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SAI Side event presentation
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Climate Intervention and Stratospheric Ozone

Introduction and results from the 2022 UNEP/WMO Scientific Assessment of Ozone Depletion

Dr. David W. Fahey
Dr. Paul A. Newman
Dr. John A. Pyle
Dr. Bonfils Safari

Co-Chairs of the Scientific Assessment Panel of the Montreal Protocol

https://ozone.unep.org/science/assessment/sap

Topics

Topics

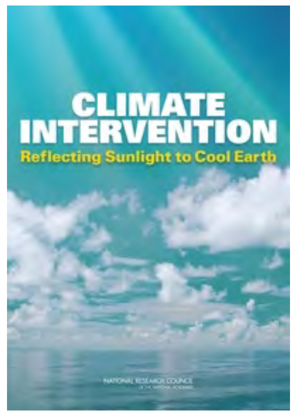
- What is climate intervention?
- What other ways have been proposed to cool Earth?
- Why does a warmer world matter?
- Is there evidence that the SAI method is a viable method to cool Earth?
- Considerations and consequences of SAI
- SAI and stratospheric ozone
- Peakshaving scenario
- SAI dynamical consequences
- SRM research in the USA
- Concluding remarks

- The motivation/objective of the Montreal Protocol (MP) Scientific Assessment Panel (SAP) activities is to provide/enhance/strengthen the scientific foundation for MP policy deliberations and decisions.
- Hence, the SAP does not advocate for actions or policies, e.g., implementation or governance of climate intervention.
- This presentation is available from the MOP35 portal.

What is climate intervention?

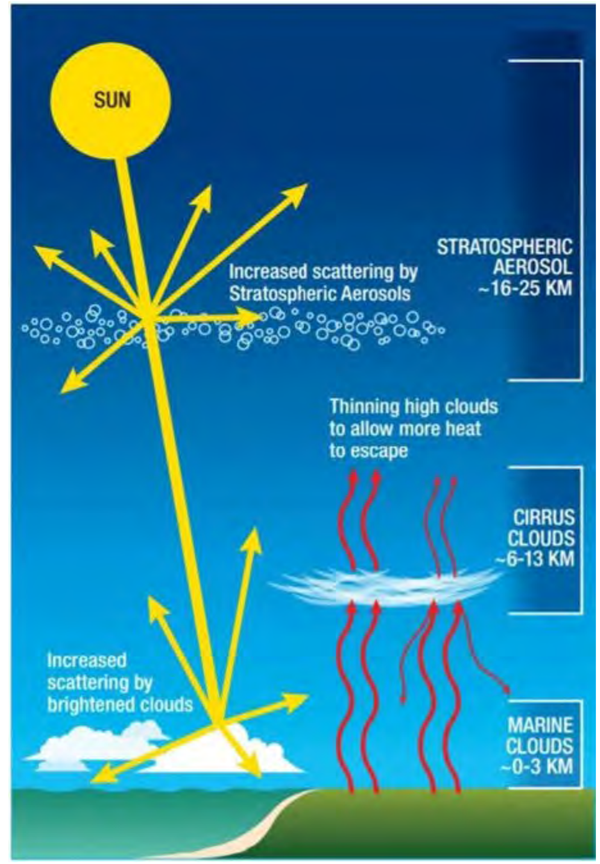
- Climate intervention, also known as *geoengineering* or *solar radiation modification* (SRM)), refers to cooling the Earth by human means to offset the warming and other impacts due to greenhouse gas accumulation.

- "Should it ever become important for society to cool Earth rapidly, albedo modification approaches (in particular stratospheric aerosol injection (SAI) and possibly marine cloud brightening) are the only ways that have been suggested by which humans could potentially cool Earth within years after deployment."



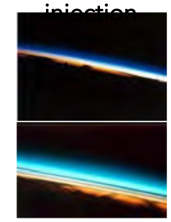
US National Academies Press, 2015

- The principal climate intervention methods are stratospheric aerosol injection (SAI), marine cloud brightening (MCB) and cirrus cloud thinning (CCT)



US National Academies, 2021

Stratospheric aerosol injection



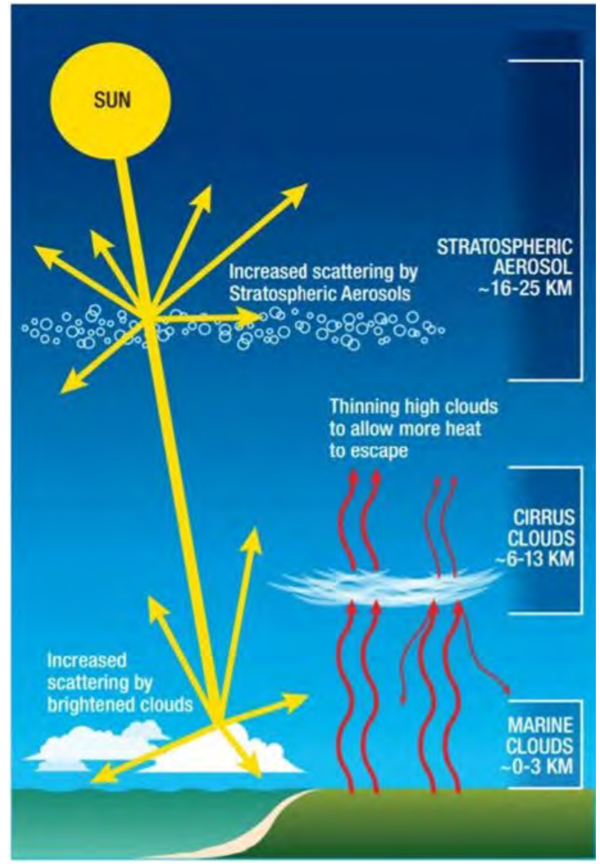
Cirrus cloud thinning

Marine cloud brightening

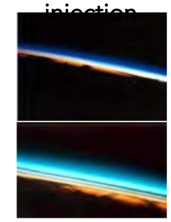
https://nap.nationalacademies.org/catalog/18988/climate-intervention-reflecting-sunlight-to-cool-earth

What is climate intervention?

- Stratospheric aerosol injection (SAI) injects aerosol or aerosol precursors (e.g., sulfur) into the stratosphere to reflect solar radiation that otherwise would add heat to the Earth system.
    - SAI is considered to be the most effective and most affordable option to cool the Earth.
- Marine cloud brightening (MCB) is a tropospheric method focused on increasing the reflectivity of cloudy regions in the marine boundary layer with injected aerosol (e.g., sea salt).
    - MCB methods are less well developed and have more uncertainty than SAI.
- Cirrus cloud thinning (CCT) focuses on changing cirrus clouds in the upper troposphere to allow more heat to escape to space.
    - CCT methods are very speculative at present.



Stratospheric aerosol injection



Cirrus cloud thinning

Marine cloud brightening

US National Academies, 2021

What other ways have been proposed to cool Earth?

