Stratospheric Aerosol Climate Intervention

Efficiency, Impacts and Uncertainties

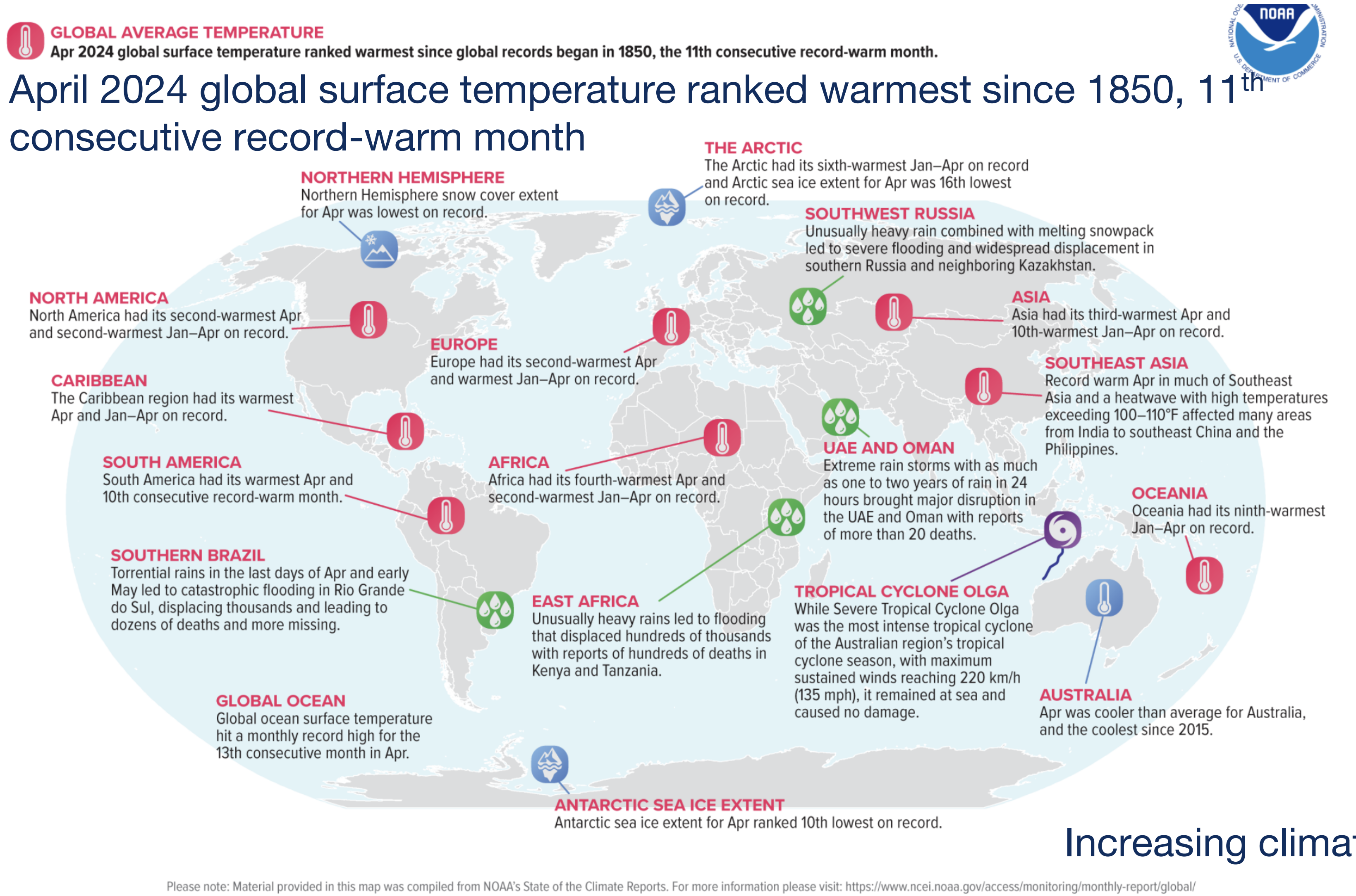
Simone Tilmes,
National Center for Atmospheric Research,
Atmospheric Chemistry Observations & Modeling Lab

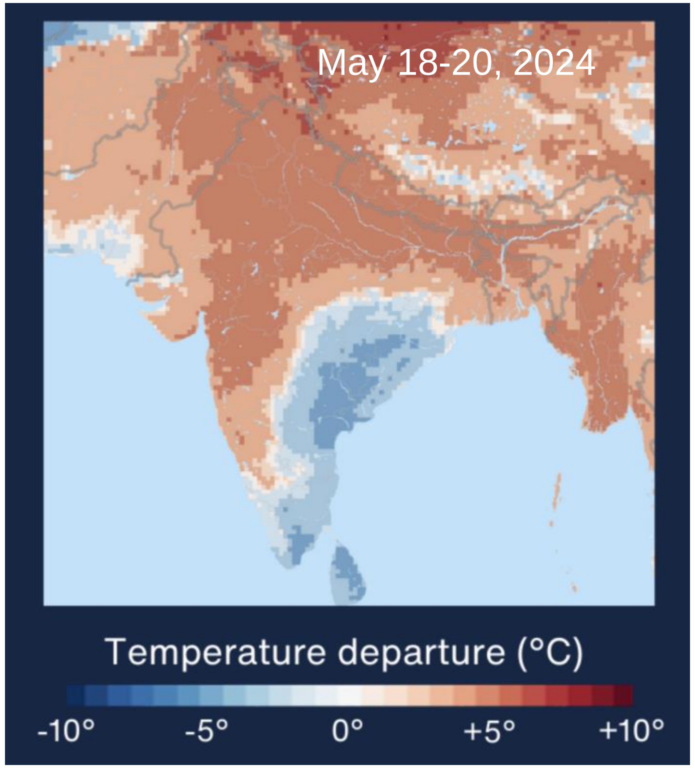
STIPMEX workshop, 2 - 7 June 2024 in Pune, India

This material is based upon work supported by the NSF National Center for Atmospheric Research, which is a major facility sponsored by the U.S. National Science Foundation under Cooperative Agreement No. 1852977.

Climate Emergency Now. Where are we going in the future?

April 2024 global surface temperature ranked warmest since 1850, 11th consecutive record-warm month



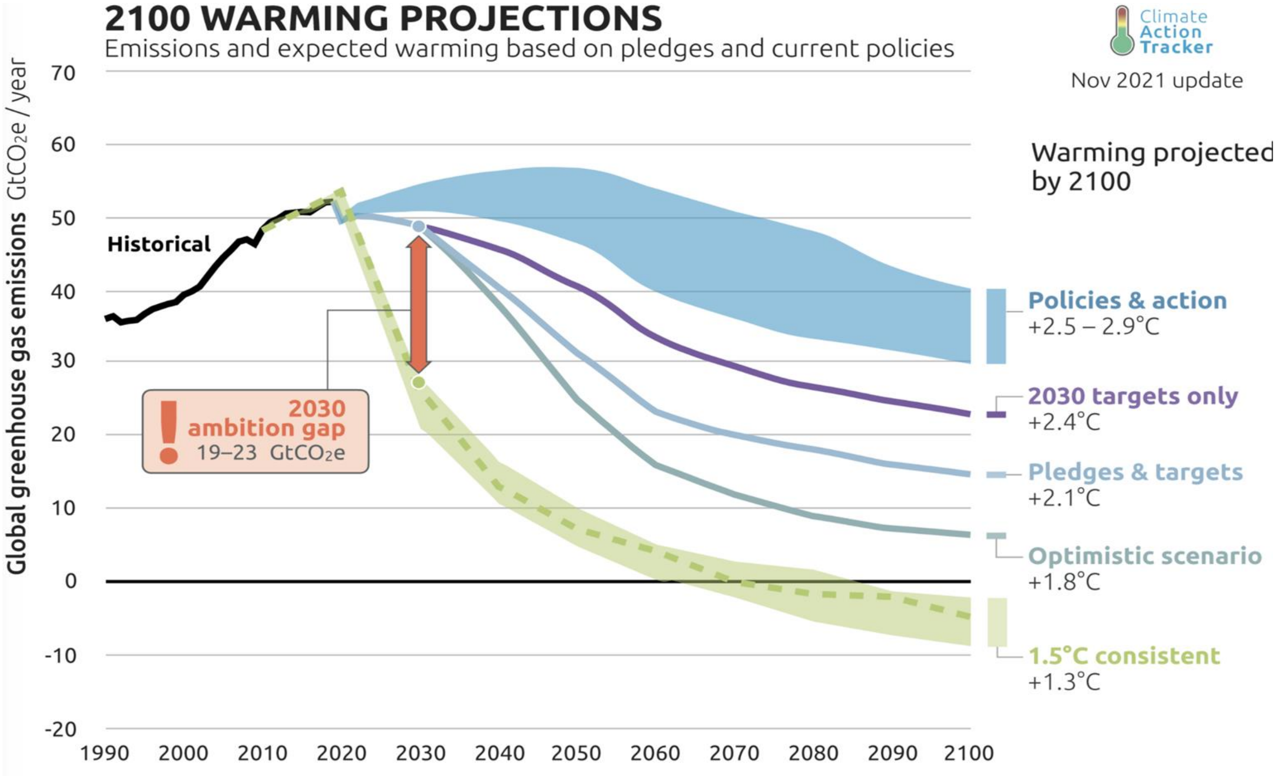


Parts of northern India scorched by extreme heat with New Delhi on high alert

On Friday, parts of New Delhi reported up to 116 degrees Fahrenheit.

