risks of global warming

- *Temporarily confined deployment could help keep surface temperatures to specific levels while GHG emissions are phased out*
  -> May allows more time to move quickly to net-zero

- *Regional applications may target high latitudes (Arctic and Antarctic) to reduce accelerated warming, for example over the Great Barrier Reef to protect ecosystems*
  -> May protect societies and ecosystems that already are most impacted

Current research is based on 'Indoor Research': modeling, and lab studies
Outdoor experiments have not been performed in any relevant scale

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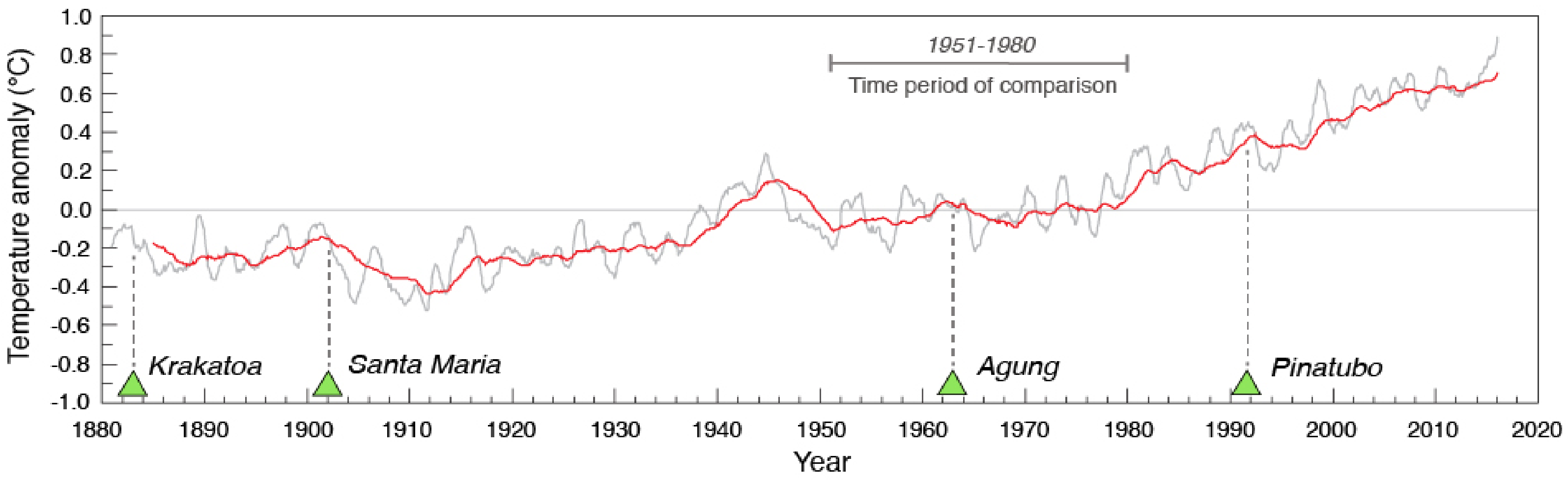
Observational Evidence: Large volcanic eruptions

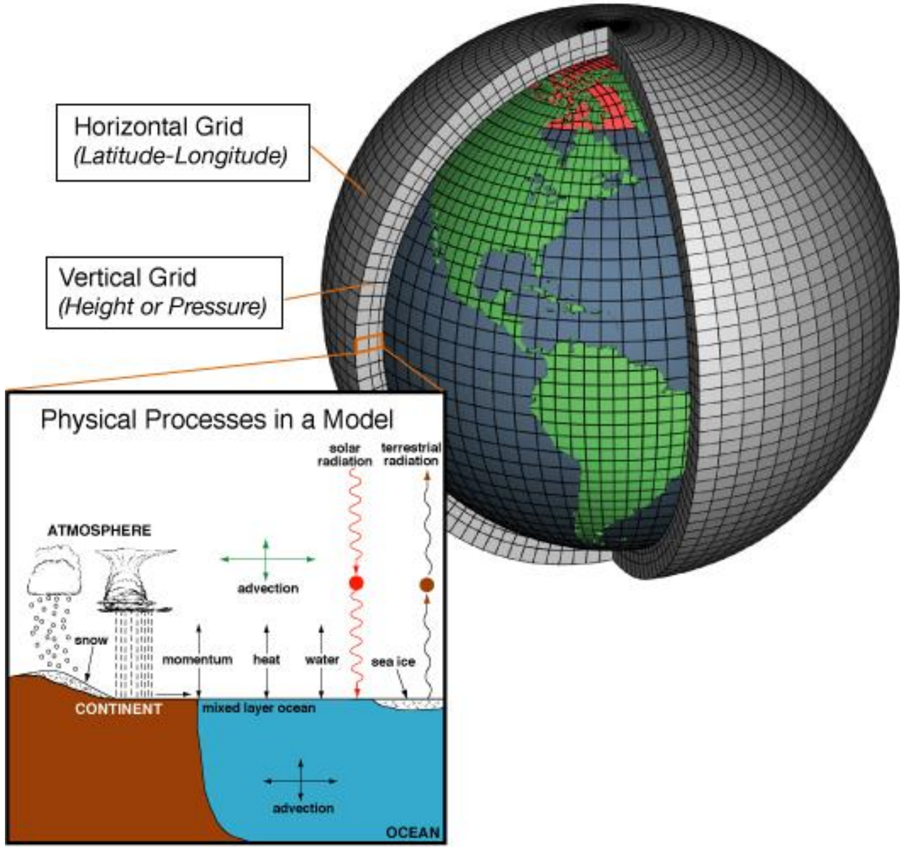


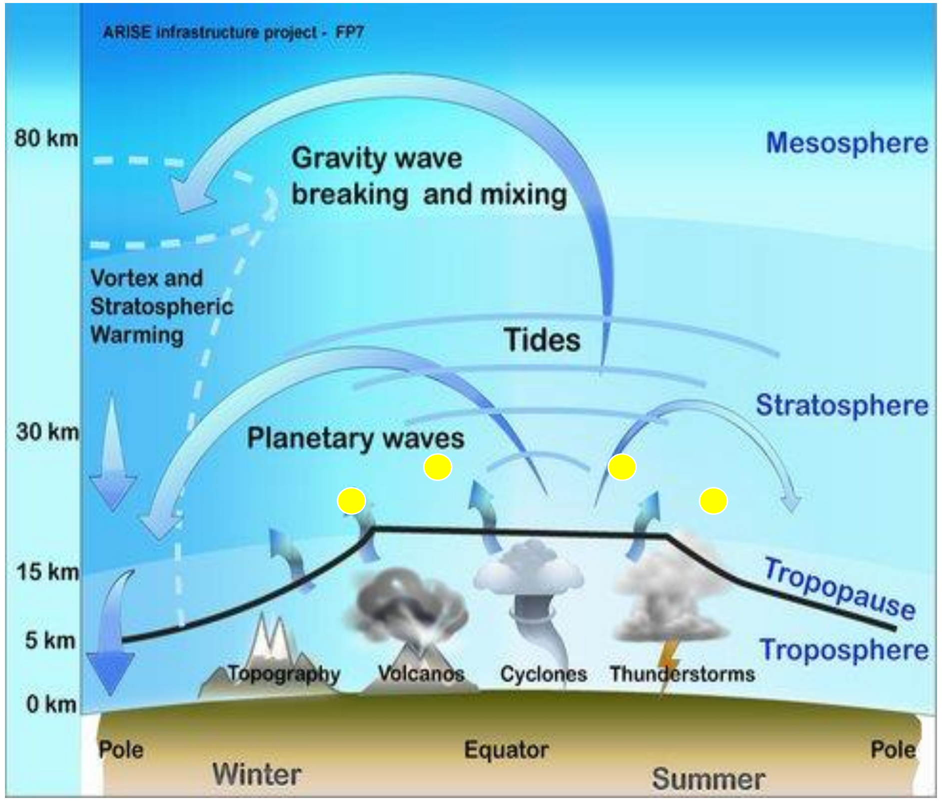
Observable reduction in surface temperature after large volcanic eruptions

Mt Pinatubo injected 10-18 $TgSO_2$ once:
~ 0.3 degree of cooling

-> Analogue for Stratospheric Aerosol Injection

SRM Research: Using Earth System Models





Continuous injections using SAI of *8-16 $TgSO_2$* for several years from using Earth System Models

~1 degree of cooling

All models agree that SAI can cool the planet, uncertainties exist in the magnitude of cooling and regional climate impacts.

Earth System Models use physical processes and equations to describe the atmosphere, land, oceans, cryosphere. These very sophisticated models are used for climate research and SRM.

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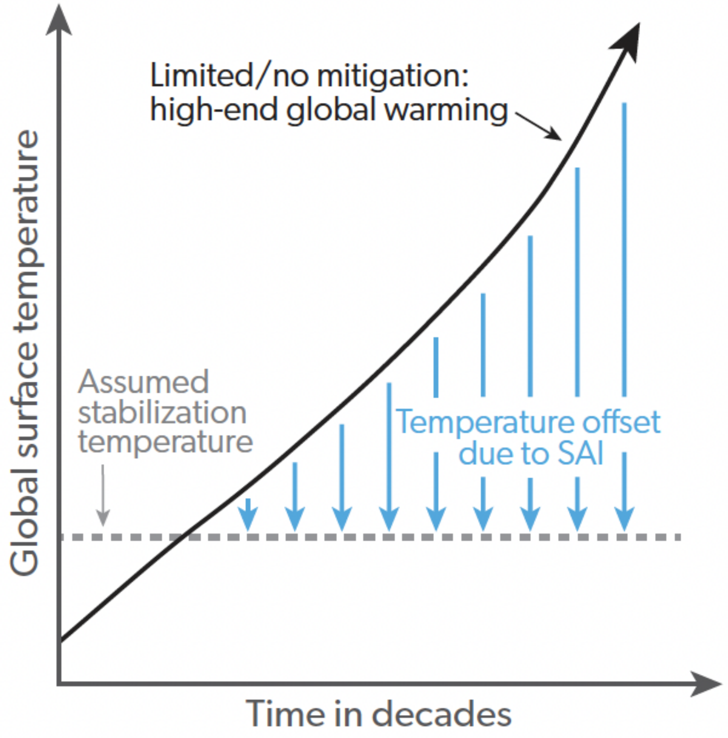
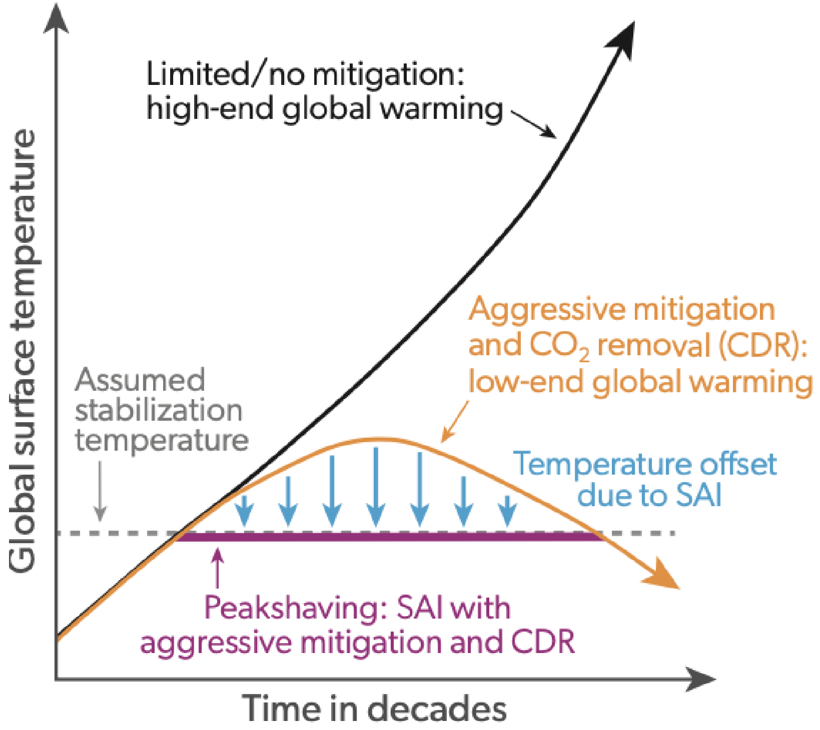
Solar Radiation Modification – Potential Scenarios