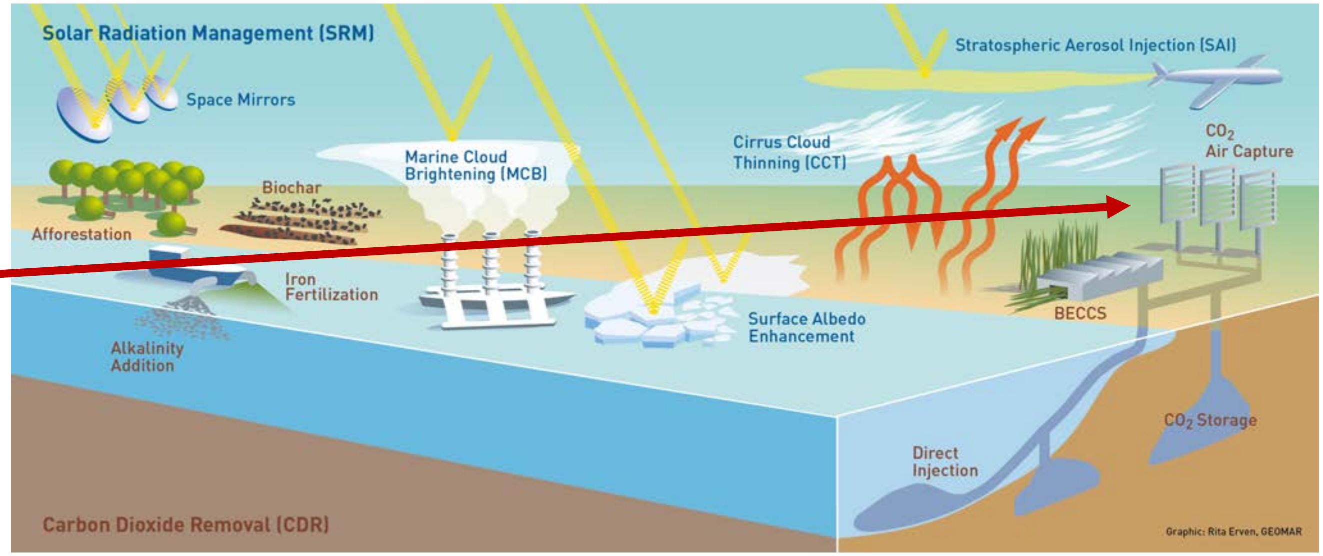
- There are many proposed methods to cool the Earth

- Climate dioxide removal (CDR) is cooling the Earth by permanently removing CO_2 from the atmosphere.

    - CDR (and emissions reductions) is required for cooling the Earth in the long term.

    - No effective and feasible CDR methods have been demonstrated at the required scale.

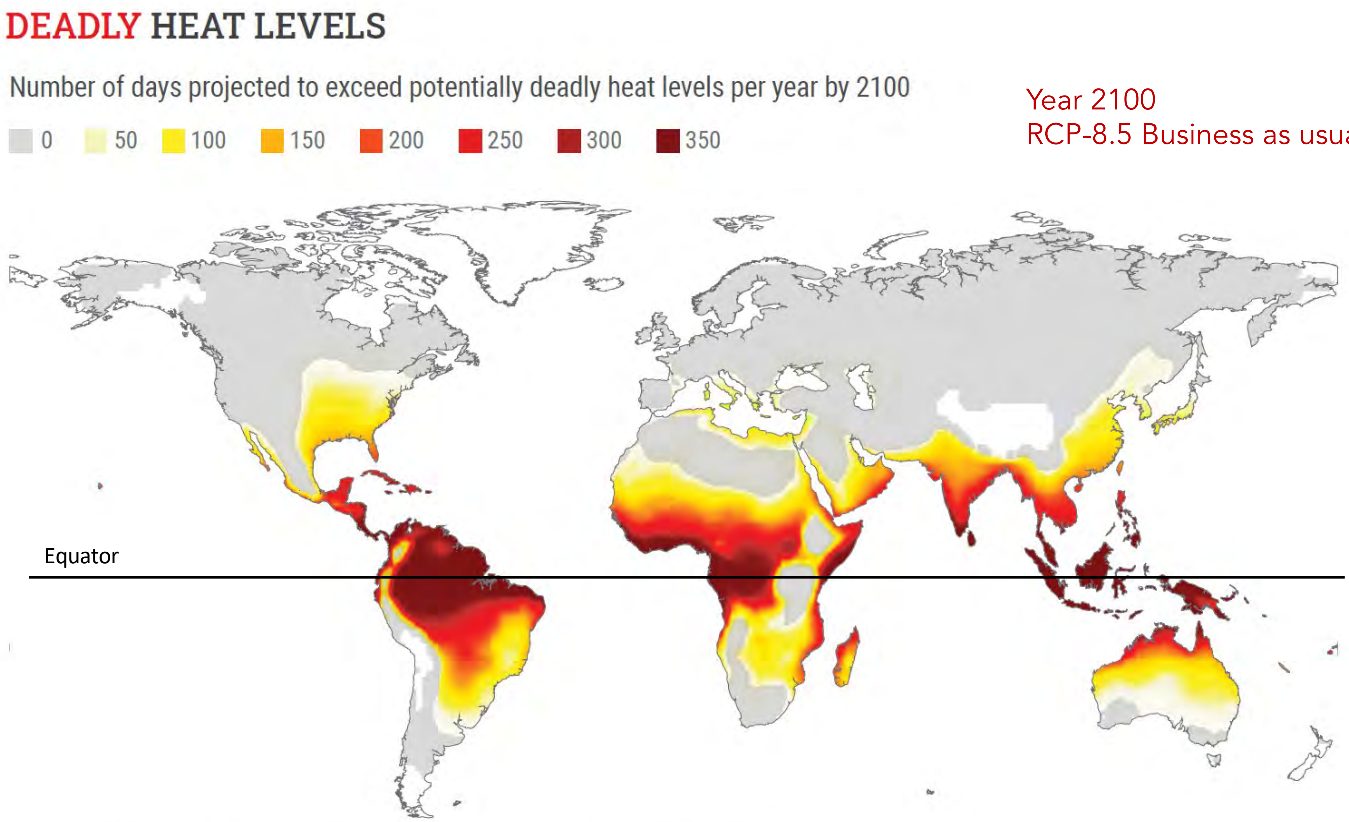
    - SAI 'buys time' to develop and achieve suitable CDR implementation (see peakshaving scenario)



BECCS = Bioenergy with carbon capture and storage

UNEP/WMO 2022 Ozone Assessment Box 6-1
Geoengineering the climate: Science, Governance and Uncertainty, The Royal Society, 2009

Why does a warmer world matter?