Increasing climate records throughout the world

Climate Emergency Now. Where are we going in the future?



Global Warming Acceleration, Sulfur emissions and Observations

James Hansen, Pushker Kharecha, Makiko Sato, 2024

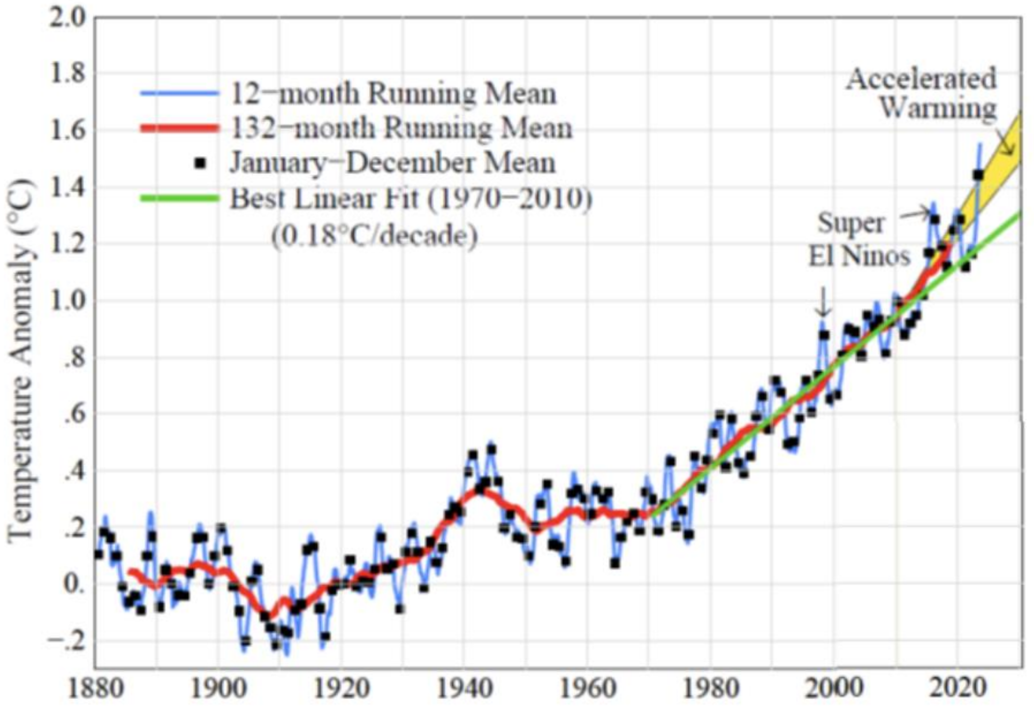
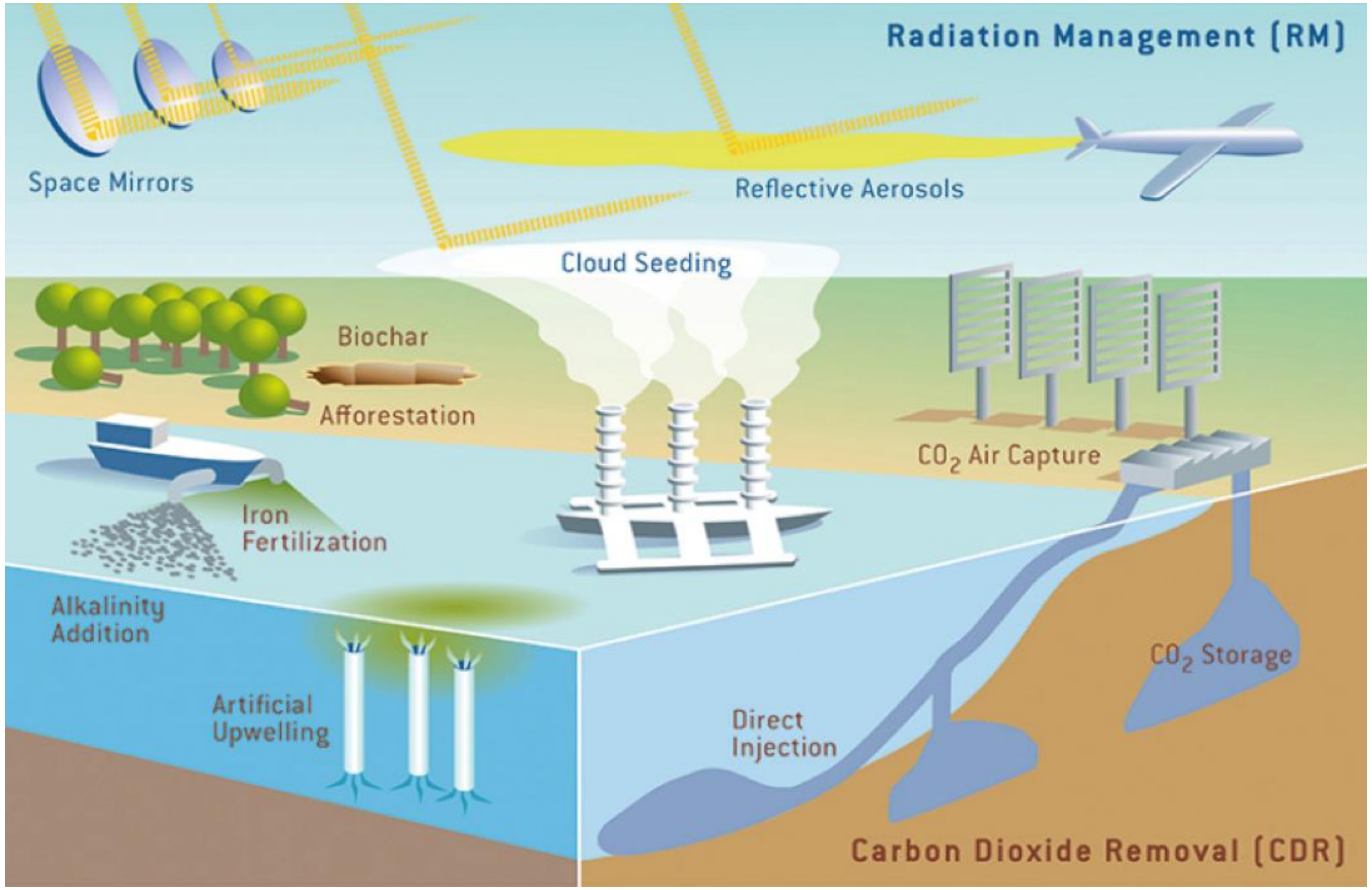


Fig. 1. Global temperature relative to 1880-1920 based on the GISS analysis.[1],[2]

- We may have already reached important climate targets
- Impacts and risks are increasing with increasing global surface temperatures
- Increased endanger of vulnerable societies and ecosystems

Climate Solutions to reduce Climate Change and its Impacts



Reduce global warming through stabilization and reduction of atmospheric GHGs

- Mitigation
- Negative emission technologies

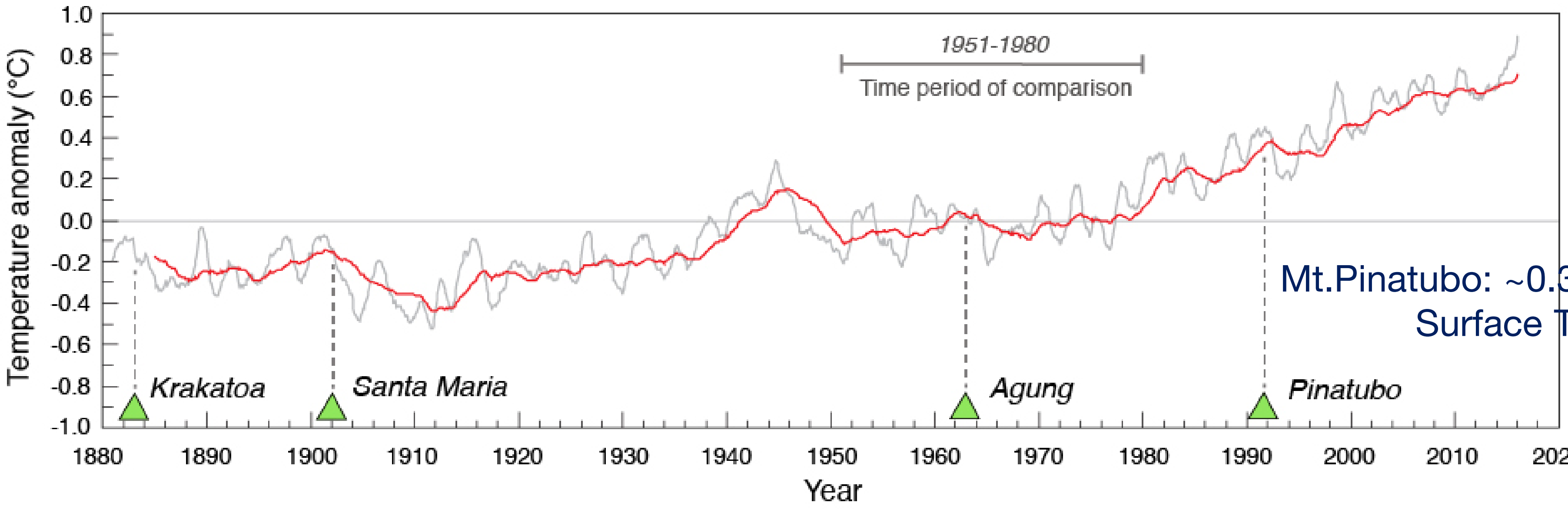
Reduce global warming through artificially changing the reflectivity of the planet