Strong SAI Scenario:
Used as a substitute to mitigation to prevent impacts of global warming.
-> Increasing side effects and risks

Peakshaving Scenario:
Used as stop-gap measure in addition to mitigation and CO_2 removal methods to sustain temperatures
-> Fewer side effects and risks



WMO 2022



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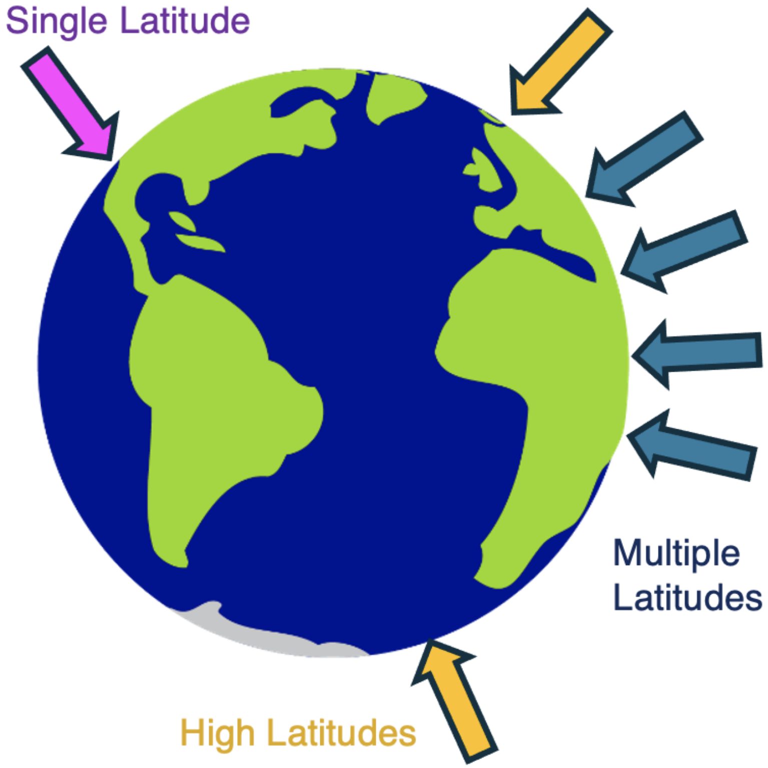
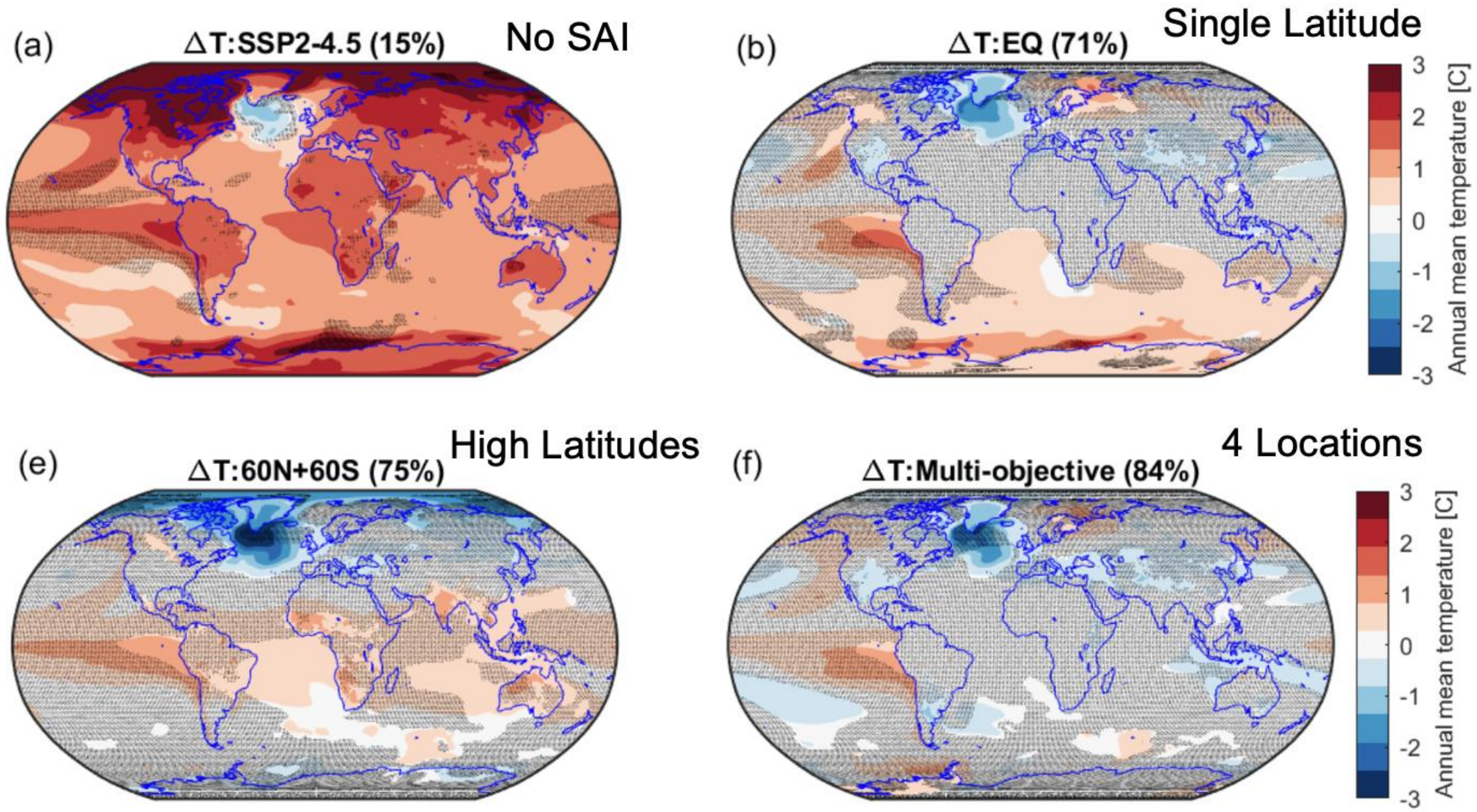
Solar Radiation Modification – Potential Strategies

Strategies Matter for Impacts: Location, Materials, Timing

Potential Injection Locations



Surface Temperature change compared to present-day

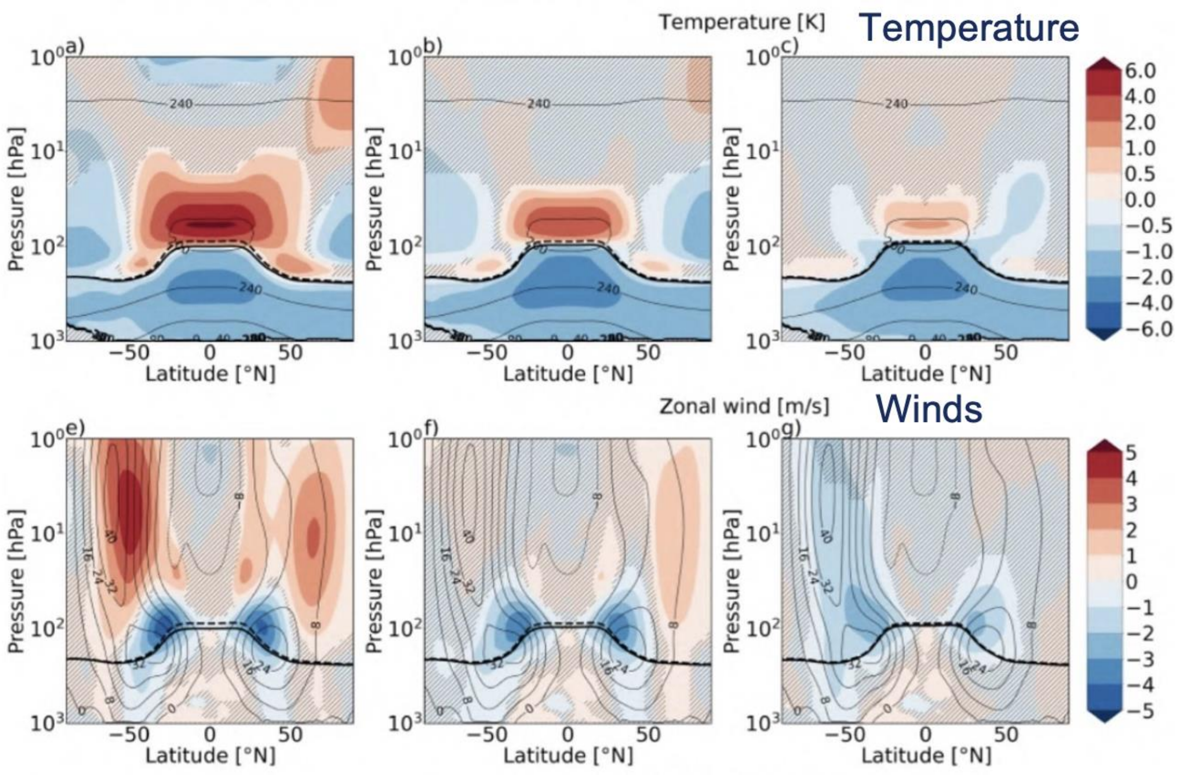


Yang et al., 2024

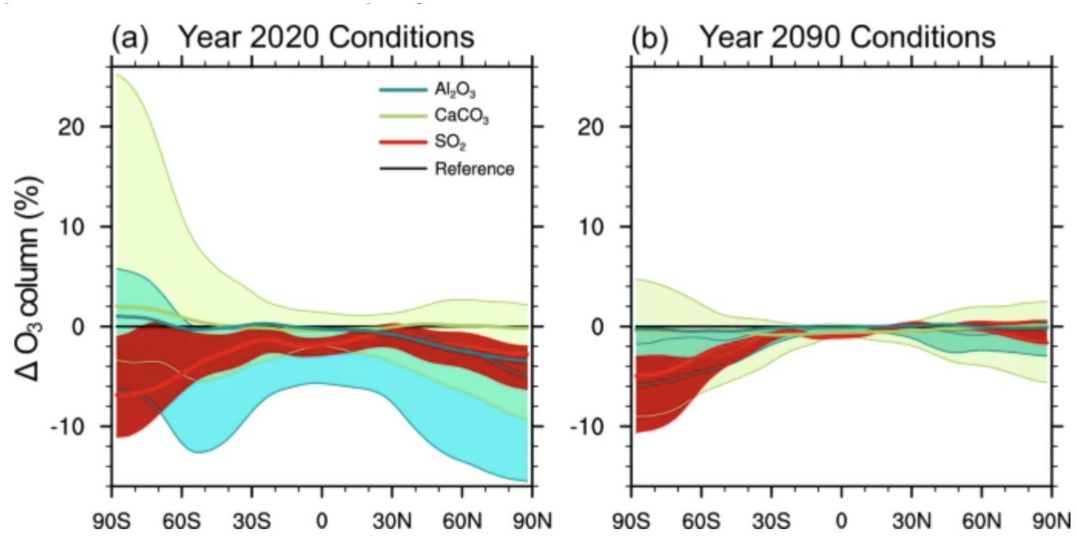
Solar Radiation Modification – Potential Strategies