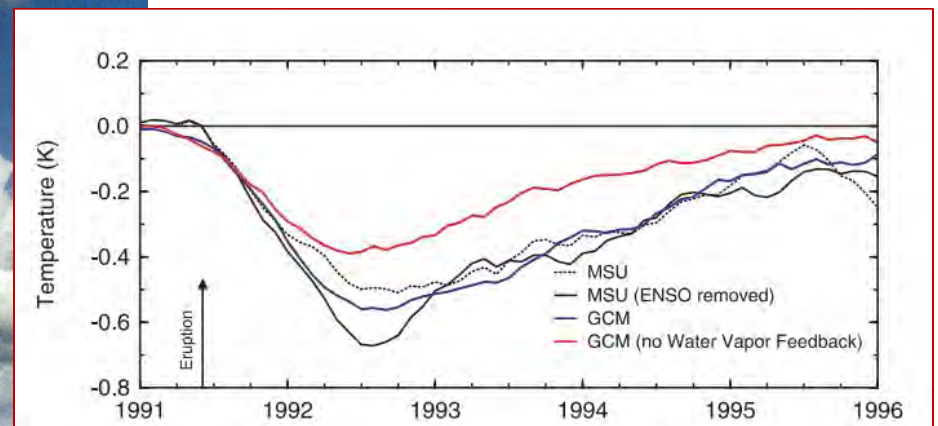
Year 2100
RCP-8.5 Business as usual

Extreme Heat, Preparing for the heatwaves of the future. (United Nations)

Mora et al., Nature Climate Change, 2017

Is there evidence that the SAI method is a viable method to cool Earth?

• Explosive volcanic eruptions demonstrate the cooling possible from stratospheric aerosol injection (SAI) of sulfur-containing aerosol, i.e., volcanic eruptions are a natural analog of SAI.



• Global temperatures in satellite (MSU) observations dropped by up to 0.5°C in the years after the Mt. Pinatubo eruption.

https://www.science.org/content/article/massive-volcanoes-could-cool-earth-more-warming-world

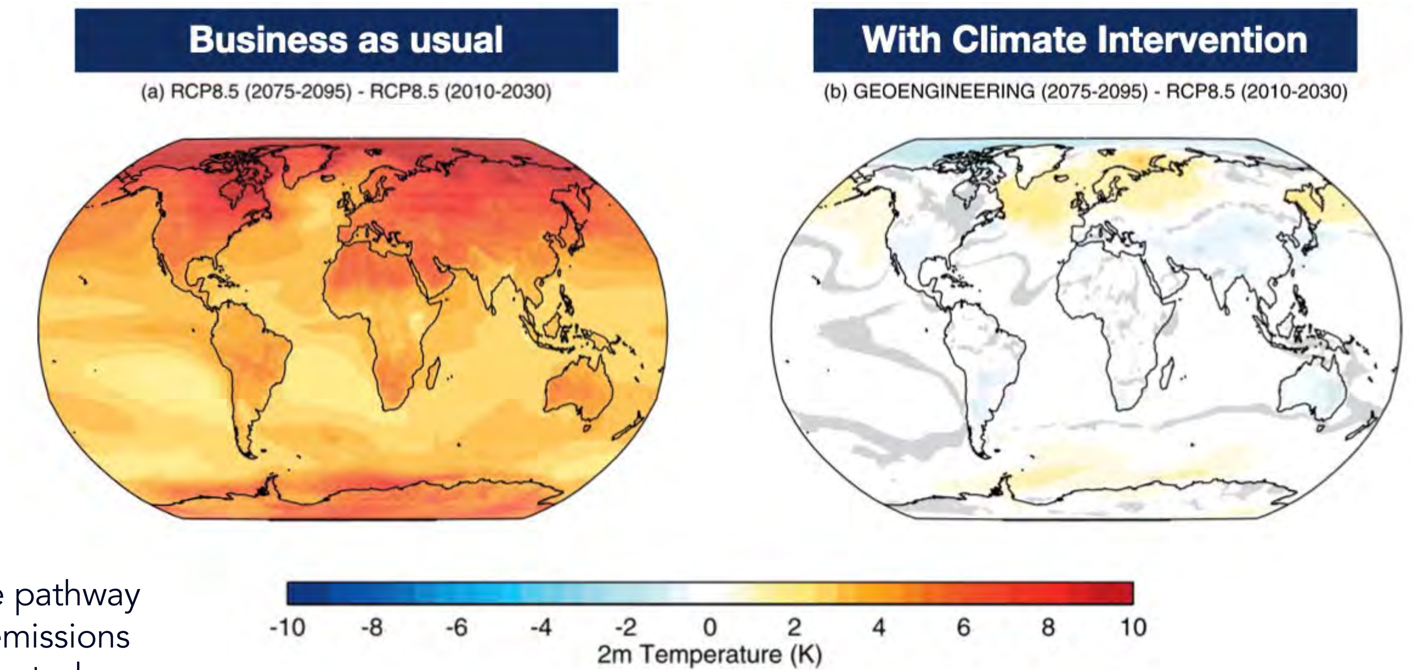
Brian J. Soden, et al. *Science* 296, 727 (2002)

Do global models show that the SAI method is a viable method to cool Earth? Yes

- Substantially cooling Earth with SAI is a robust feature of SAI global modeling

- NCAR model scenario:

  IPCC RC8.5 (2075-2095)
  minus
  IPCC RC8.5 (2010-2030)



Note: RCP8. 5 is a future pathway where greenhouse gas emissions continue to grow unmitigated

Courtesy of J. Richter, US National Center for Atmospheric Research (NCAR)

GLENS = Geoengineering Large Ensemble (with CESM1-WACCM)
https://www.cesm.ucar.edu/projects/community-projects/GLENS/

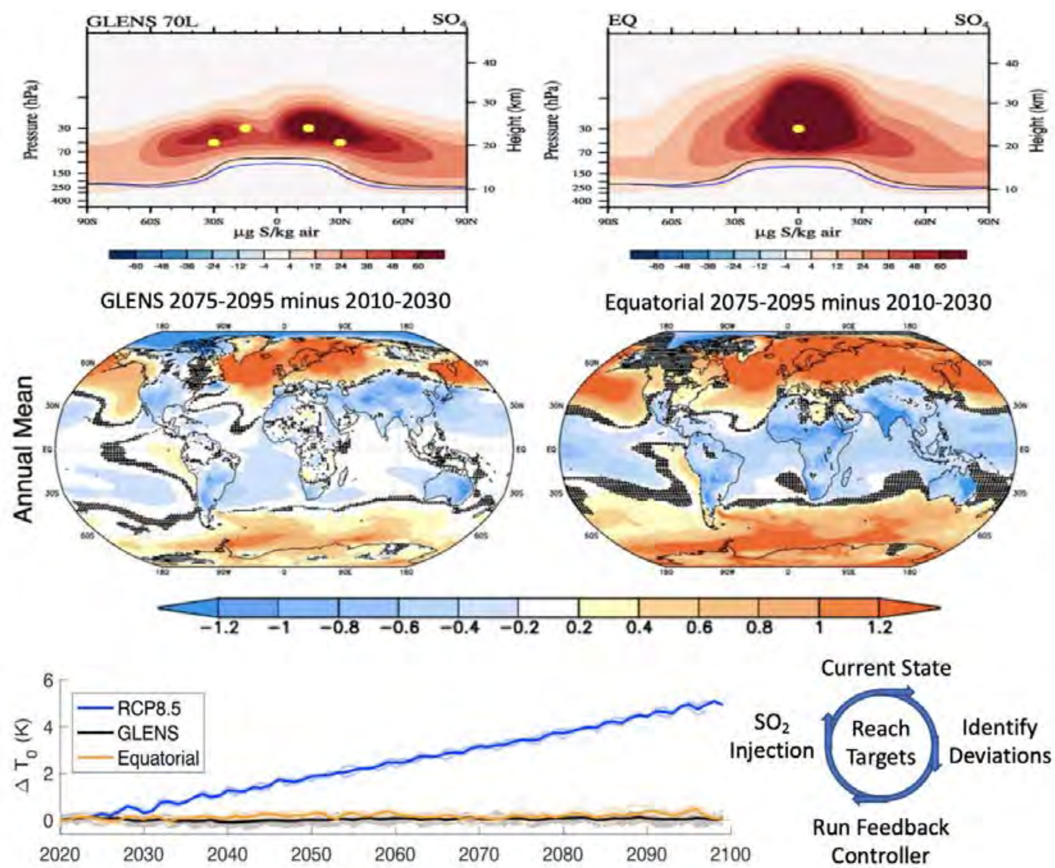
ARISE-SAI = Assessing Responses and Impacts of Solar climate intervention on the Earth system with Stratospheric Aerosol Injection (with CESM2-WACCM)
https://www.cesm.ucar.edu/projects/community-projects/ARISE-SAI/

Do differences in SRM injection strategies matter?