- Stratospheric Aerosol Intervention
- Marine Cloud Brightening
- Surface Albedo Modification
- Planetary Systems

Reduction of impacts and suffering

- Adaptation
- Regional SRM

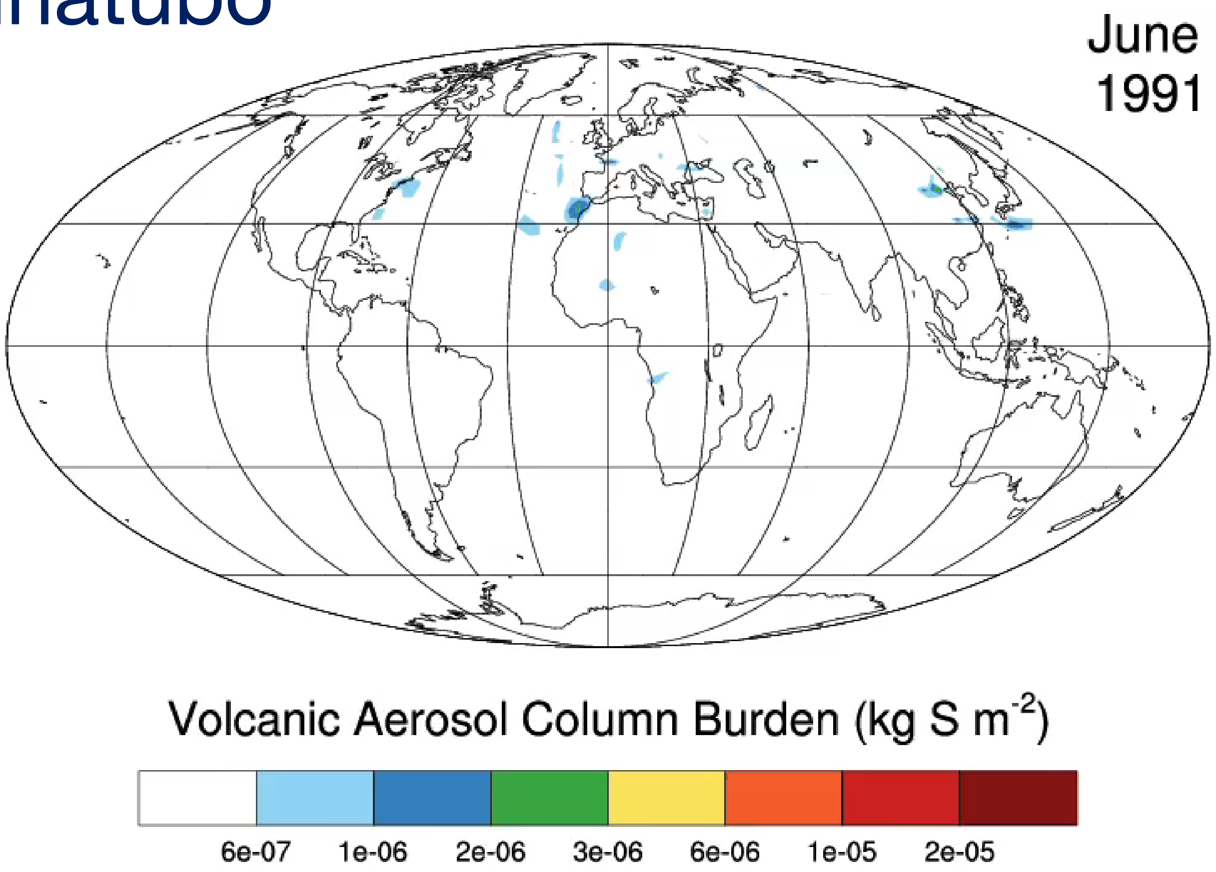
Natural Analogues: Volcanoes



Mt.Pinatubo: ~0.3degree reduction in Surface Temperature

Natural Analogues: Volcanoes

Pinatubo



Mills et al., 2016

Tropical volcanic eruption leads to highest aerosol concentrations in the Tropics but aerosol spreads to both hemispheres

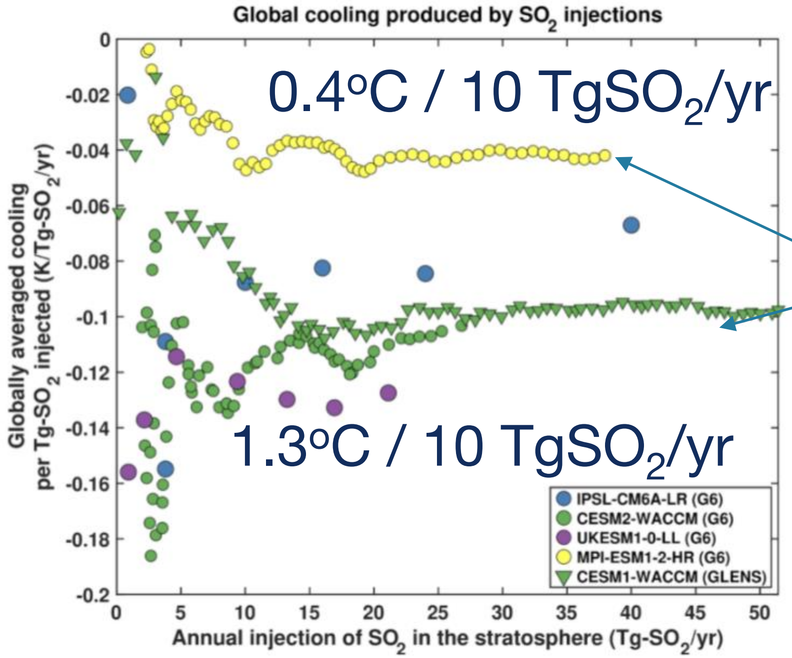
Stratospheric Aerosol Interventions
-> Continuous injections of sulfur or aerosols to achieve global dimming
-> Requires different injection locations for more optimal aerosol distribution
-> Long-term continuous applications

Considered to be the most effective global method to reduce surface temperature

Efficiency: SAI Effects on Surface Temperature and Uncertainties

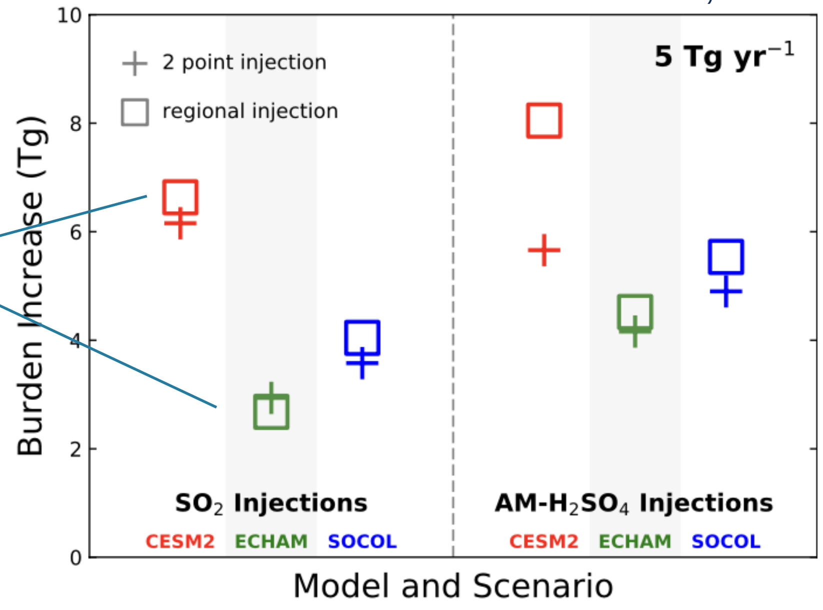
WMO2022

Global Cooling per $TgSO_2/yr$



Aerosol burden for the same injection amount

Weisenstein et al,. 2021



Modal Model
1deg res.

Sectional Model
2.8deg res.

Modal Model
2.8deg. res.

Large model spread in forcing and cooling efficiency of SAI (factor 2)

-> For $10TgSO_2/yr$ injections model reach between **0.4 and 1.3 degree of cooling**

Implications for uncertainties in the required injection amount

-> More sulfur injections result in more impacts (climate and ozone)