Strategies Matter for Impacts: Location, Materials, Timing

Sulfur Aluminum Calcite



Stratospheric Ozone Effect:
Sulfur, Aluminum, Calcite



Modeling and laboratory research can reduce large uncertainties in our understanding of SAI

Stefanetti et al., 2024

Vattioni et al., 2025

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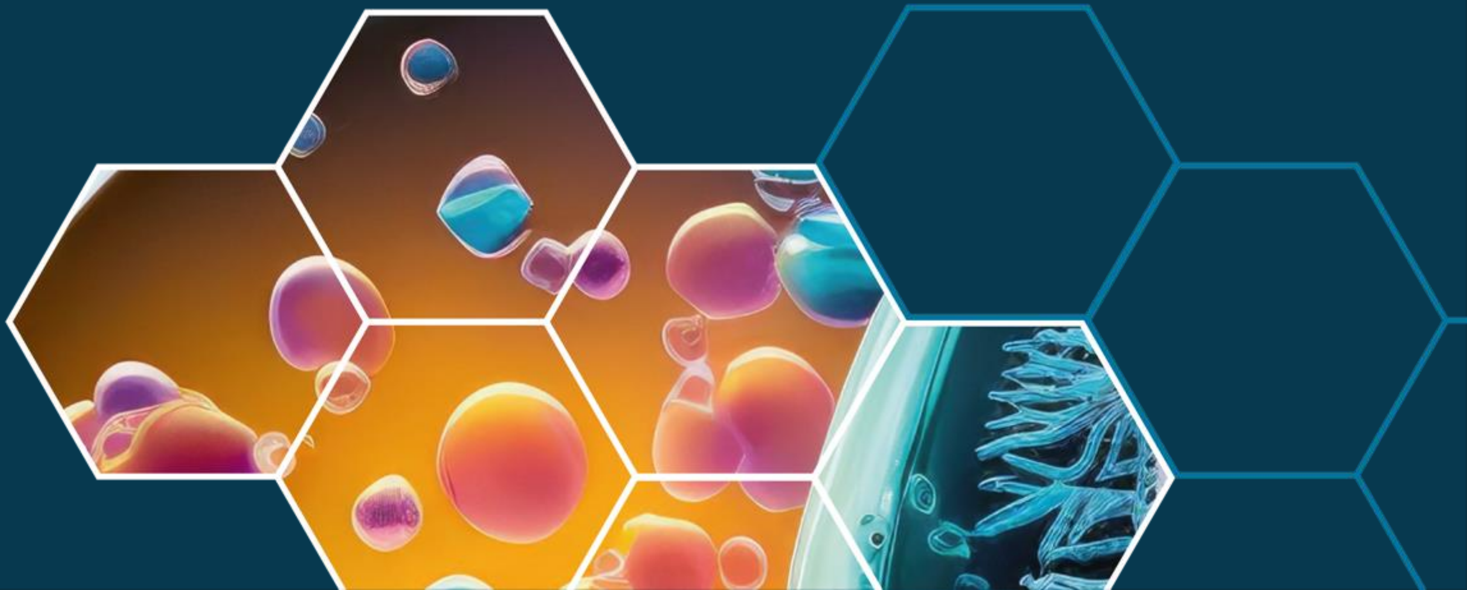
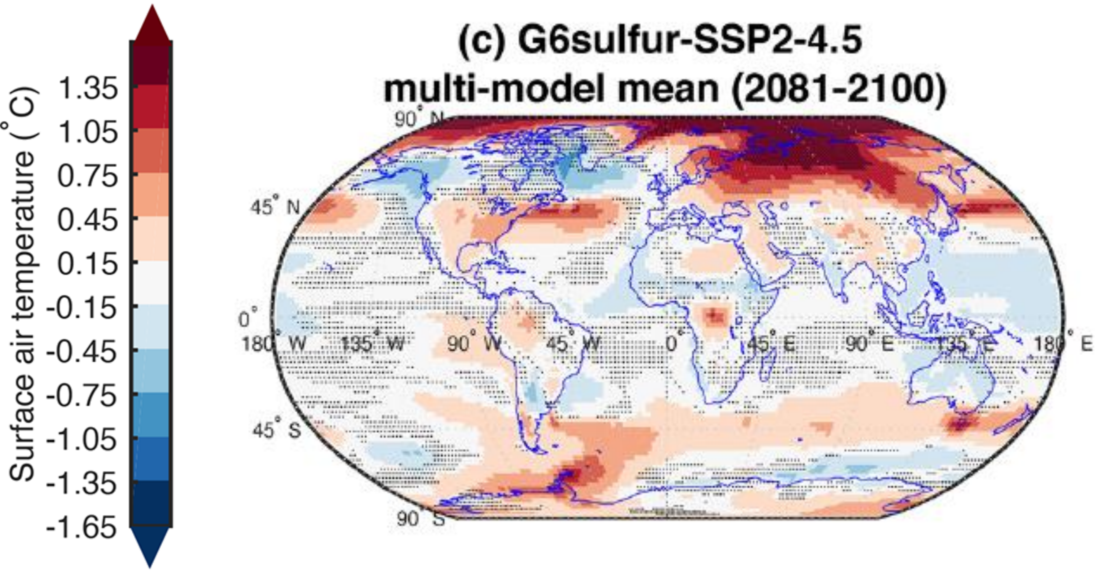
Solar radiation modification – stratospheric aerosol, (side-)effects and impacts

Gabriel Chiodo

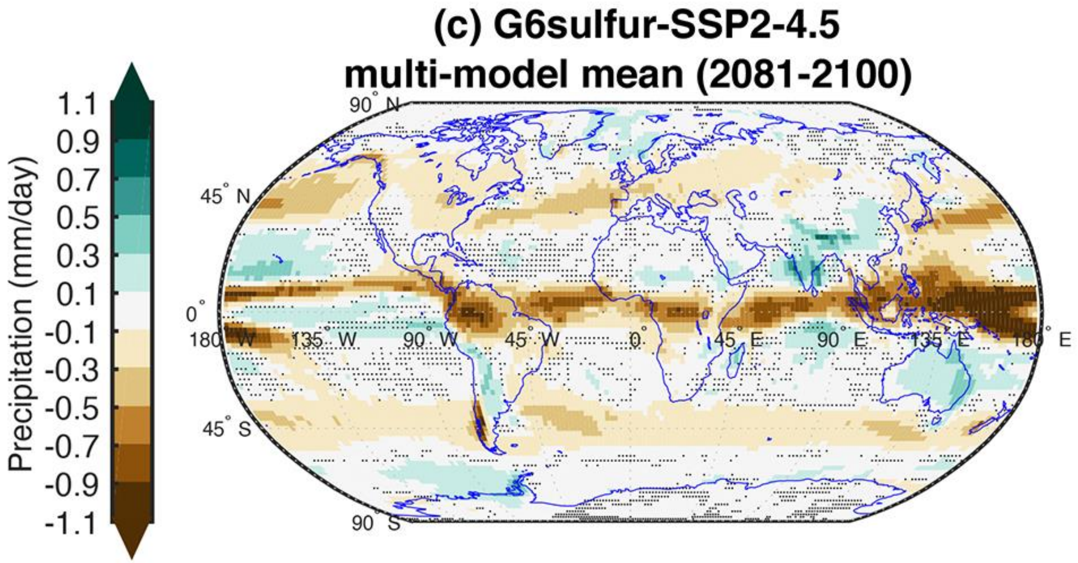


Potential effects of SRM via SAI: not “fixing” climate everywhere

- SAI would have regionally diverse impacts on temperature and precipitation (drying)



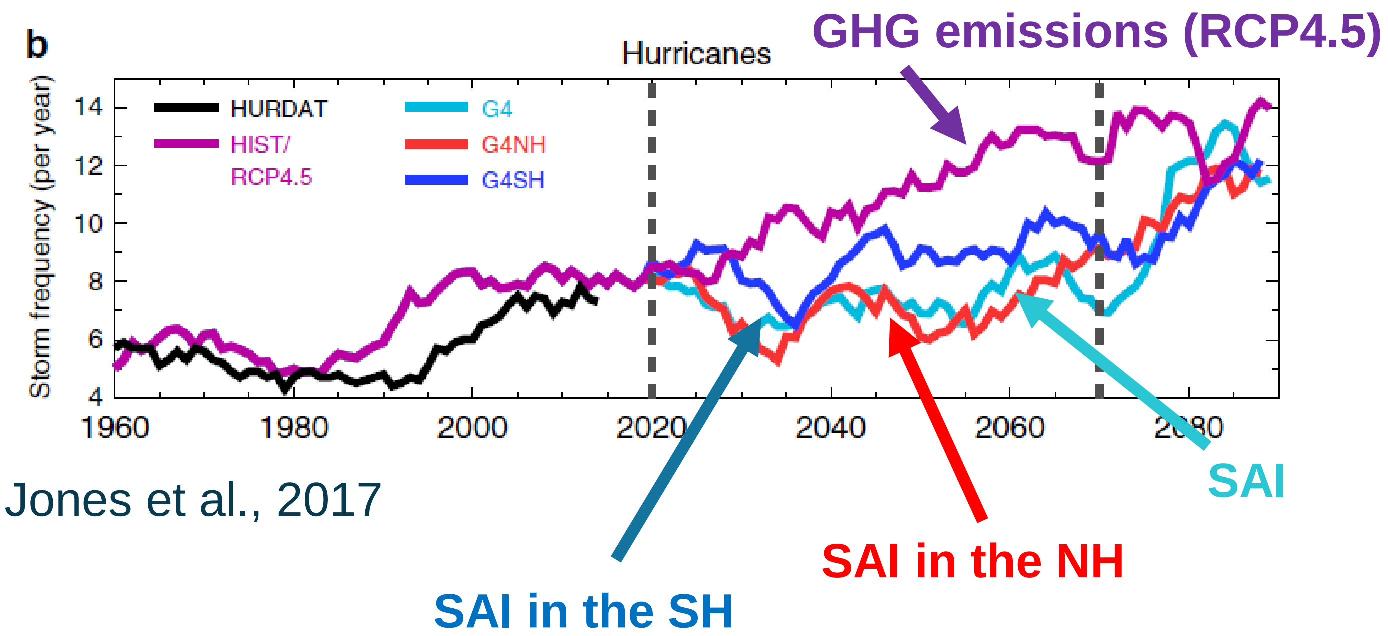
Visioni et al., 2021



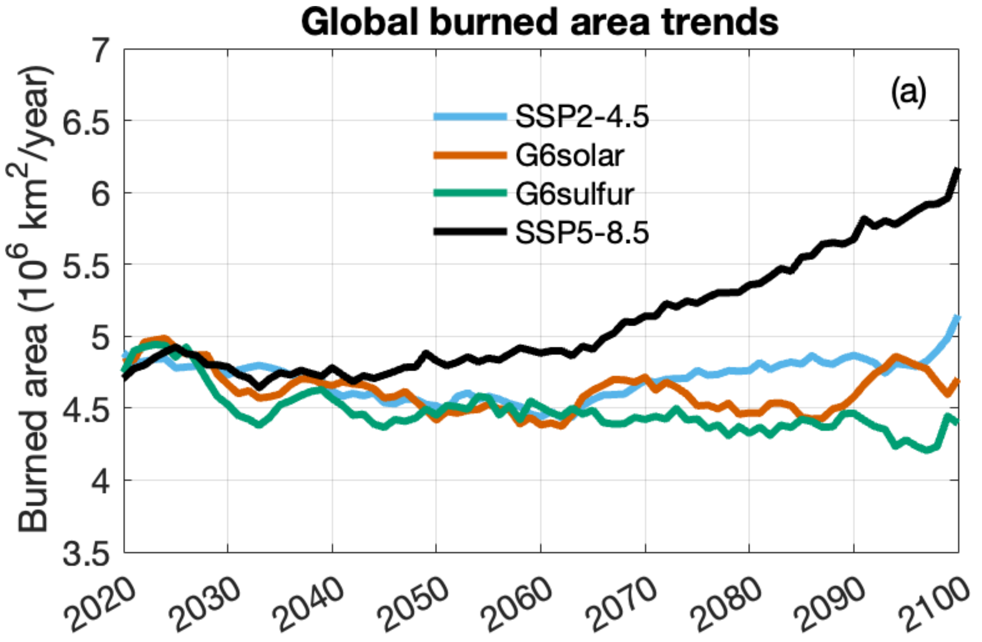
some regions (tropics) would may be disproportionately affected