SAI Implementation Strategies

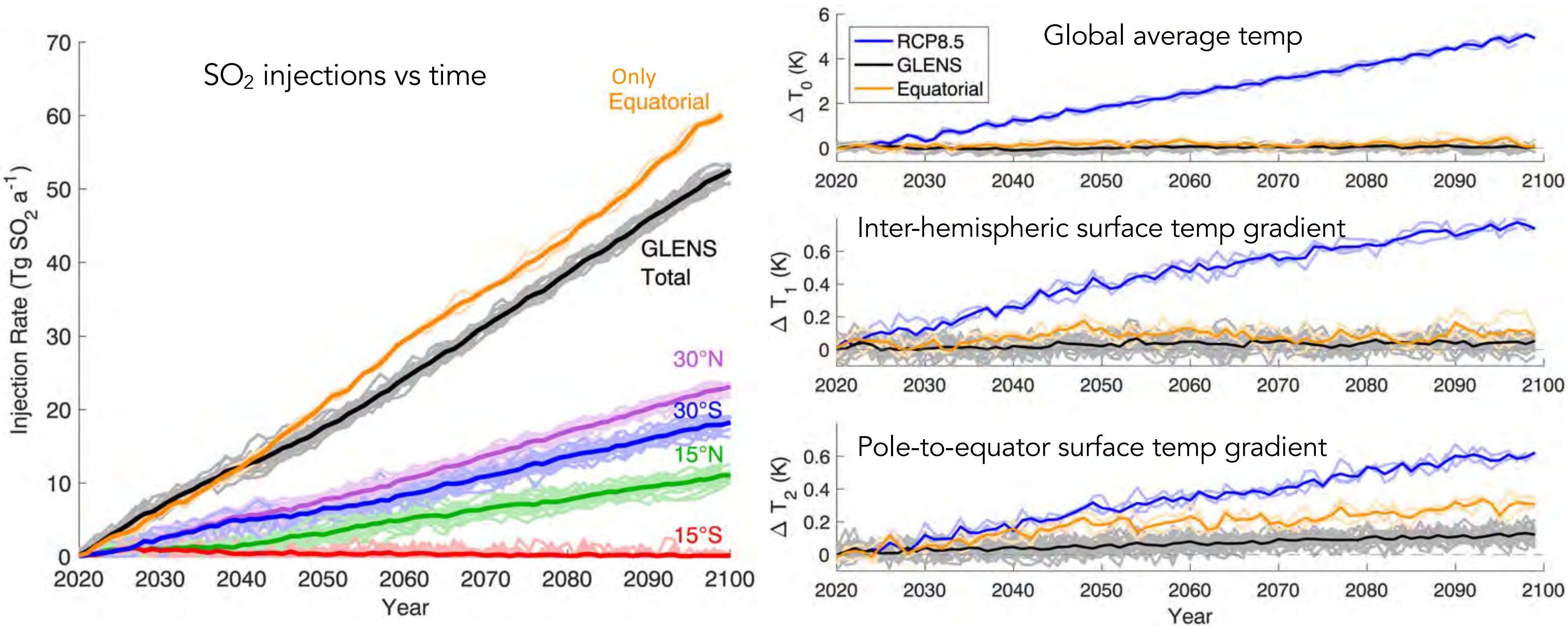
- Multiple injection points avoid large gradients in temperature reductions
- Minimize residual climate impacts such as regional temperature and precipitation changes, shifts in tropical precipitation.
- Some strategies target minimising impacts on stratospheric ozone (e.g. injection material and seasonality of injection).
- Consider practical limitations of delivery systems.

Single point versus multiple-point injections



UNEP/WMO 2022Ozone Assessment

How much injected sulfur (SO_2) is needed for RCP8.5?



- The amount of SO_2 needed to stabilize surface temperature increases with time.
- As a comparison, Mt. Pinatubo injected between 10 and 20 Tg of SO_2 in 1991.
- The required SO_2 injection rate in 2100 is 3-6 Pinatubo eruptions per year. The GLENS experiment injected SO_2 5km above the local tropopause.

Kravitz 2019: https://doi.org/10.1029/2019JD030329

Are there unintended consequences for cooling the Earth with SRM?

All solar radiation modification methods

- Cannot fully offset the widespread effects of global warming (e.g., precipitation)
- Risk of termination shock
- Uneven inter-hemispheric response
- Continued ocean acidification
- Reduced sea level rise

SAI method

- Stratospheric ozone layer changes
- Weakened hydrological cycle
- Tropospheric circulation and regional climate changes
- Impact on acid rain
- Impact on tropospheric ozone
- Impact on vegetation and crops
- Impact on surface ultraviolet (UV) and visible radiation

Montreal Protocol on Substances that Deplete the Ozone Layer

- Cooling the Earth with stratospheric aerosol injection (SAI) is expected to have unintended consequences of changing stratospheric ozone chemistry and stratospheric heating which potentially alters the global ozone distribution

↓

- The Montreal Protocol parties asked the Scientific Assessment Panel for:
  "An assessment of information and research related to solar radiation management and its potential effect on the stratospheric ozone layer."