-> Economical uncertainties on costs and technical aspects

Technical Feasibility of Stratospheric Aerosol Interventions

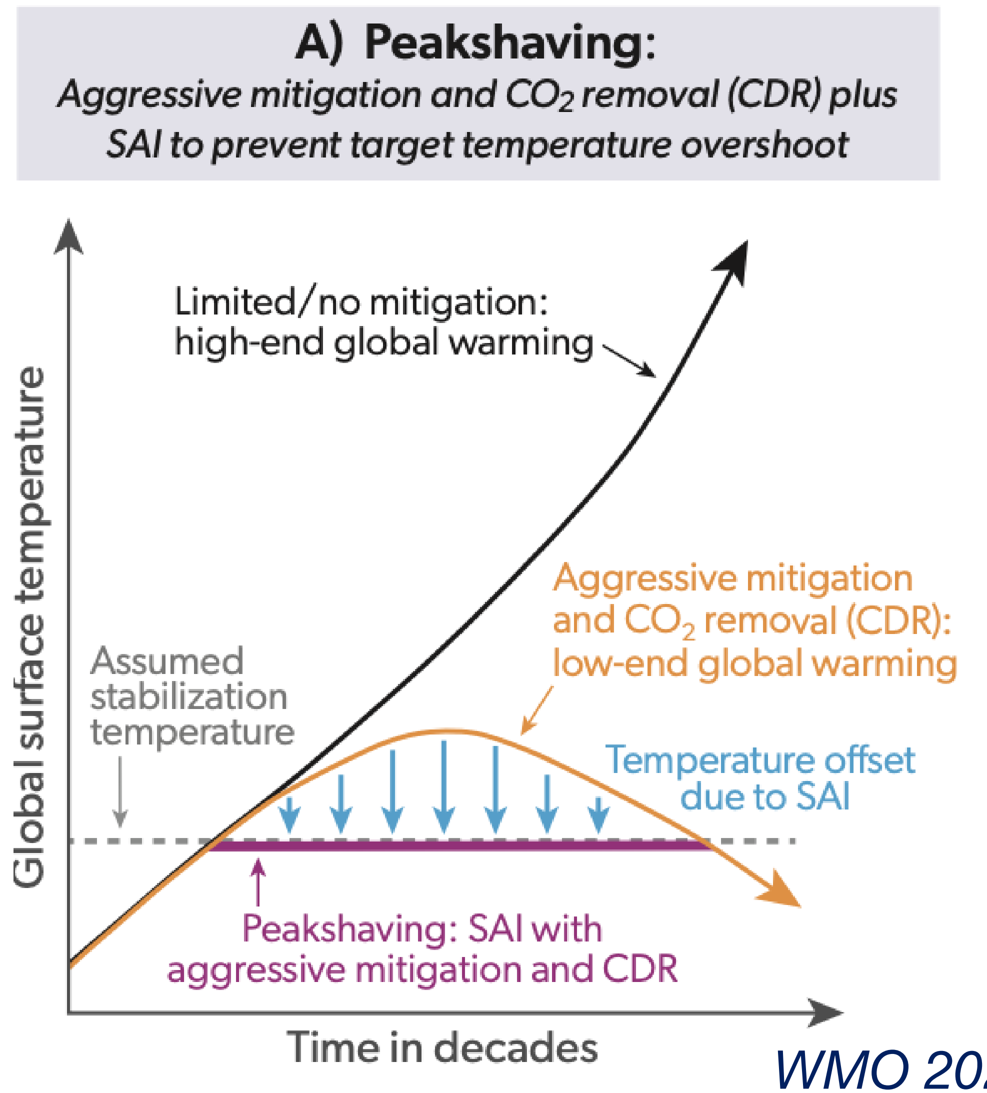
Requirement: lofting materials to 20km

- Aircraft
- Balloons
- Rockets
- Missiles
- Tethered Hose
- Solar lofting combined with absorbing aerosols

More seriously considered so far:

- Needs for a newly developed high altitude tanker aircraft
- Costs: 1.4 billon/yr for 1 $TgSO_2$ injections, 4000 flights in year one and steadily increasing
- At least 8-10 times the amount to cool the surface by 1K
- Mt Pinatubo injected around 14 $TgSO_2$ (Fisher et al., 2019)

Scenarios and Strategies of Stratospheric Aerosol Interventions



WMO 2022

Peakshaving Scenario: Uses SAI as stop-gap measure and as little as possible (in magnitude and time) to prevent side effects. Goal is to reduce impacts of climate change.

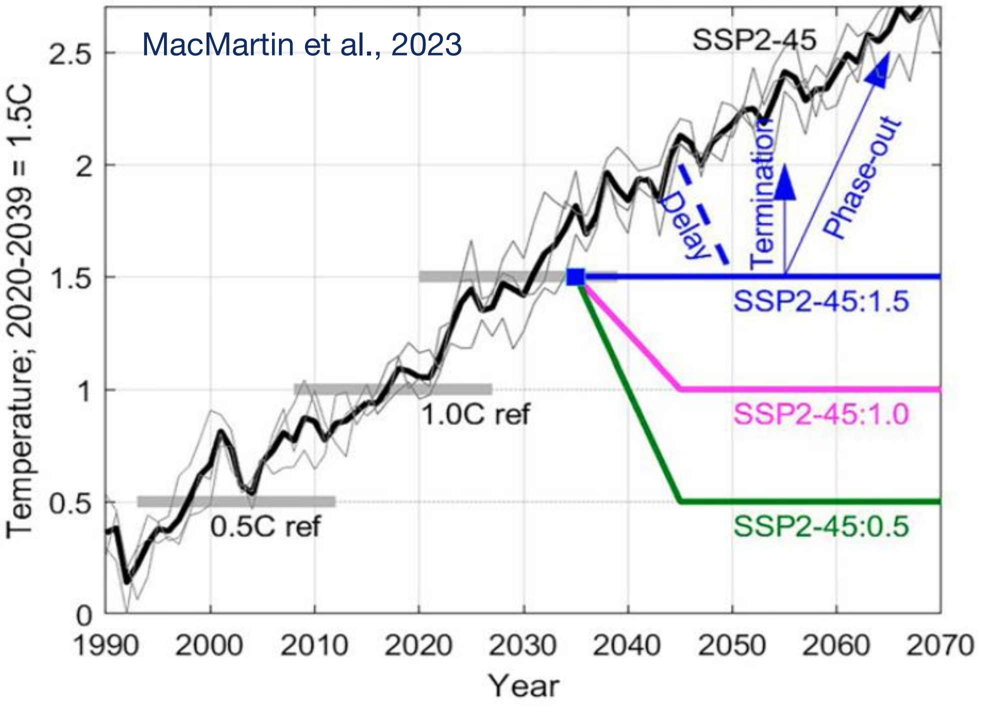
Requirements (most optimistic scenario)

- ***Strong Decarbonization*** is required to keep GHG and surface temperatures towards a minimal increase
- ***Governance and Ethical requirements***: cooperative, representative, legitimate and just applications -> UNEP report, AGU ethical framework development
- ***Assessments to achieve a comprehensive understanding of benefits, risks and side effects*** -> reduce rather than increase suffering for societies and ecosystem.

Scenarios and Strategies of Stratospheric Aerosol Interventions

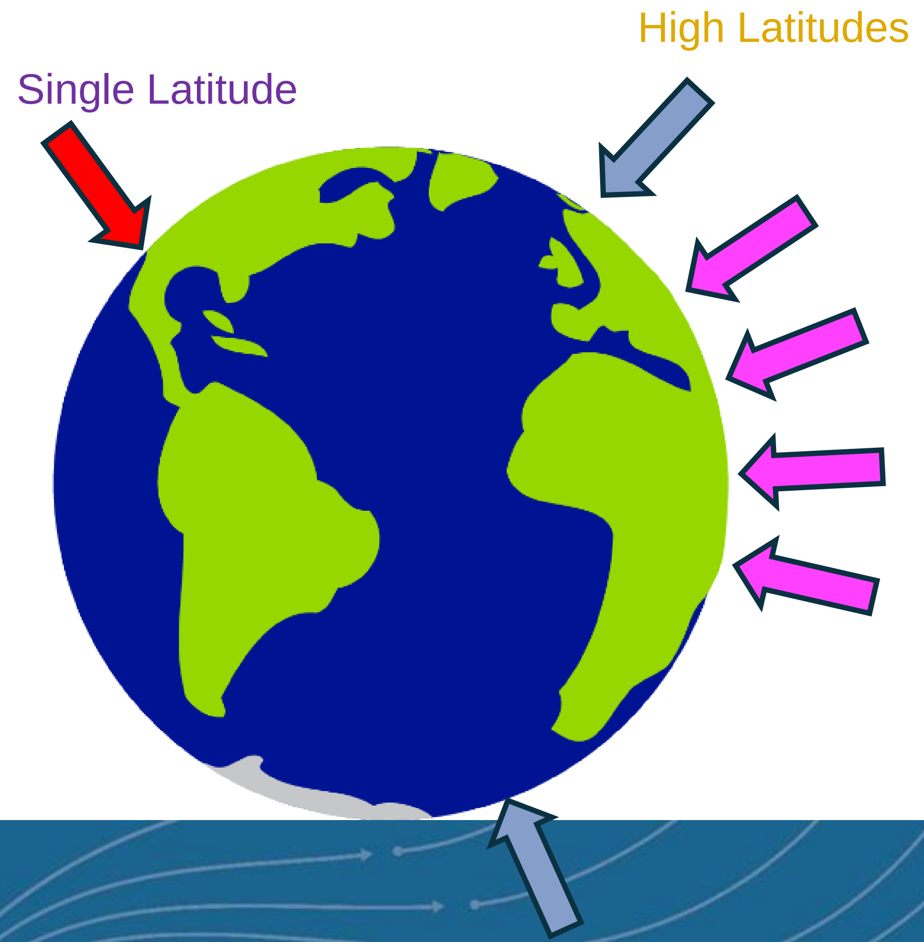
Proactive and well coordinated (international agreement), aim for specific global temperature targets or other impact relevant targets

- Multiple point injections



Reactive and less coordinated:

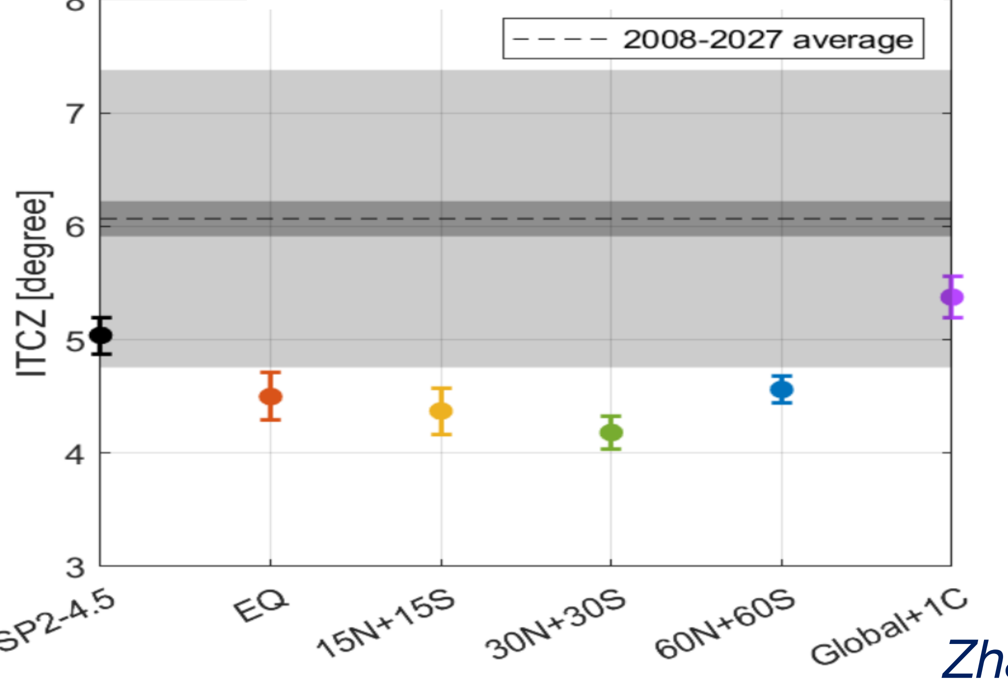
- Response to climate extremes and impacts
- Single actor or cooperations of some nations
- Single point injections



Scenarios and Strategies of Stratospheric Aerosol Interventions

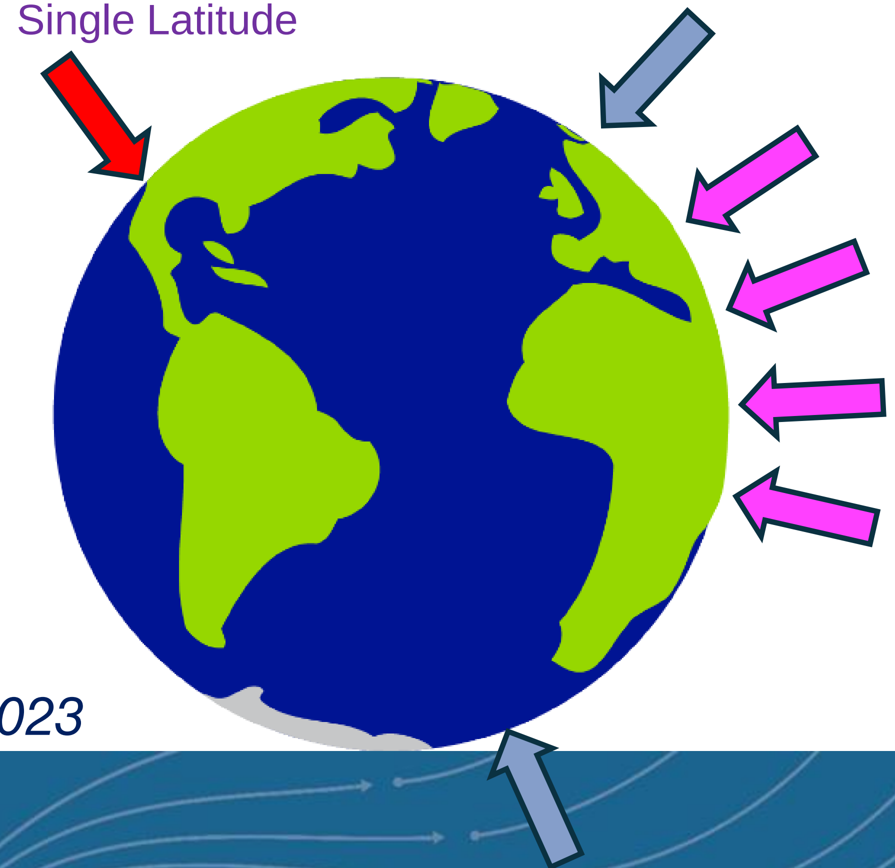
Proactive and well coordinated (international agreement), aim for specific global temperature targets or other impact relevant targets

- Multiple point injections



Reactive and less coordinated:

- Response to climate extremes and impacts
- Single actor or cooperations of some nations
- Single point injections

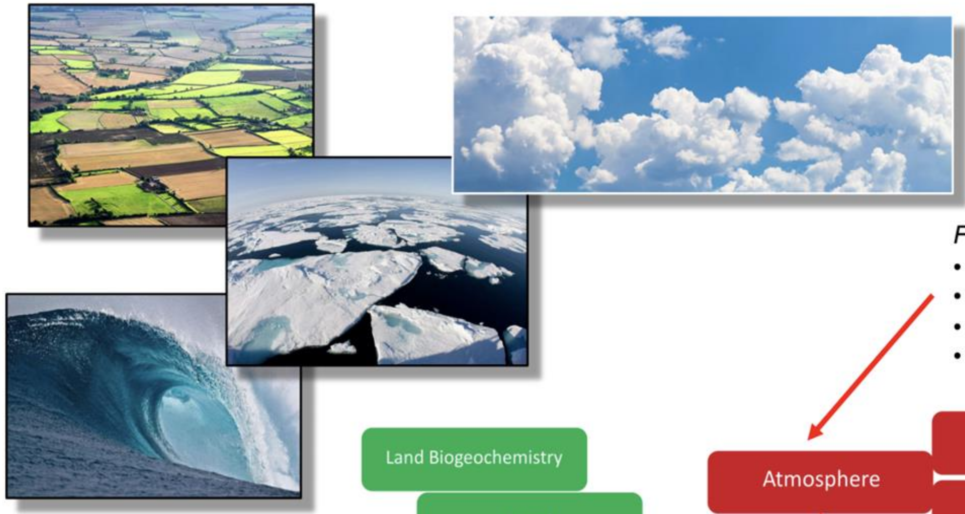


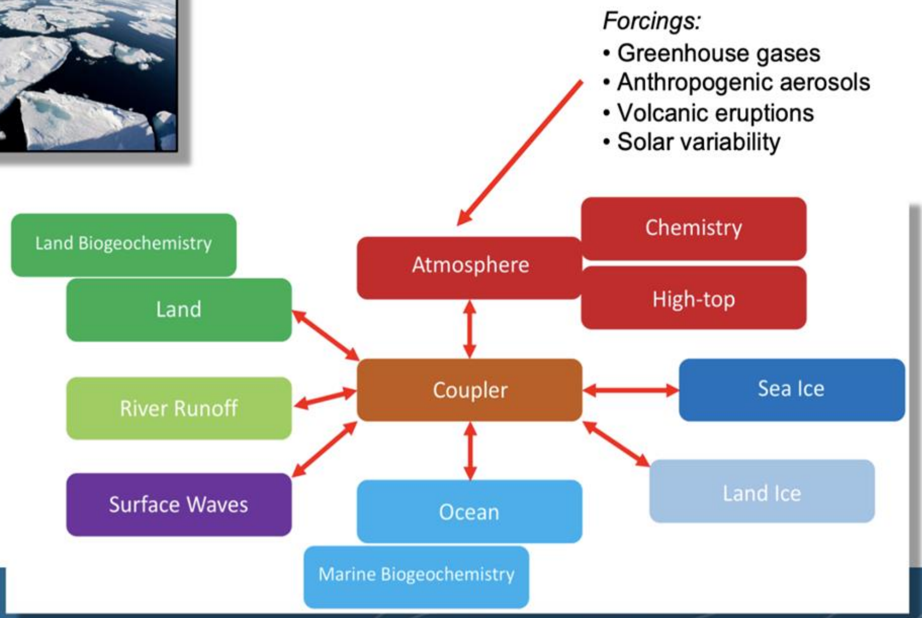
Zhang et al, 2023

Modeling Tools Required to Assess Impacts of SAI

State of the Art Earth System Models are the only tools to assess climate impacts of Climate Interventions

- Complex process in both troposphere an stratosphere are needed, cloud-aerosol and chemistry processes
- Coupling for land and ocean carbon cycle, sea-ice model, land model
- Modeling across scales: actional science application to address water, food, and health
- Evaluation: lab and field experiments and observing system, satellites, aircraft (monitor volcanoes, ship tracks)