Potential effects of SRM via SAI: reductions in extreme events

- SAI would decrease tropical cyclone activity and wildfire risk compared to mid-level GHG emission scenario



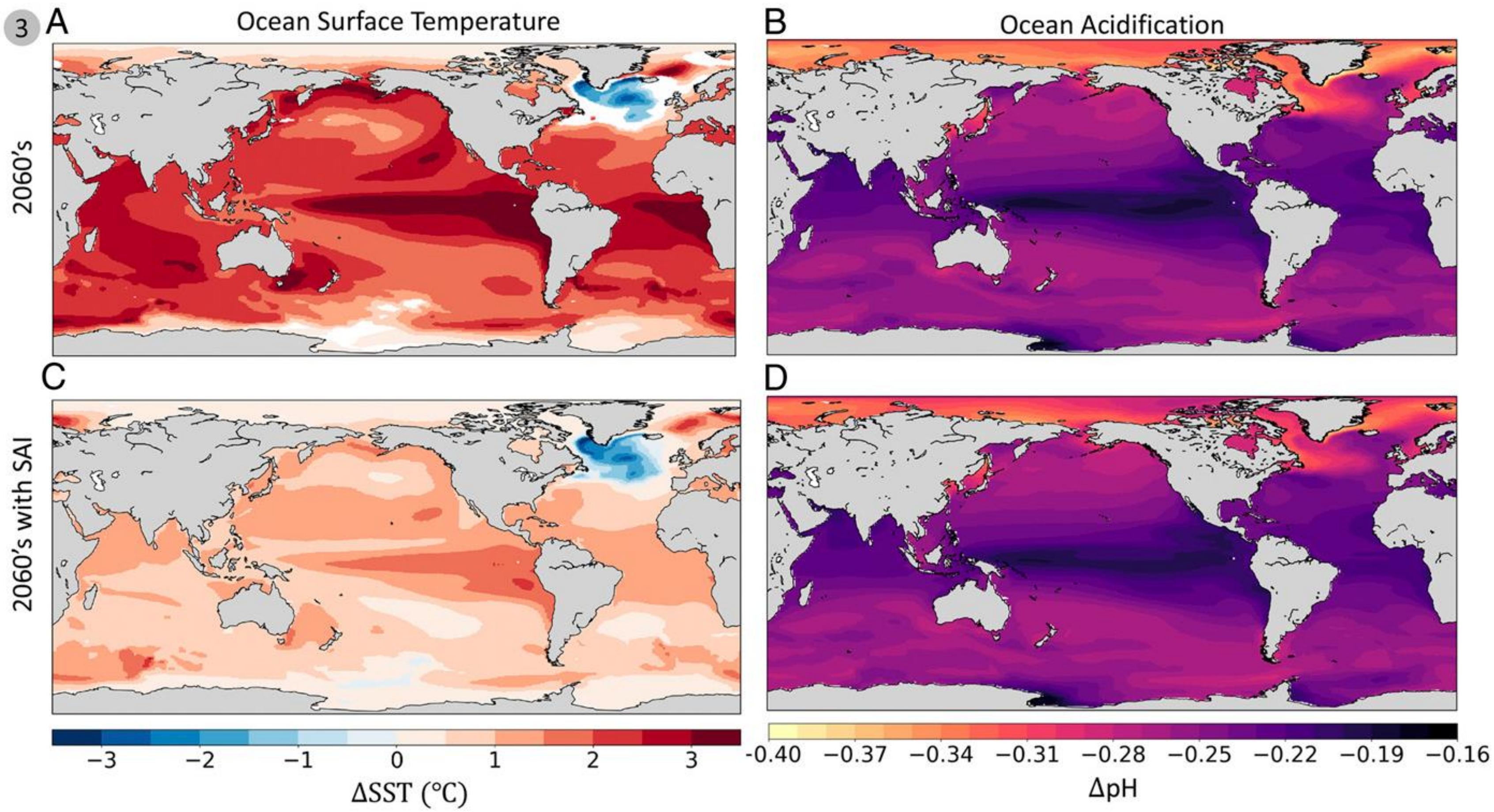
Jones et al., 2017

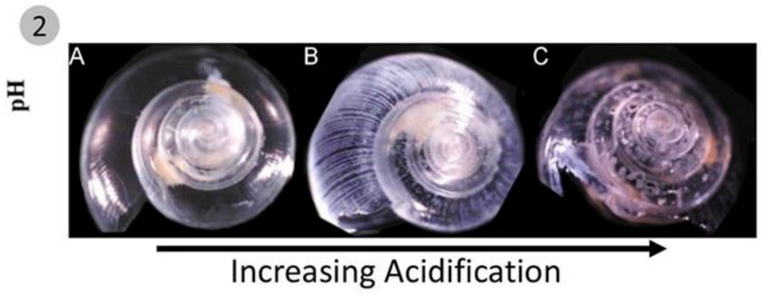


Tang et al 2024

Potential effects of SRM via SAI: not solving ocean acidification

- However, SRM does not address some of the direct impacts of CO_2



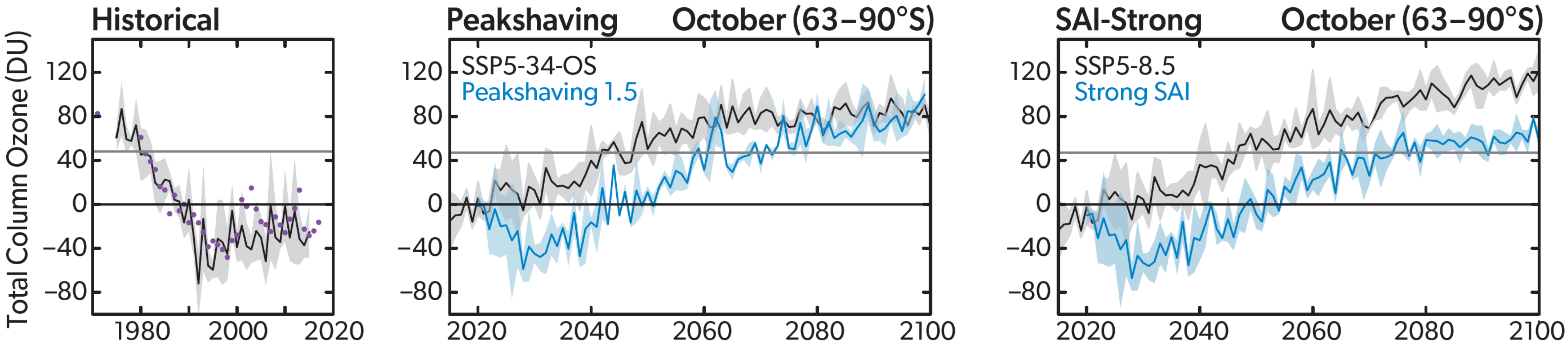


Zarnetske et al., 2021

Potential effects of SRM via SAI: Antarctic ozone depletion

Peakshaving Scenario:
We reverse effects of Montreal Protocol, then delay the recovery by about 20 y, but eventually we catch up.

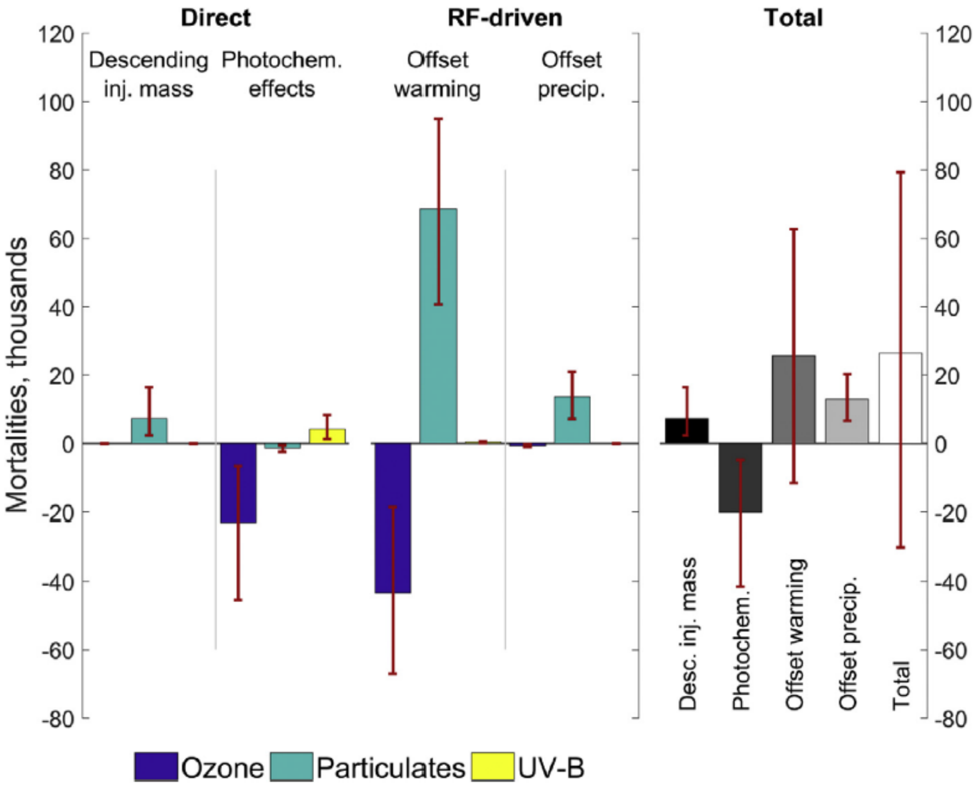
Strong SAI Scenario:
We reverse effects of Montreal Protocol, then delay the recovery by about 20 y, but never catch up.



Tilmes, Haywood et al., 2022

Potential effects of SRM via SAI: increased mortality?