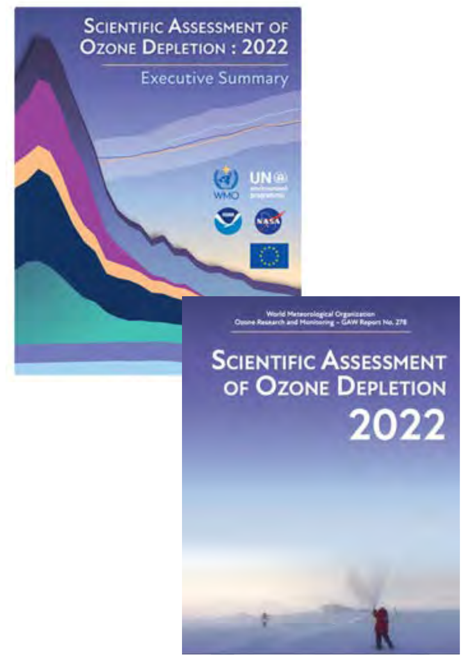
→

UNEP/WMO 2022 Scientific Assessment of Ozone Depletion

Chapter 6 – Stratospheric Aerosol Injection and Its Potential Effect on the Stratospheric Ozone Layer

Lead Authors
James Haywood (UK Met O)
Simone Tilmes (USA NCAR)

Co-Authors
Frank Keutsch (USA)
Ulrike Niemeier (Germany)
Anja Schmidt (UK)
Daniele Visioni (USA)
Pengfei Yu (China)

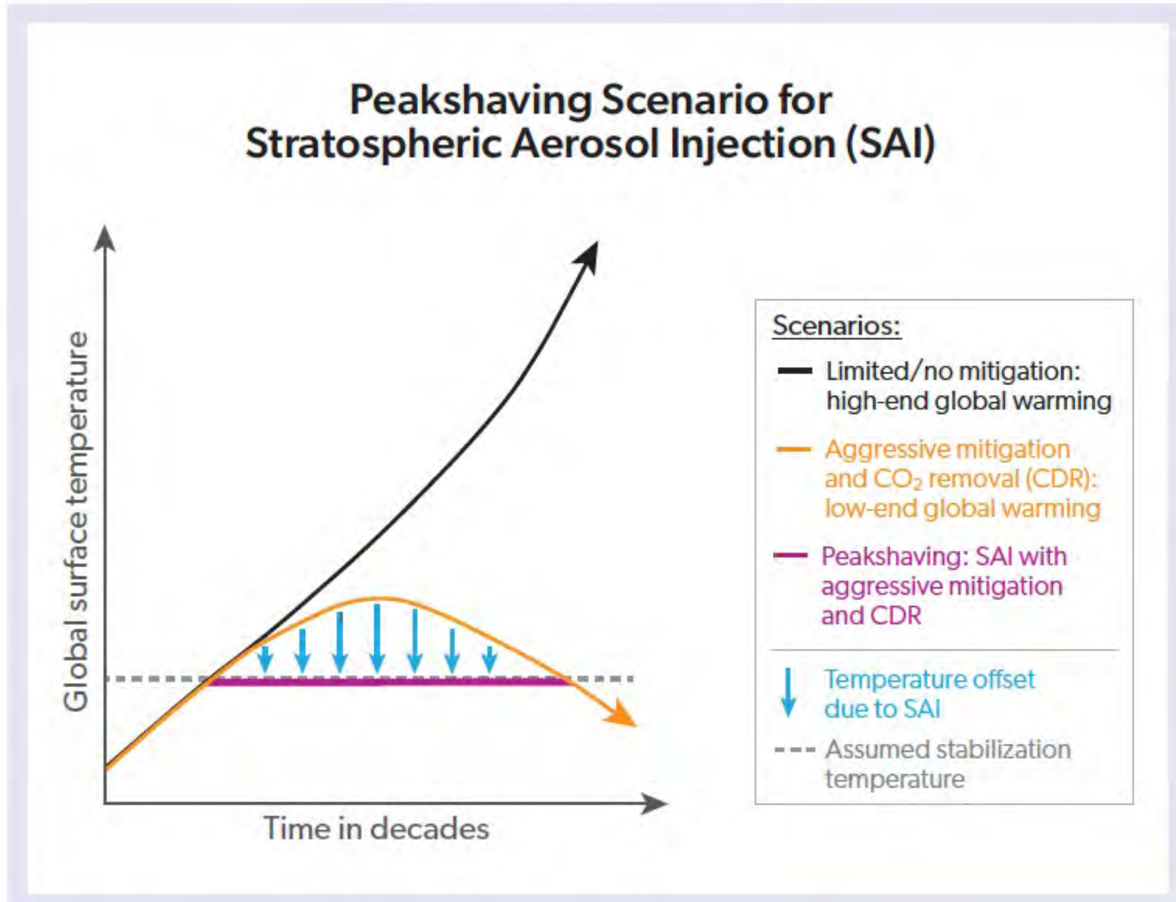


https://csl.noaa.gov/assessments/ozone/2022/

What is the *peakshaving* scenario for climate intervention?

- The concept of the peakshaving scenario is an essential framework to discuss SAI options

- The unlimited implementation of SAI seems unlikely because of the unintended consequences



UNEP/WMO 2022 Ozone Assessment Executive Summary, Figure ES-7

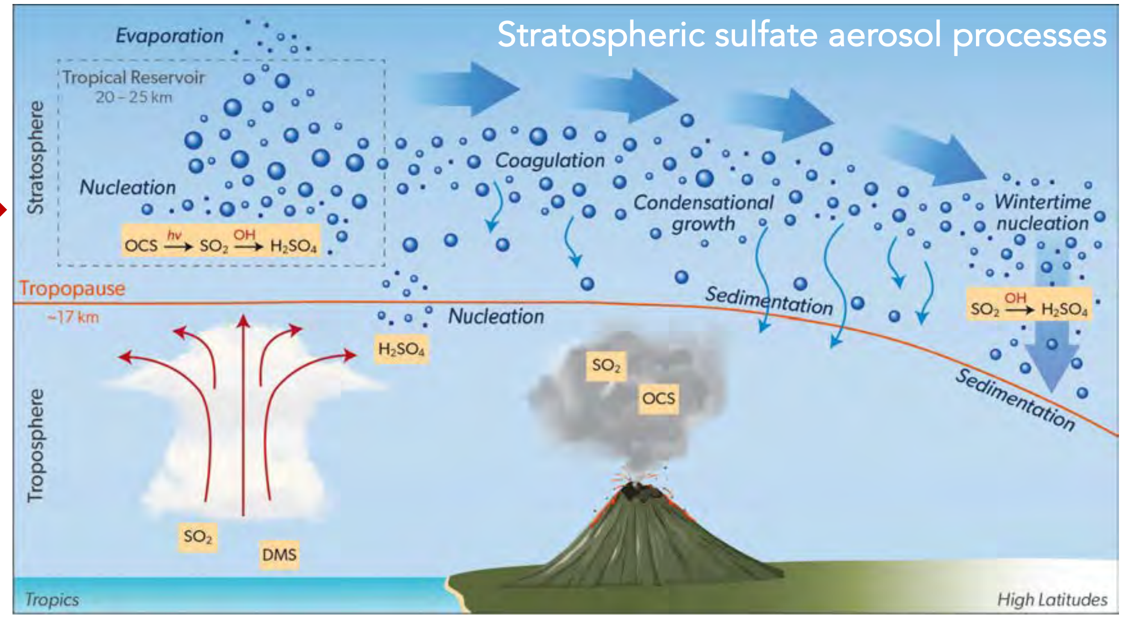
What are the mechanisms for SAI impacts on ozone?

- The combined effects of large-scale, long-term SAI on ozone mainly are driven by
    - i) reactions on increased aerosol (small particles) amounts
    - ii) aerosol-induced heating of the stratosphere
    - iii) stratospheric halogen and nitrogen concentrations

which change stratospheric ozone chemistry and stratospheric dynamics

- Effects are an increase or decrease of ozone, depending on latitude/altitude and season, injected material, halogen and nitrogen content and changes in water vapor.

- Aerosol-induced heating can cause a general increase of ozone concentrations in the tropics and mid- to high latitudes through enhanced transport from the tropics to high latitudes.