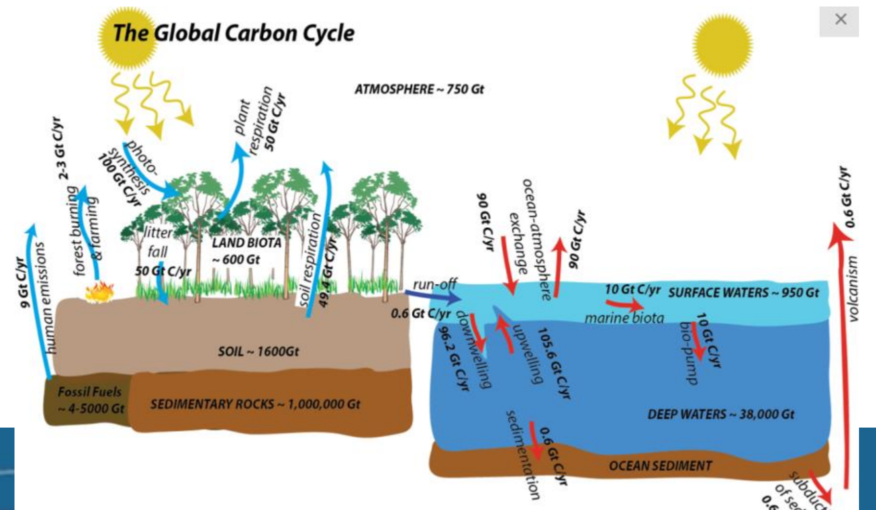




Community Earth System Model

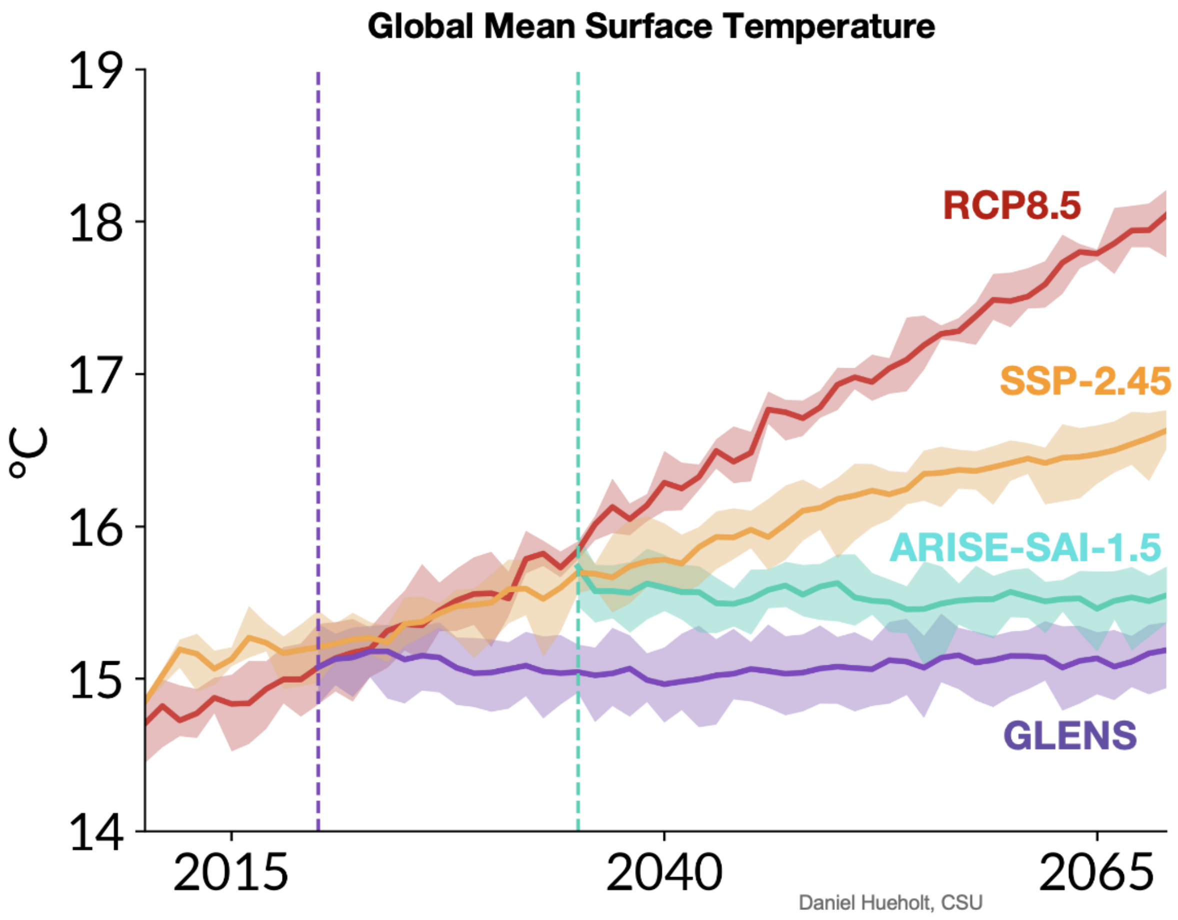
Volcanoes

Ship Tracks



The Global Carbon Cycle

Impact Assessments: Community Large Ensemble Simulations / GeoMIP



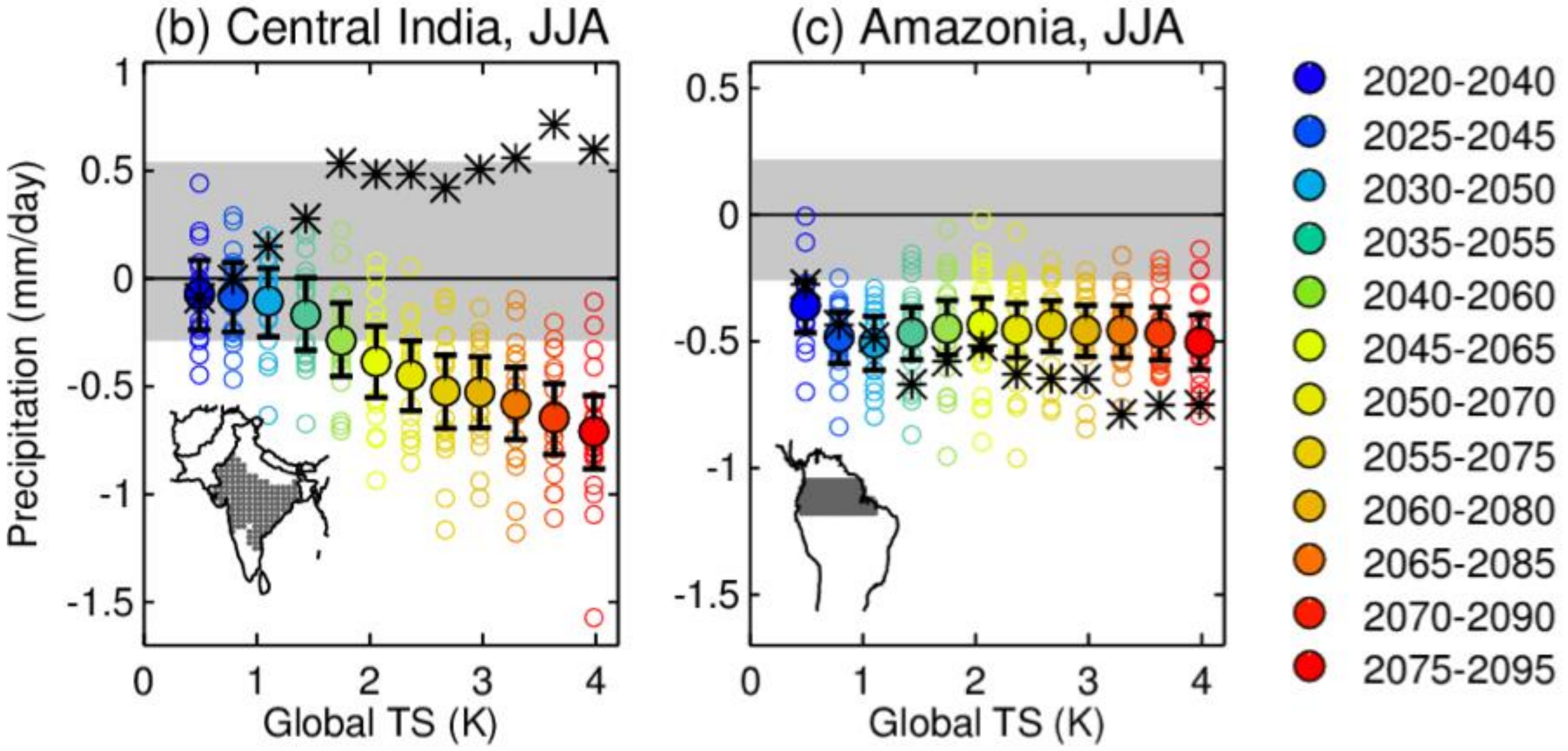
Whole Atmosphere Community Climate Model Simulations

- Geoengineering Large Ensemble Simulations (**GLENS**) (Tilmes et al., 2018): 20-member ensemble
- Assessing Responses and Impacts of Solar climate intervention on the Earth system (**ARISE**) SAI and MBC (Richter et al., 2022): 10-member ensemble

Community Resources to Study:

- Climate impacts within the natural variability
- Large signal to noise to understand processes
- Differences in scenarios and temperature targets
- Differences between different model version

Regional SAI Impacts: Precipitation Changes



CESM1(WACCM) GLENS: Impacts of Climate change and SAI for different regions
SAI (circles); RCP8.5 (stars)