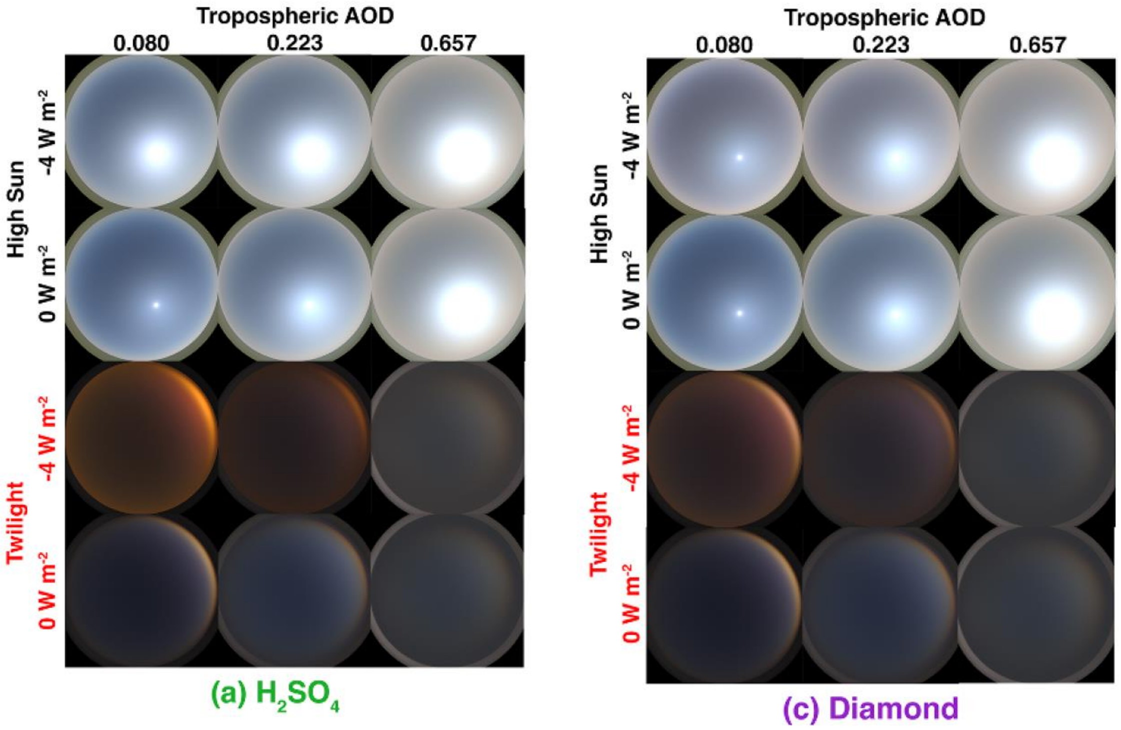
- SRM via SAI would lead to increased mortality from PM2.5 exposure…
- …but less mortality due to near surface-ozone decreases!
- <u>Estimates very uncertain</u>!



Eastham et al., 2018

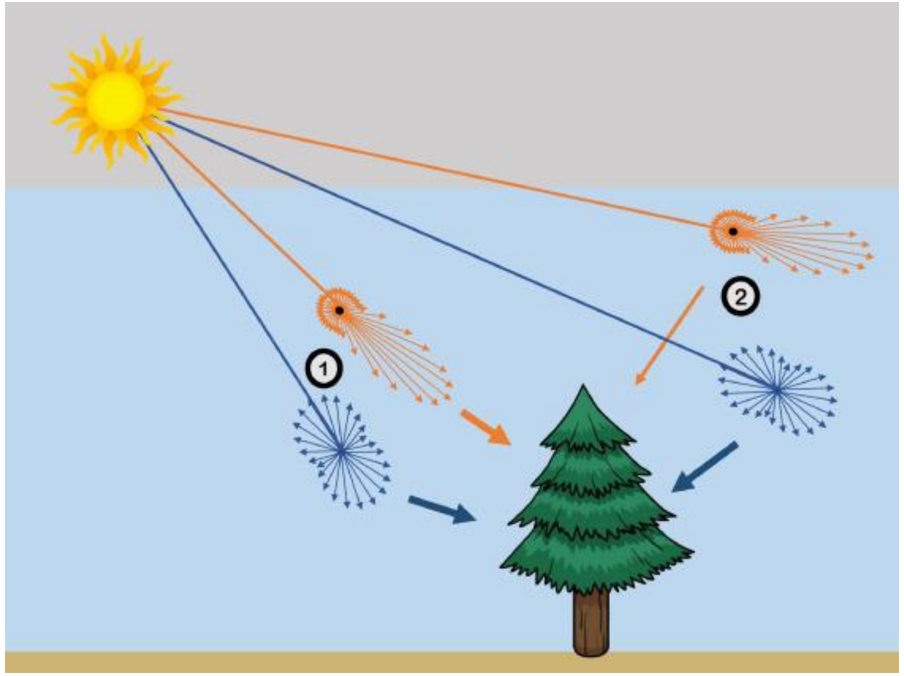
Potential effects of SRM via SAI: environmental impacts

- SRM via SAI would lead to whitening of the sky



Lemon et al., 2024

- … but scattering could also lead to enhanced photosynthesis

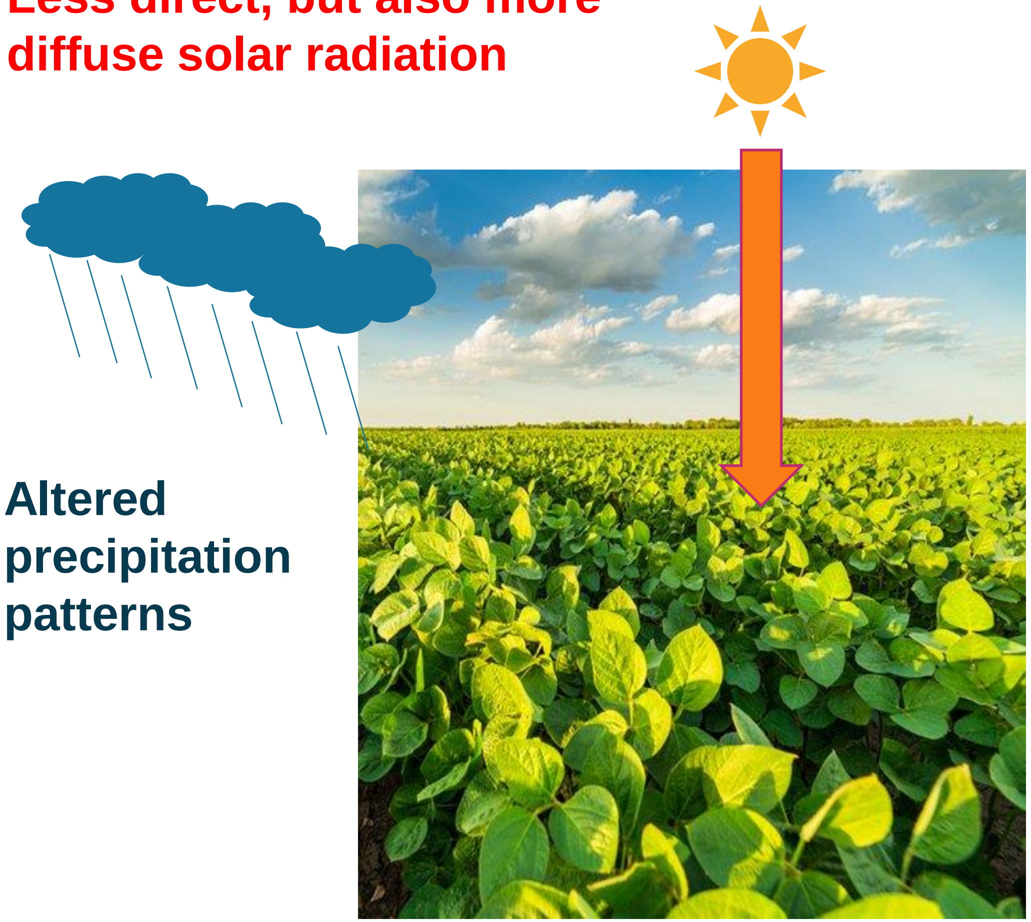


Xia et al., 2016

Potential effects of SRM via SAI: crop yields

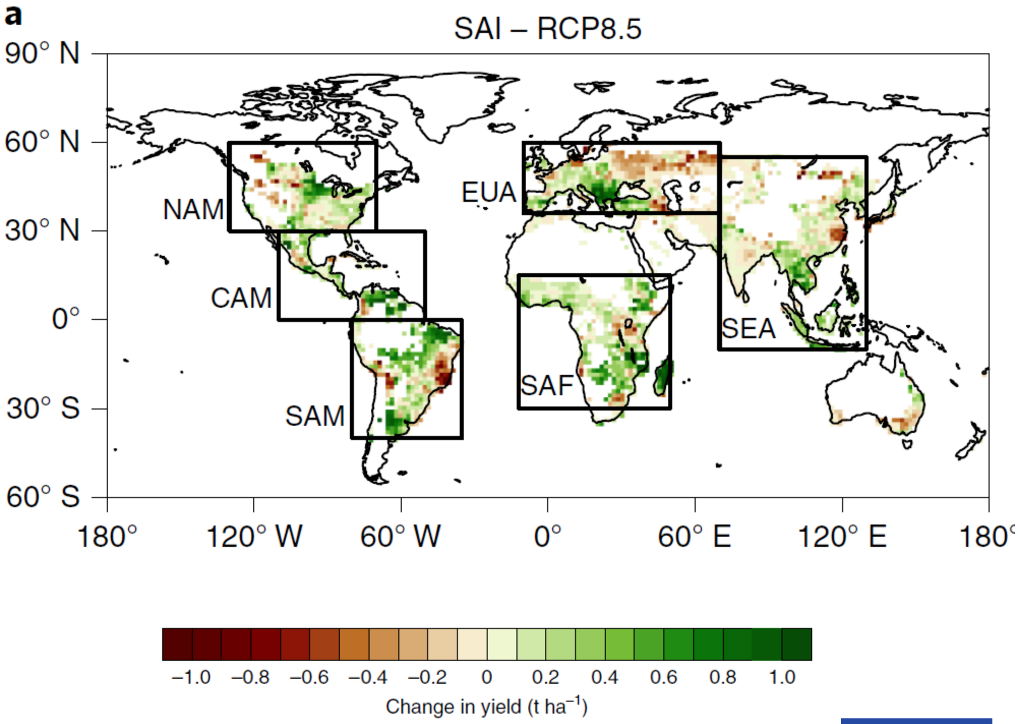
- … net result depends on type & region!

Less direct, but also more diffuse solar radiation



Altered precipitation patterns

Lower surface temperatures



Fan et al., 2021

Limitations of SRM via SAI: some take-aways

- Studied so far only in climate models
  - Impacts depend on strategy and magnitude of SAI forcing
  - However, models not yet able to anticipate all effects and impacts
  - Some relevant processes are only coarsely integrated or still missing

- Technology readiness level (TRL) is very low (need to develop fleet of aircrafts flying high enough, nozzle design, tethered balloons, etc.)