Climate intervention strategies require a control panel and not an on/off switch.

UNEP/WMO 2022 Ozone Assessment, Figure 6-3

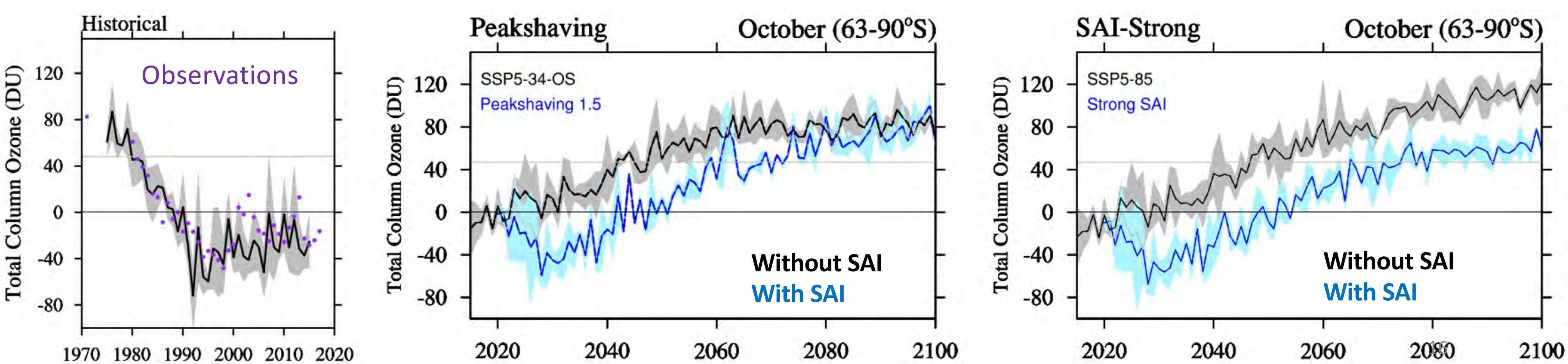
What are the modeled SAI impacts on future polar and global ozone?

- Future Total Column Ozone (TCO) change is primarily impacted by halogen loading and climate change
- Additional significant changes due to SAI (based on existing model studies starting in 2020 and stabilizing global surface temperatures at 1.5°C) include:
  - **Antarctica:** Significant ozone depletion is simulated in spring, with magnitudes dependent on the injection rate and timing. Simulations suggest an ozone hole no deeper than that already experienced (in the 1990s) considering 2020 or lower chlorine levels.
  - **Arctic:** Simulated ozone depletion is much more uncertain and can reach around 5% compared to no SAI.
  - **Mid- and high latitudes:** In the winter Northern Hemisphere, an ozone increase is simulated by the end of the century under moderate and strong SAI compared to no SAI.

UNEP/WMO 2022 Ozone Assessment, Chapter 6

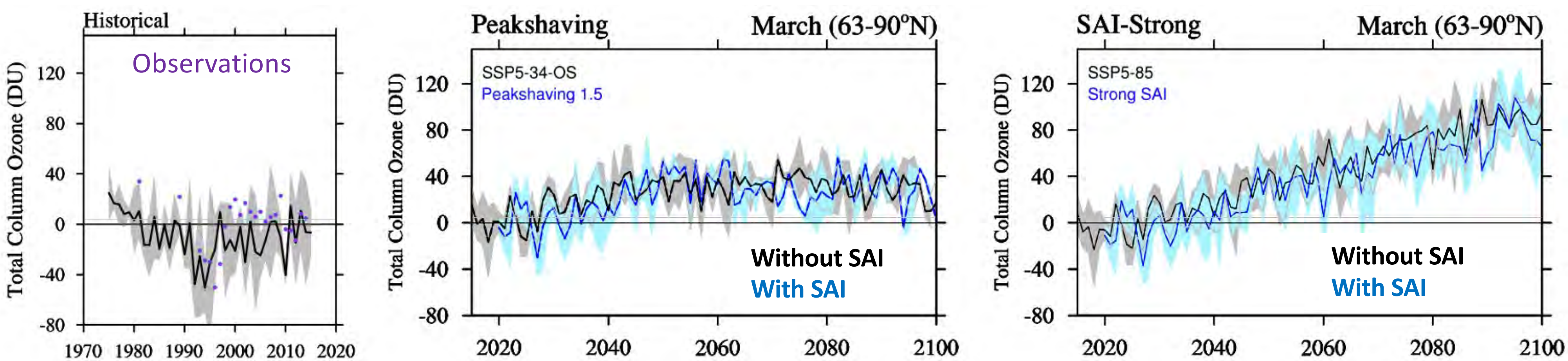
SAI impact the Antarctic Ozone Hole

- **The phase-in of SAI** to achieve a cooling of 0.5°C in the first 20 year, assuming 2020 (halogen) conditions, results in an initial reduction of TCO by around **55 +/- 15 DU**, which brings TCO values close to the observed minimum in the 1990s.
- Antarctic ozone is reduced by **55 to 65 DU** in October throughout the 21st century **for strong SAI** and continuously increasing injections. In this case, the ozone hole recovery from ozone-depleting substances (ODSs) is delayed between 25 to 50 years. Different models and strategies can change these numbers by +/- 20 DU.
- **An early phase-out of SAI** leads to smaller reductions towards the second half or the 21st century



SAI impact on Arctic Total Column Ozone (TCO) in Spring

- In the Arctic in spring, the injections of SAI to achieve cooling of 0.5°C by 2040 (starting in 2020), result in TCO reductions between **13 DU +/- 10 DU and 22 +/-21 DU** (~5% reduction) compared to no SAI based on two different models.
- Large uncertainty due to both chemical changes and dynamical variability in this region
- Smaller initial injection rates and change after 2040 are not significant.