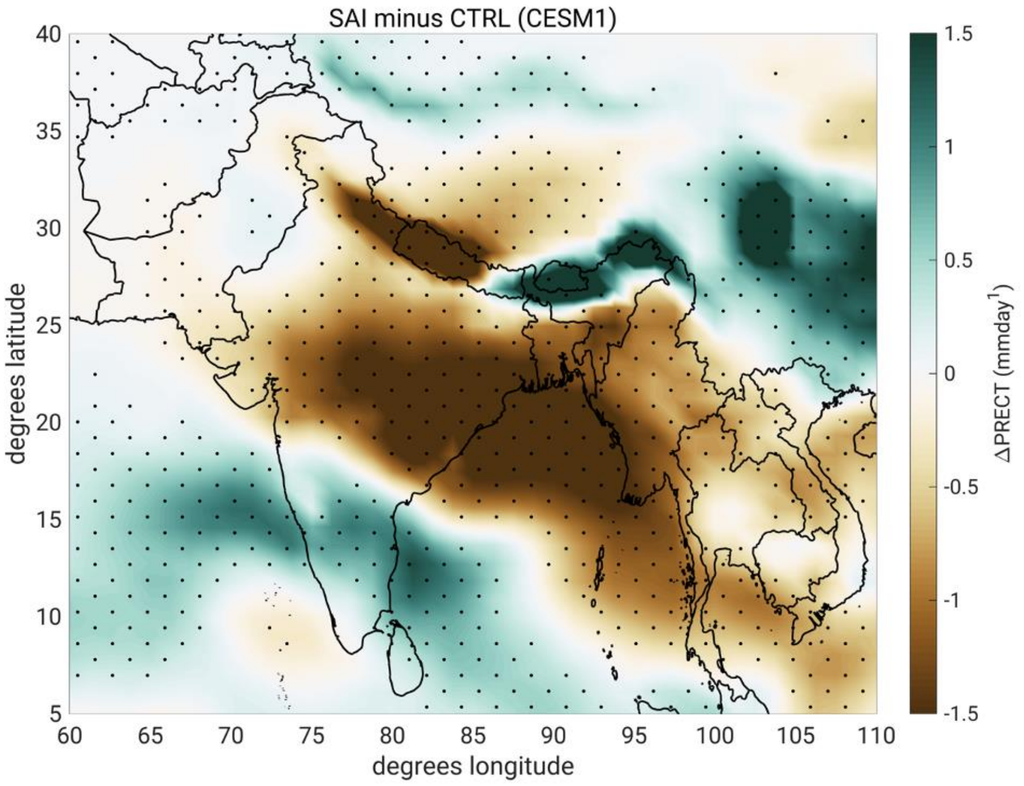
Simpson et al., 2019

Regional SAI Impacts over India: Model Differences

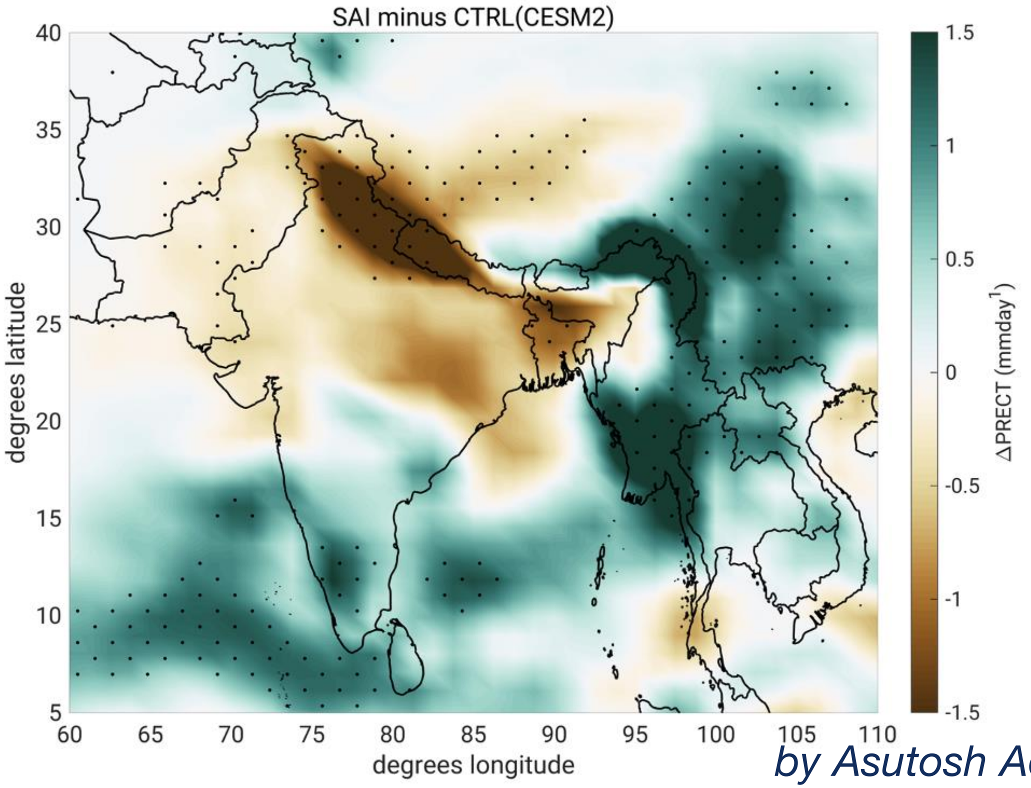
Rainfall changes in JJA during the Asian Summer Monsoon show model differences

- Need for understanding important processes that lead to changes in rainfall
- Identify implications of changes and differences for societies and ecosystems

CESM1(WACCM)
SAI (2070-2090) minus RCP8.5 2010-2030

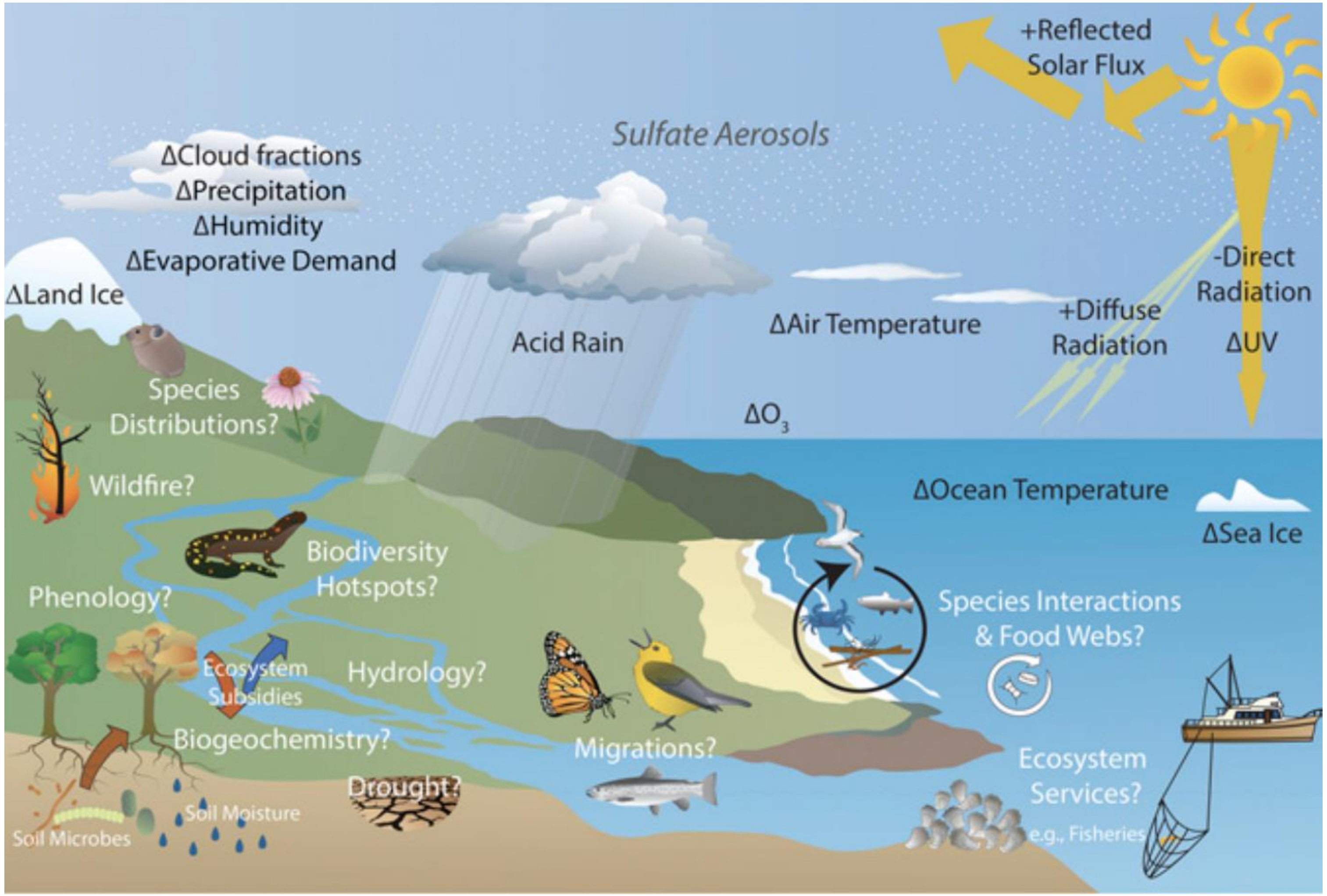


CESM2(WACCM) SSP5-8.5
SAI 2070-2090 minus SSP5-8.5 2010-2030



by Asutosh Acharya

Effects on Societies and Ecosystems



Zarnetske et al., 2020

How can we best assess impacts on societies and ecosystem, given differences in scenarios, strategies and model outcomes?