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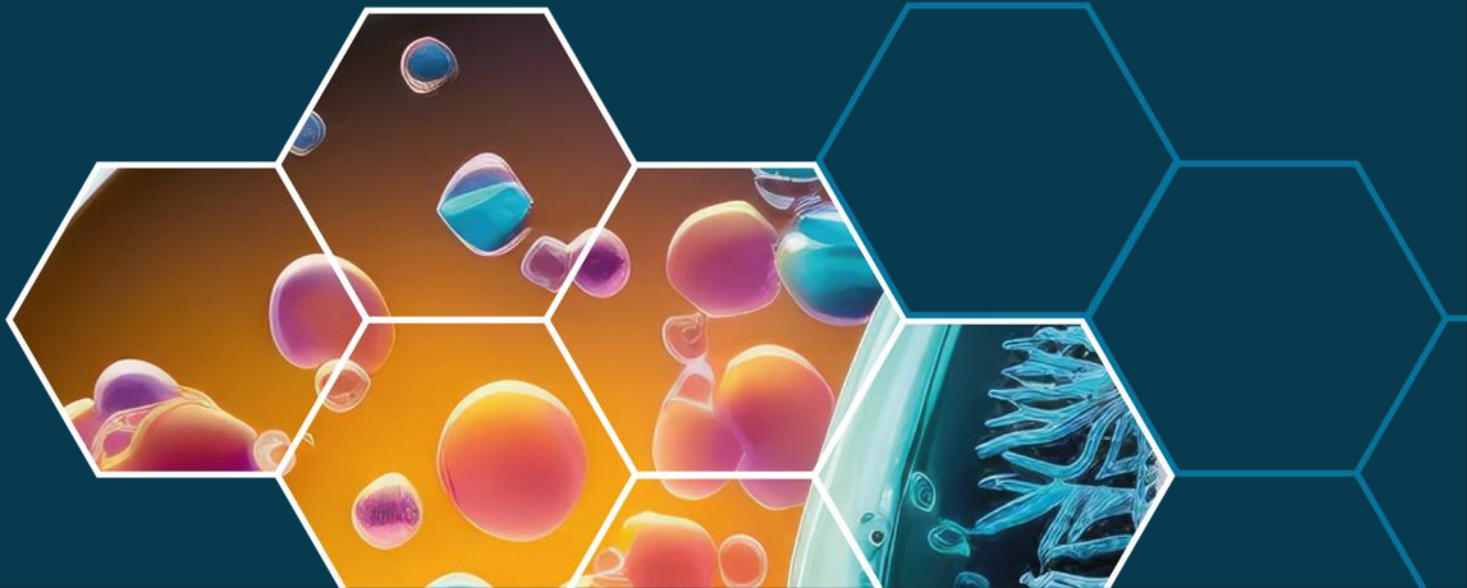
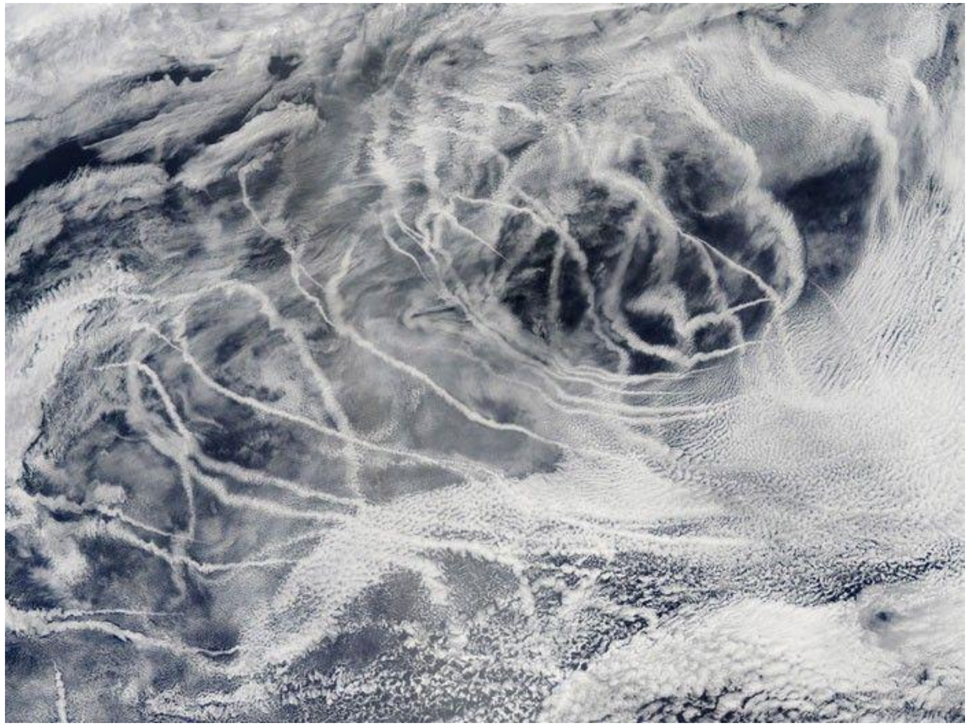
Solar radiation modification – cloud brightening, limited-area SRM, prerequisites

Johannes Quaas



Cloud brightening

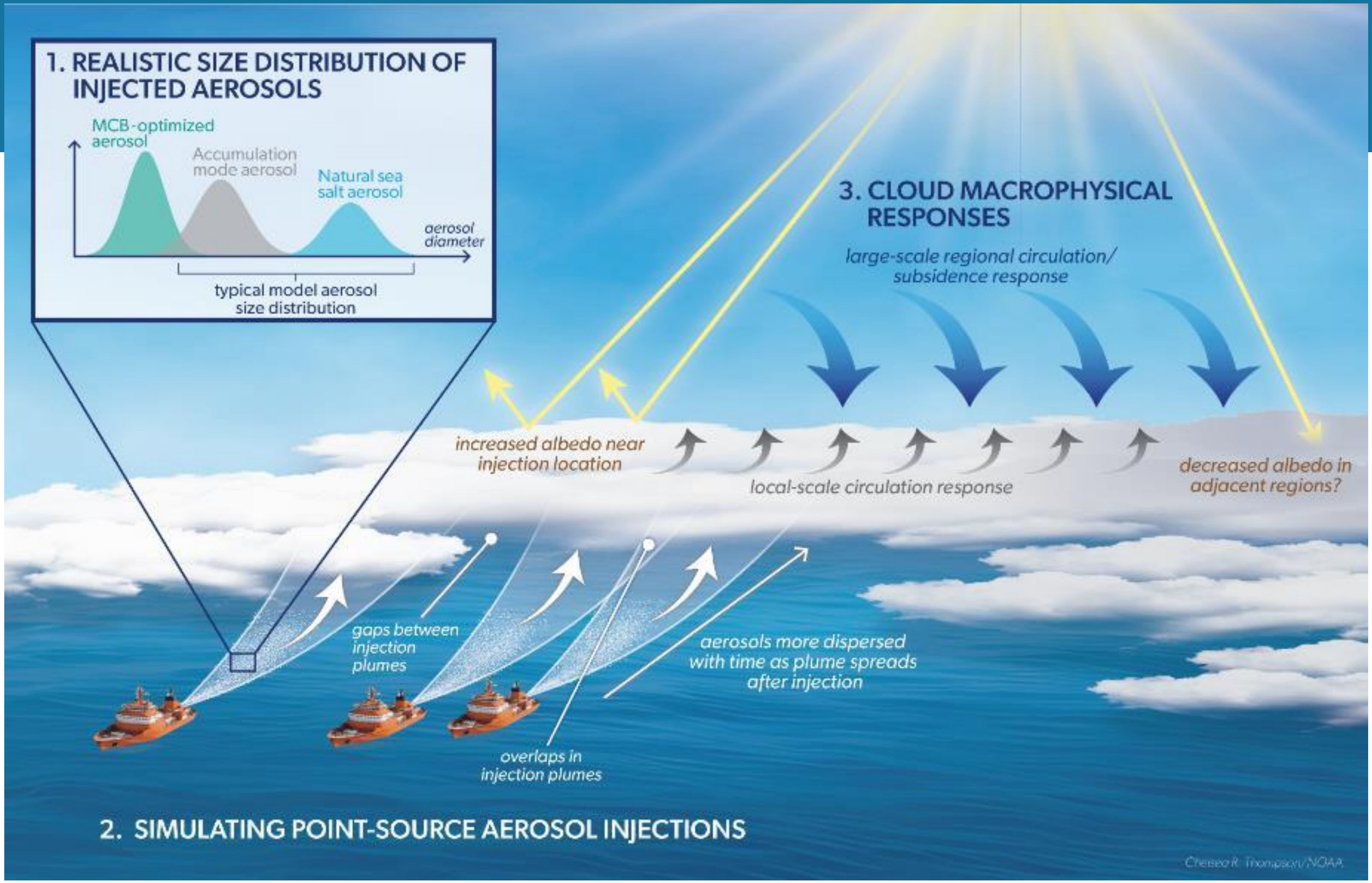
- Cloud droplets from on cloud condensation nuclei = aerosols
- More aerosols → more droplets → cloud brighter
- Seed clouds
- ↔ weather modification



https://science.nasa.gov/resource/ship-tracks/

Cloud brightening

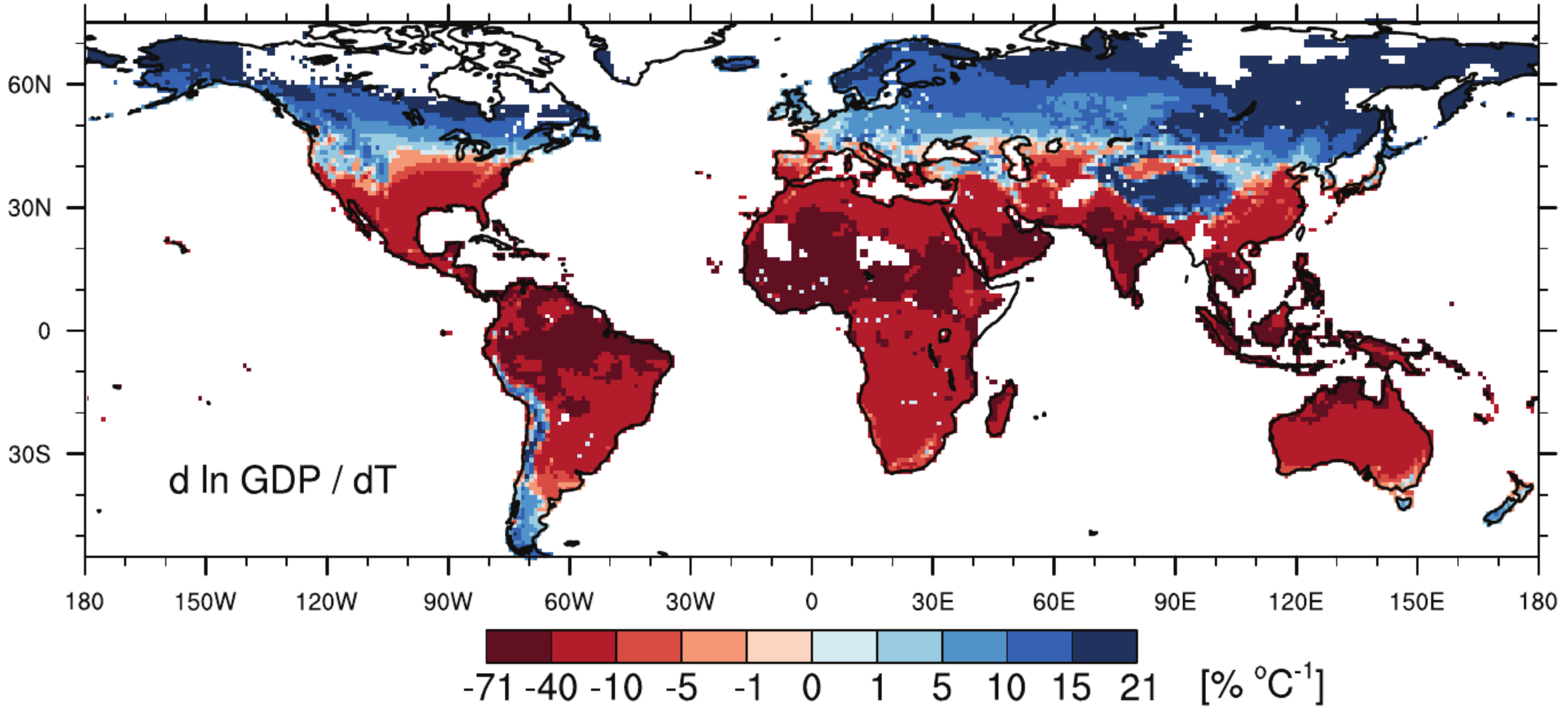
- Many uncertainties
- Modelling challenges
- Monitoring challenges