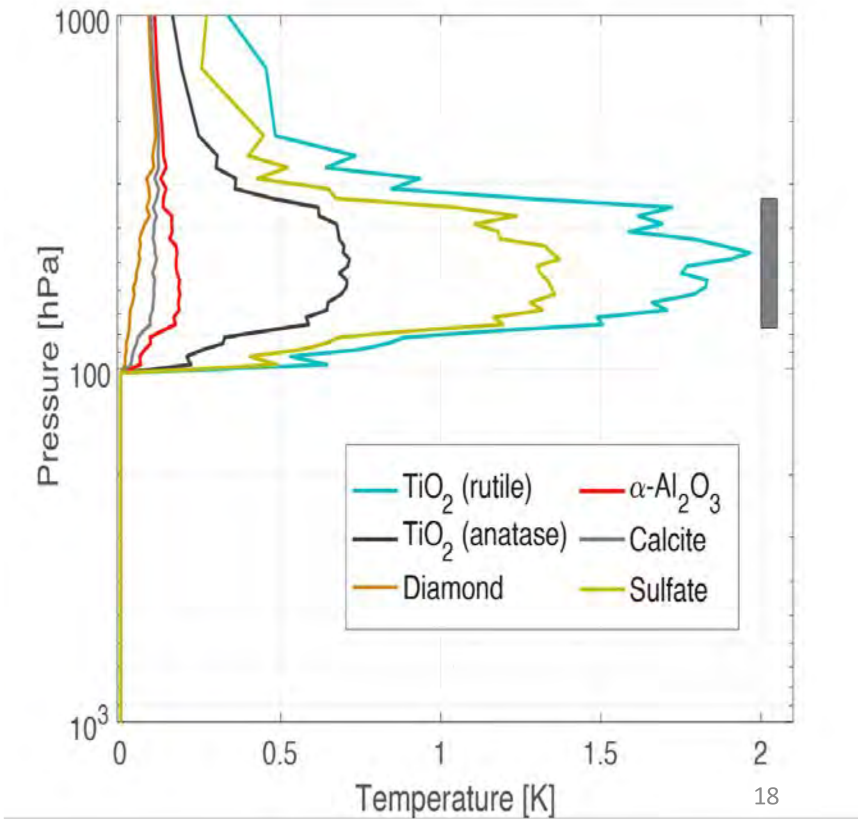


SAI effects using other material than sulfate

The injection of aerosols other than sulfate is expected to change the effects on ozone via associated changes in heterogeneous chemistry and dynamics and transport.

- Aerosol types that are more chemically inert and absorb less solar radiation may reduce chemical and dynamical impacts on stratospheric ozone respectively.
- Laboratory tests and climate model simulations to quantify these effects have yet to be performed.

Stratospheric temperature change with aerosol type to achieve 1 Wm^2 shortwave RF



SAI and UV changes

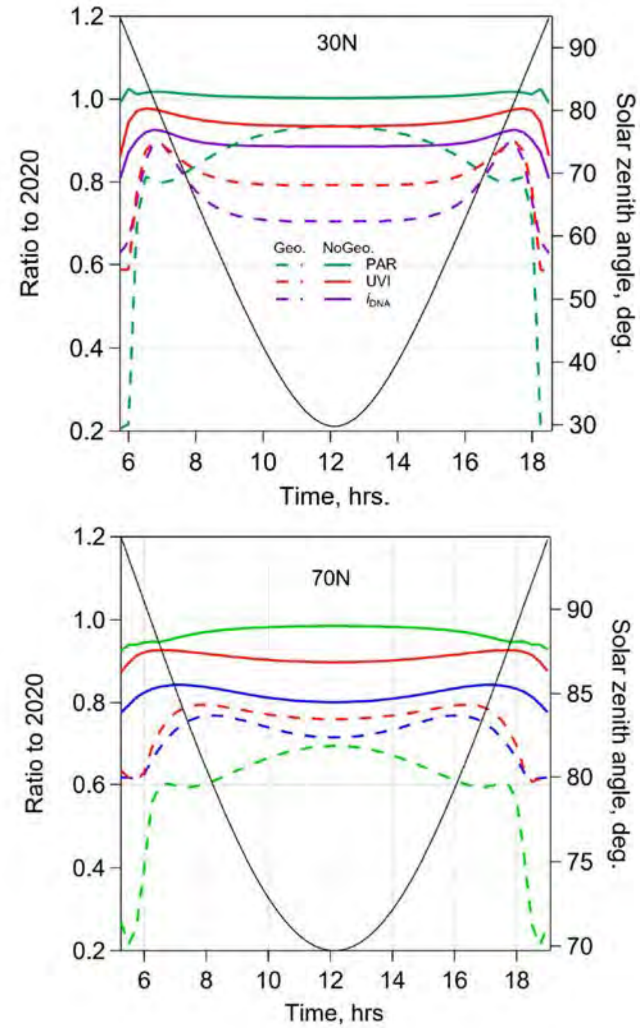
• Surface radiation changes from stratospheric aerosol are studied by the Montreal Protocol Environmental Effects Panel (EEAP)

• Important unintended consequences from SAI are changes in biologically active radiation at the Earth's surface, in March 2080 relative to March 2020, for:

- DNA-weighted irradiance iDNA (blue),
- UV index (UVI) (red), and
- photosynthetically active radiation PAR (green),

without geoengineering (solid curves) and with sulfur geoengineering (dashed curves).

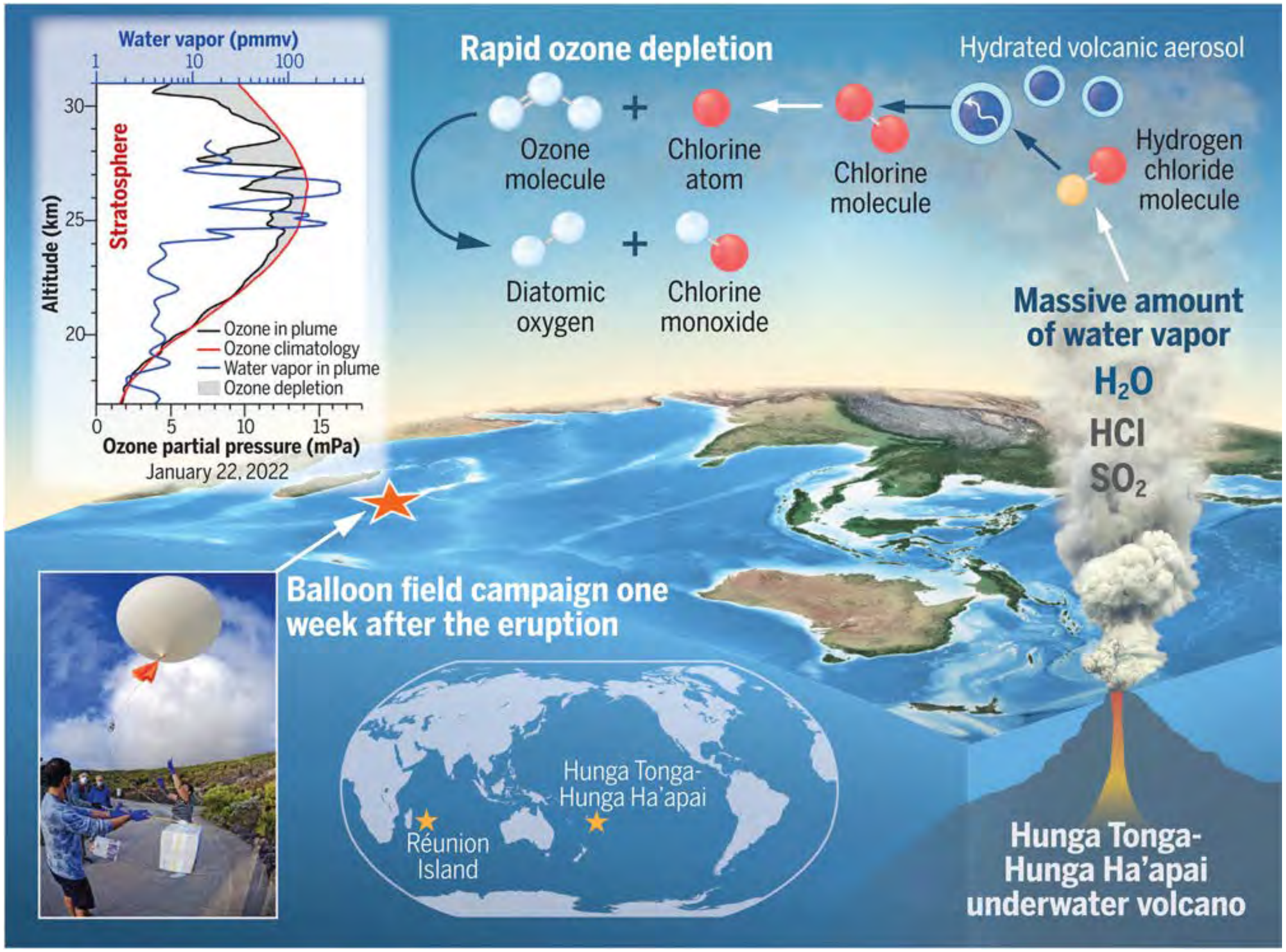
Note: The geoengineering simulation was designed to keep global surface temperatures at 2020 values while using the RCP8.5 greenhouse gas scenario between 2020 and 2099.