- Understand physical processes that lead to certain impacts (e.g., changes in direct to diffuse radiation)
- Separate well know from very uncertain impacts
- Perform a risk-risk assessment of benefits and impacts

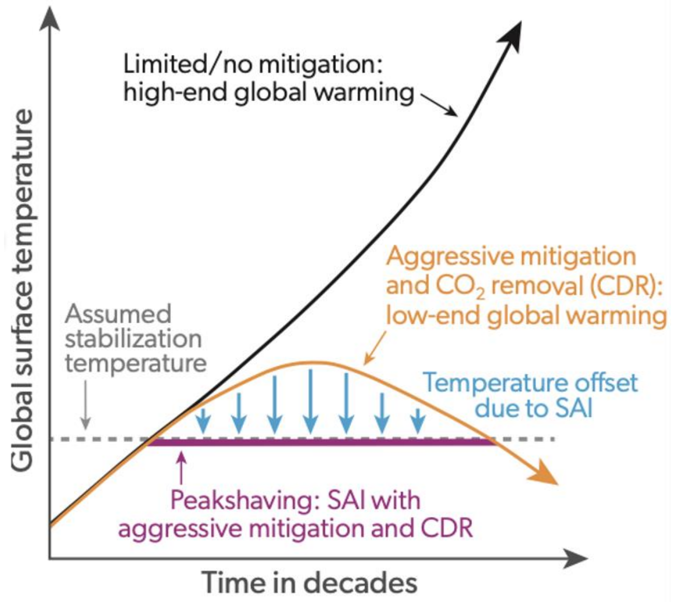
Additional Risks of Stratospheric Aerosol Interventions

Natural risks

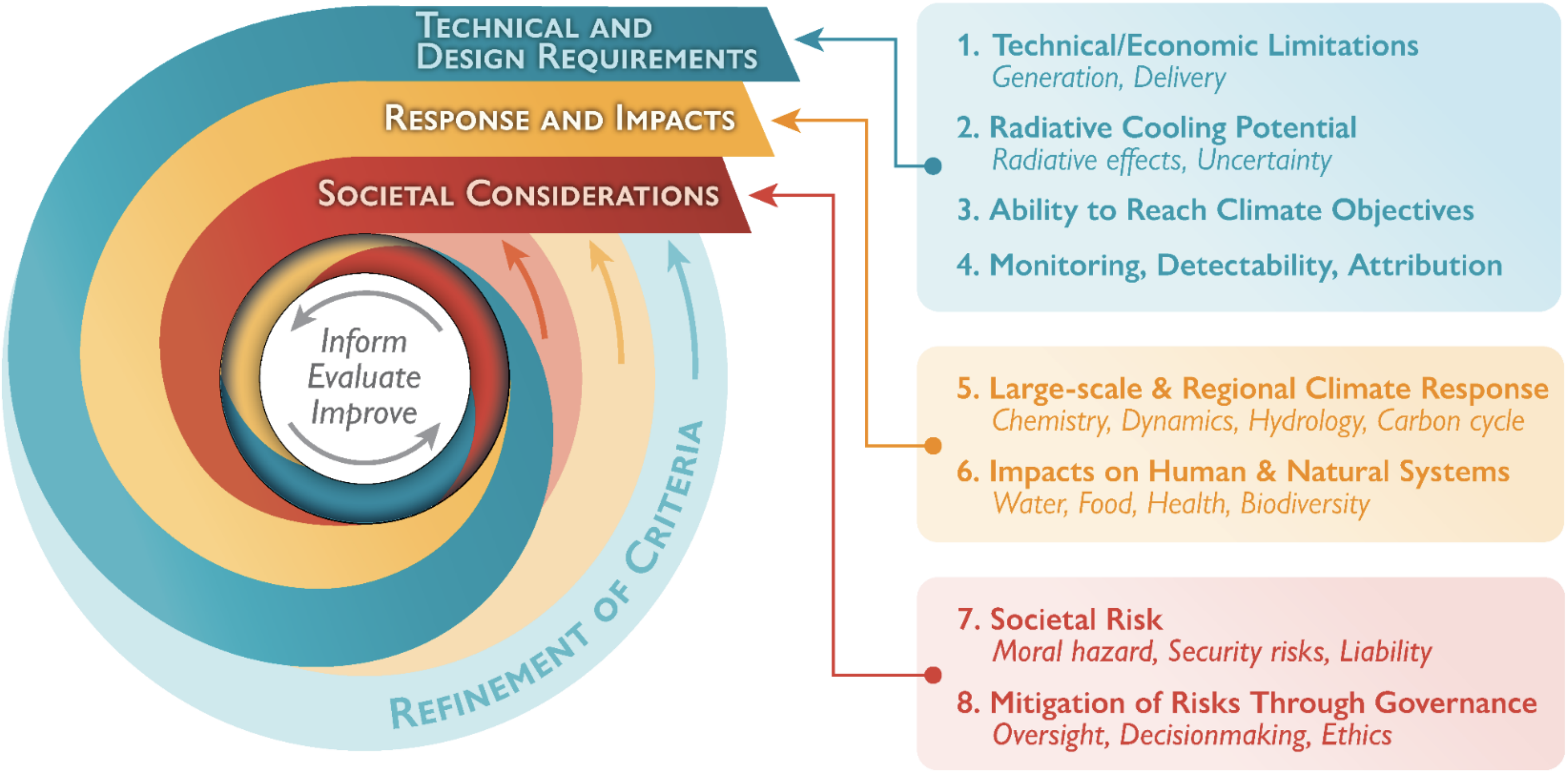
- Unexpected events, e.g., large volcanic eruptions
- Unexpected warming through, e.g., methane leaks, resulting in increasing GHGs -> prolonging for SAI applications

Societal risks

- Moral hazard (reduced mitigation incentive after start
- Communication risks, missing governance oversight, international conflicts and security risks
- Interruption of deployment (due to politics, or other events like war) -> Termination shock



Assessment Criteria for SAI Scenarios and Strategies



Tilmes et al., 2024

Interdisciplinary Assessment

- Engineering, Economics
- Earth System Models, process level models
- Observations (remote, in-situ)

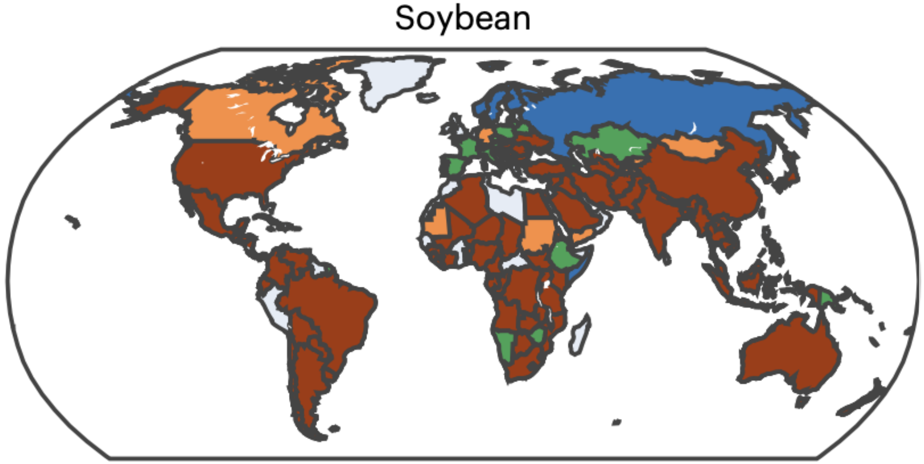
- Artificial intelligence, integrated assessment models
- High resolution output (downscaling)
- Impact modelers, ecologists, health experts

- Ethical frameworks
- Governance
- Stakeholders and interest groups

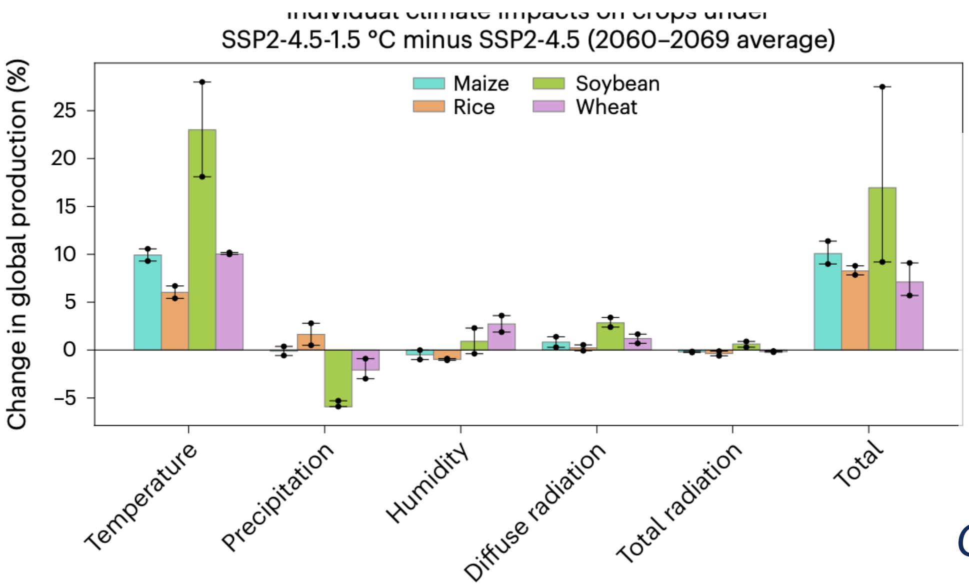
Extras

Impacts on Human and Natural Systems: Scenario Differences

Impacts on Human and Natural Systems Water, Food, Health, Biodiversity



SSP2-4.5
SSP2-4.5 1.5
SSP2-4.5 1.0
SSP2-4.5 0.5



Maize
Rice
Soybean
Wheat

Clark et al., 2023

Risk-risk assessment: Identify differences between a warmer world and a world with SAI

- Different temperature targets and strategies result in different outcomes
- What are the tradeoffs, e.g., more cooling vs. longer commitment?
- What is the societal perceptions and impacts of (mis-) information?