Eastham et al., J. Adv. Model. Earth Syst. in revision

Limited-area SRM

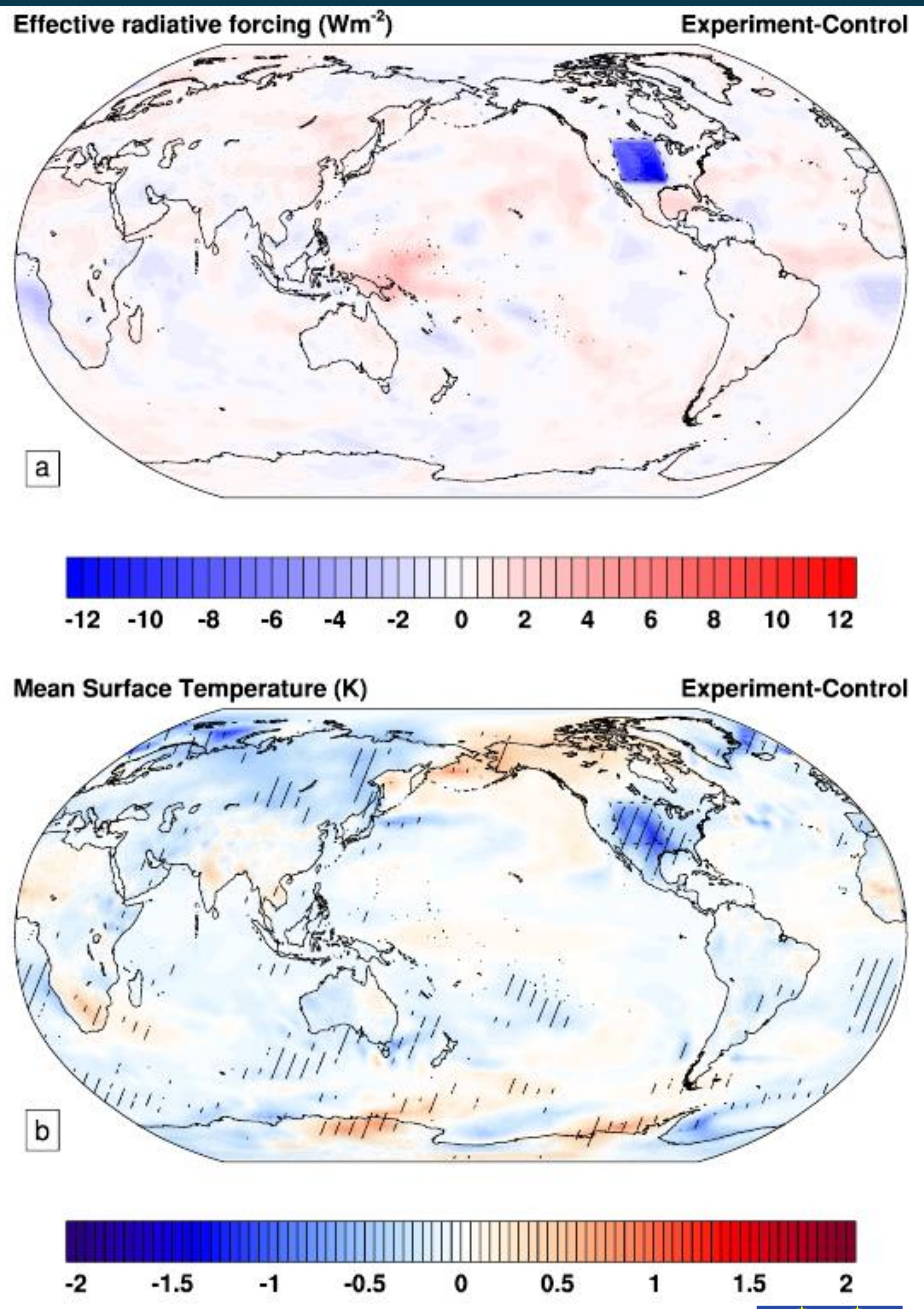
- Regionally diverging preferences
- Cloud brightening in principle scalable in space and time



Quaas, Quaas, Rickels, Boucher, Earth's Future 2016

Prerequisites: modelling

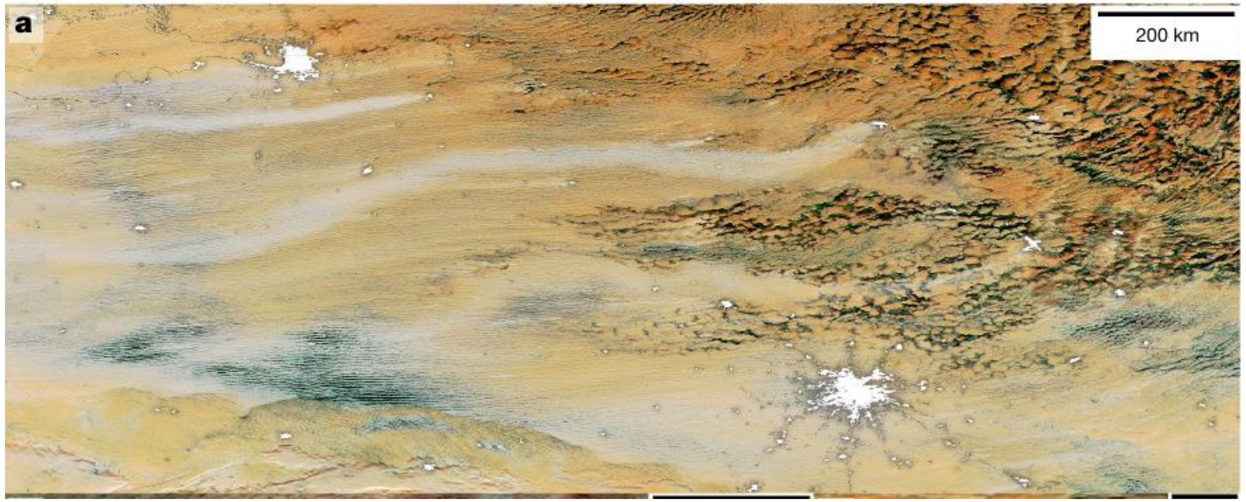
- How to anticipate all effects and side-effects?
- Would models be accepted in governance?



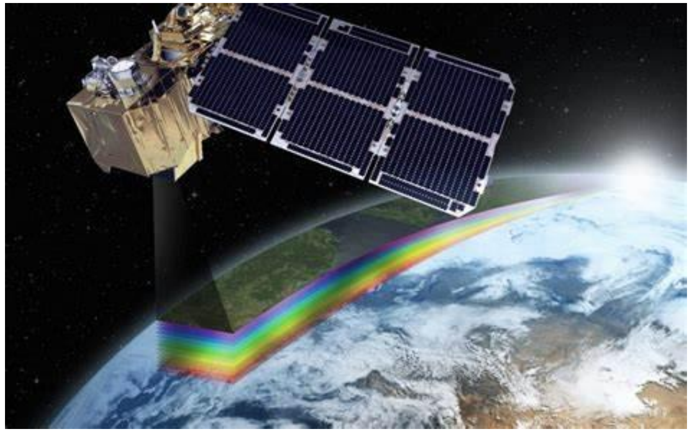
Quaas, Quaas, Rickels, Boucher, Earth's Future 2016

Prerequisites: detection and monitoring

- Detect field experiments, deployments
- Quantify effects



Toll et al. Nature 2019



Scientific Advice Mechanism
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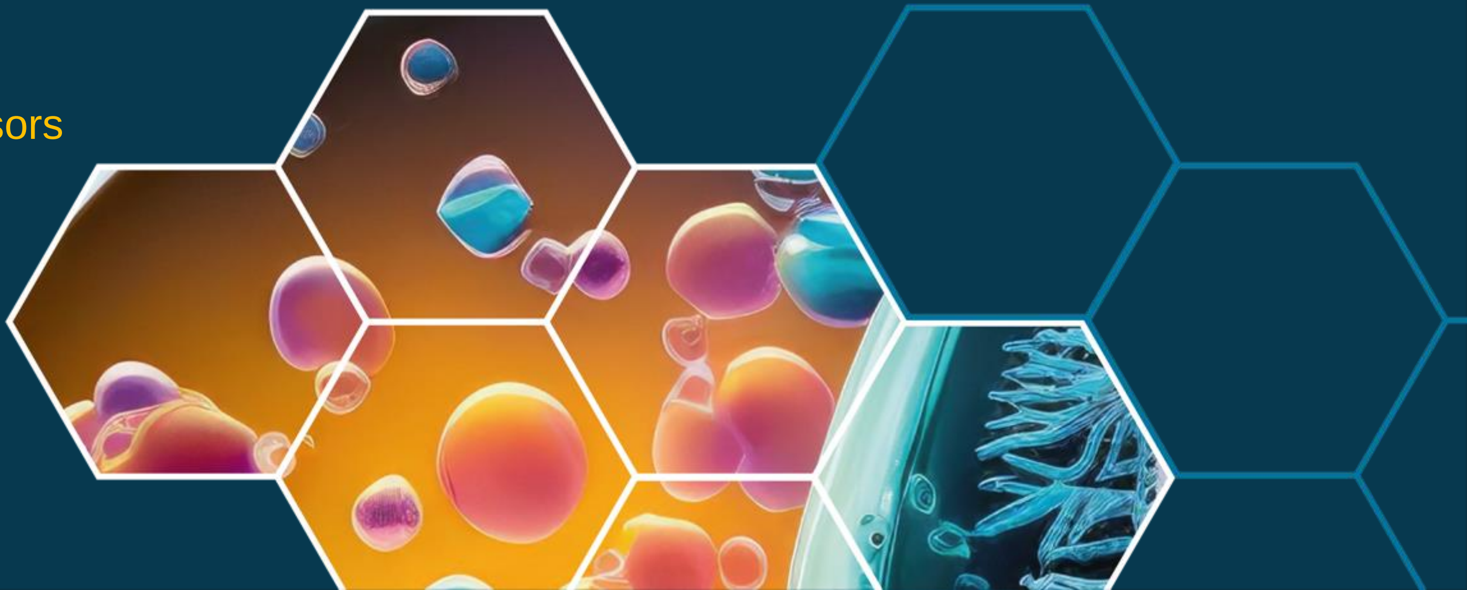
GCSA recommendations
Scientific Opinion

Solar Radiation Modification (SRM)