EEAP 2022 Assessment Report
Madronich et al., *Atmosphere* 2018

Hunga Tonga-Hunga Ha'apai Volcanic Eruption of January 2022

- The Hunga Tonga Hunga Ha'apai volcano resulted in rapid ozone loss in the lower stratosphere due to surfact halogen chemistry
- SPARC/WCRP is conducting an assessment of the HT eruption impacts due for completion in December 2025.
- Understanding volcanic injections will improve assessment of SRM projected impacts.

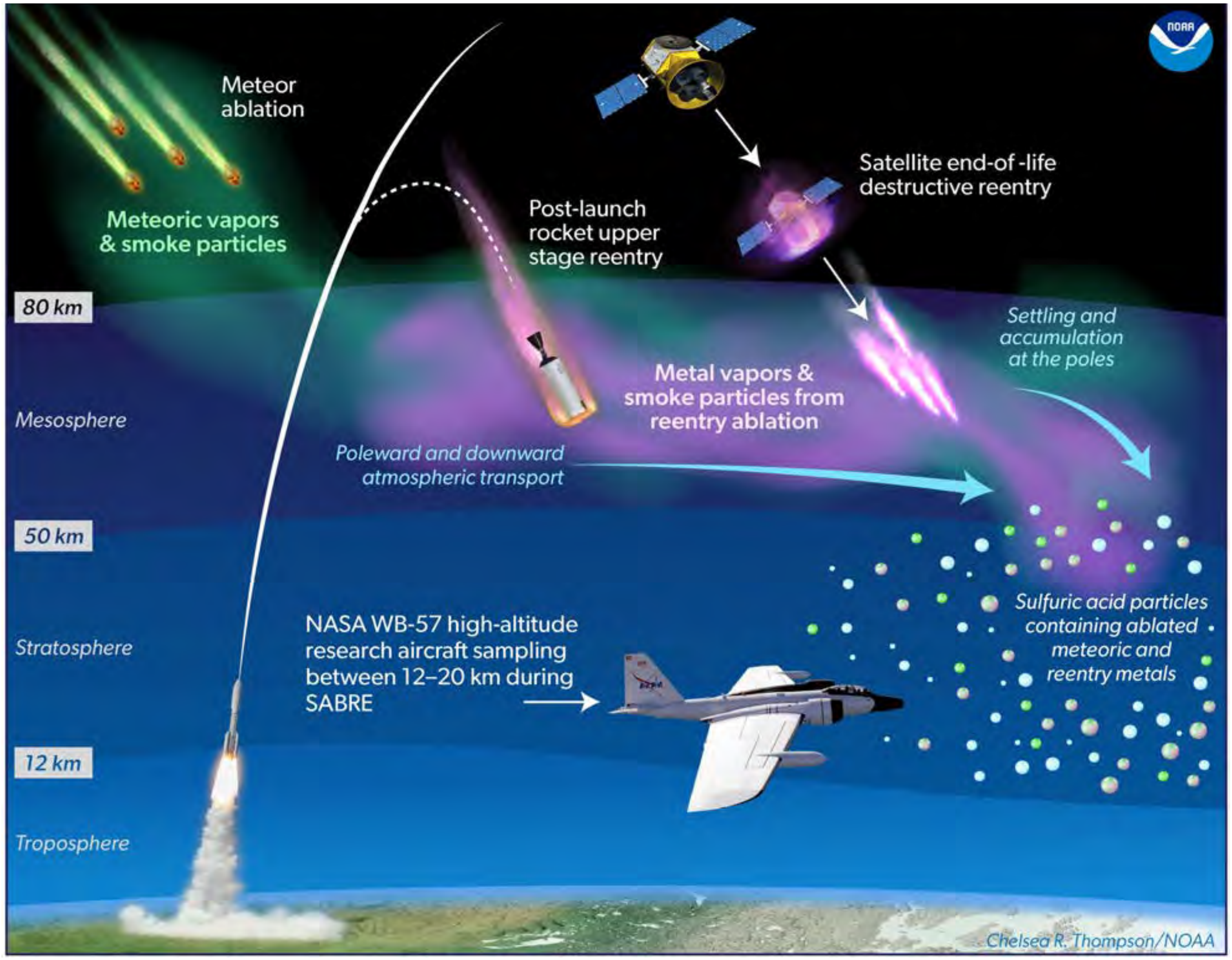


Evan et al., *Science*, 2023
[DOI: 10.1126/science.adg2551]

https://www.sparc-climate.org/2023/01/27/new-sparc-activity-on-hunga-tonga-stratospheric-impacts/

Discovery of space debris in stratospheric particles

- Airborne particle sampling identified over 20 distinct elements from spacecraft and satellite reentry, including silver, iron, lead, magnesium, titanium, beryllium, chromium, nickel, zinc, and lithium.
- An estimated 10% of stratospheric sulfuric acid particles currently contain traces of metals from rockets and satellites.
- The consequences for the surface reactivity of these stratospheric particles is unknown at this time.



Murphy, D.M, *PNAS*, doi:10.1073/pnas.2313374120, 2023.

The UNEP One Atmosphere Report on SRM

- The *One Atmosphere Report* provides an extensive set of Key Questions and Answers about SRM

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https://www.unep.org/resources/report/Solar-Radiation-Modification-research-deployment

Concluding Remarks

- Solar radiation management (SRM) is the only known method to cool the Earth rapidly within a few years after deployment.

- Stratospheric Aerosol Injection (SAI) has been suggested as a potential SRM mechanism for reflecting sunlight back to space thereby offsetting some surface warming and other climate impacts.

- Global warming has reached approximately 1.2˚C above pre-industrial levels. Climate scenarios indicate continued future warming without strong mitigation and SRM.

- The peakshaving scenario is an essential framework to discuss SAI options

- Simulated ozone changes from SAI are highly scenario and model dependent → large uncertainties → active area of research.
    - Strong SAI would increase Antarctic ozone depletion with magnitudes dependent on the injection rate and timing.
    - Strong SAI would increase total column ozone (TCO) in mid-latitudes (40–60˚N) in the winter Northern Hemisphere

- The evaluation of the unintended consequences of SAI requires focused research

- Studying volcanic eruptions will inform SAI research

- Materials other than sulfate aerosol may be more effective in SAI implementation