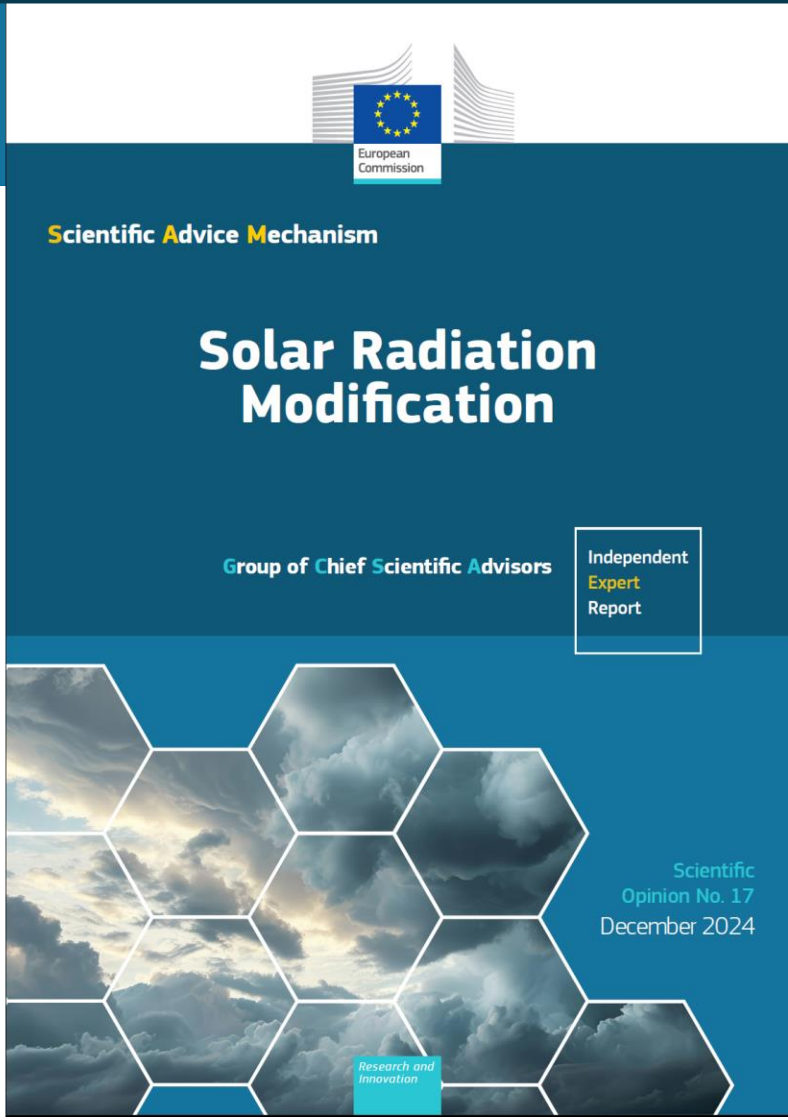
Professor Nebojša Nakićenović, Deputy-Chair,
Group of Chief Scientific Advisors
Professor Eric Lambin, Group of Chief Scientific Advisors



Scientific Opinion on SRM

1. Examines how the EU can address the risks and opportunities associated with research on Solar Radiation Modification and with its potential deployment.

2. Presents the possible options for a governance system for research and potential deployment taking into account different technologies and their scale.



Recommendation 1

Prioritise reducing GHG emissions as the main solution to avoid dangerous levels of climate change.

The EGD, FIT for 55, 90% reductions by 2040 and net-zero by 2050 are the best goals

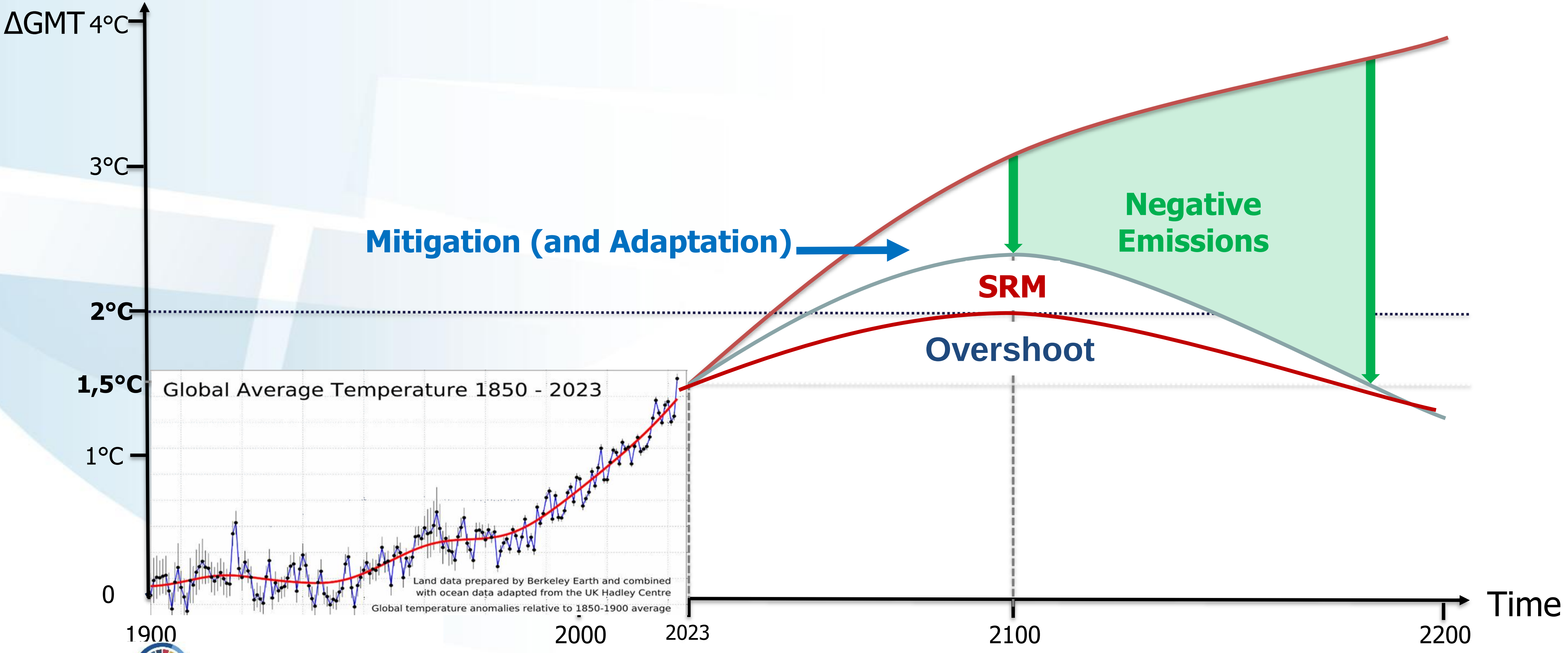
1.1 ***Continue to treat emissions reductions and adaptation to climate change as the highest priority in reaching net zero by mid-century and minimize "overshoot" and its adverse effects***

- Efficiency improvements and substitution of fossil through carbon-free energy sources
- Mitigation of land-use emissions and enhancing sinks (nature-based solutions)
- Carbon removal from fossil fuels (CCS)
- Carbon dioxide removal from the atmosphere (CDR)

1.2 ***Continue to actively and vigorously invest in research on and deployment of climate mitigation and adaptation.***

Global Average Temperature

Climate Restoration: Repair or Despair!



Source: Earth, 2024; Schellnhuber & Köllner 2022

Recommendation 2

Agree on an EU-wide moratorium of SRM deployment as a measure for offsetting climate warming (and reevaluate periodically, every 5-10 years)

The many climate, ecological and social risks and uncertainties of SRM deployment remain high, insufficiently understood and inherently not fully predictable.

2.1. ***Acknowledge that there is currently insufficient scientific evidence that SRM would avoid dangerous climate change by reducing some of the resulting global warming.***

- ➲ Model simulations, observations and theoretical considerations indicate that SRM would not completely offset or reverse dangerous climate change but only temperature raise with differing regional changes.

2.2. ***Recognise that the deep uncertainties associated with possible SRM deployment are inconsistent with the precautionary and "do no harm" principles.***

Recommendation 3

Proactively negotiate a global governance system for research and deployment of SRM by means of a multilateral process with international legitimacy. Given the current state of knowledge, the EU position in these negotiations should be for the non-deployment of SRM in the foreseeable future.

Governance system under the aegis of UN organizations such as UNFCCC, UNEP, WMO, UNCBD.

3.1. Base the EU negotiating position on relevant international and EU law.

3.2. Carry out a broad and inclusive public consultation to inform the negotiation of the international agreement.

3.3. Include an exemption in the international treaty, with a clear permitting process that specifies conditions under which to authorise some limited outdoor SRM research, with appropriate consideration of the risks this research poses to the environment and associated social, economic and cultural impacts.

3.4. Ensure that the global governance system addresses the risk of militarisation of SRM technologies in an international treaty.

3.5. Invest in operational Earth observation satellite and other technologies to improve the EU's capability to detect and quantify any undeclared deployment of SRM by public or private actors, anywhere in the world.

3.6. Oppose the use of 'cooling credits' derived from SRM technologies in future negotiations on the implementation of multilateral climate agreements.

Box 3: Cost Estimates for SAI

Development and deployment of SRM technologies at scale would require resources, including the delivery mechanisms for injecting aerosols in the stratosphere. Various estimates published in the literature indicate large uncertainties, in the range of USD 18 to 107 billion per year to offset 0.5 - 1 °C of warming (Niemeier & Tilmes, 2017; Robock, 2020; SAPEA, 2024; Smith, 2020)

B.1. Aircraft used to deliver aerosols would have to fly at altitudes of around 25 km for the most efficient injection. Concorde cruised at 18,3 km, U-2 'Dragon Lady' spy plane at 21 km, SR-71 at 24 km. The aircraft that would be required do not yet exist and would need to be developed in the coming decades.

B.2. The estimated amount of sulphur needed to offset 0.5 to 1°C of global warming generally ranges between 5 and 10 million tonnes per year (5 - 10 TgSO_2/yr).

B.3. Wake Smith and Wagner proposed a fleet of SAIL (Stratospheric Aerosol Injection Lofter) aircraft with capacity of 25 tons per flight. They estimated needing around 100 such aircraft, each making about 4,000 flights per year, resulting in 10 million tonnes per year.

Aircraft	Development Time	Original Cost (USD)	2023-Adjusted Cost (USD)	Total Produced
Boeing 747	4 years	$1 billion (1970)	$7.7 billion	1,574
Airbus A380	10 years	$15–18 billion (2000s)	$22–25 billion	254
Concorde	13 years	$2.2 billion (1976)	$12–15 billion	20

B.4. Once initiated, sulphur injection into the stratosphere or upper troposphere would need to continue 24/7 for many years, until climate change stabilization goals are reached, to avoid a termination shock.

Recommendation 4

Ensure that research on SRM is conducted with scientific rigor, responsibly and in accordance with EU ethical principles in research. This should include research into the full range of the direct and indirect effects and unintended impacts of SRM on the climate system, biosphere and humankind, including governance and justice issues.

The high uncertainties in the potential benefits and risks of SRM can only be addressed by further research, which should be supported by public funding.

4.1. Create clear ethical requirements for research projects on SRM, whether they are funded publicly or privately.

4.2. Develop guidelines for outdoor research project on SRM.

4.3. Ensure that any public funding for SRM research is additional to and not instead of public funding for research on climate change mitigation and adaptation.

4.4. Impose a moratorium on large-scale outdoor SRM experiments.

Recommendation 5

Reassess the scientific evidence on risks and opportunities of SRM research and deployment periodically, every 5-10 years.

Including research on both atmospheric physics and chemistry, and on the governance related to SRM could evolve quickly.

5.1. Consider supporting the participation of the scientific community in intergovernmental assessments.

5.2. Set up citizens' assemblies to initiate a debate on SRM, promote transparency and develop fair governance.

5.3. Support the development or adaptation and operationalisation of detection-attribution modelling tools, which could cover the range of time horizons and deployment scenarios under consideration.

Scientific Advice Mechanism
to the European Commission

Thank you for your attention!