Comparison between a sectional and modal aerosol model in CESM2 for present-day and future aerosol injection experiments

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Community Earth System Model (CESM2)

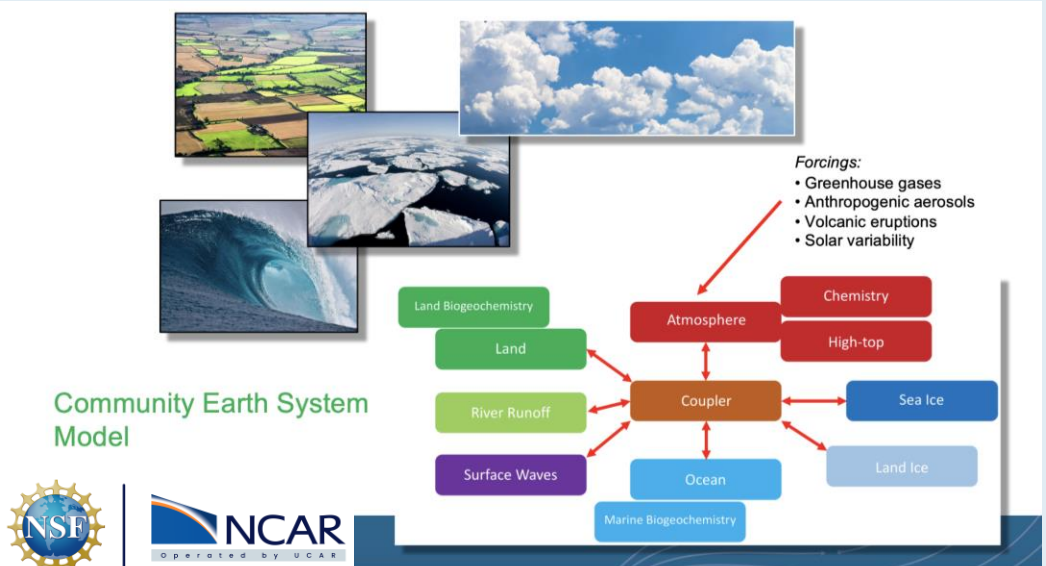
CESM2 is the latest version on the Community Earth System Model

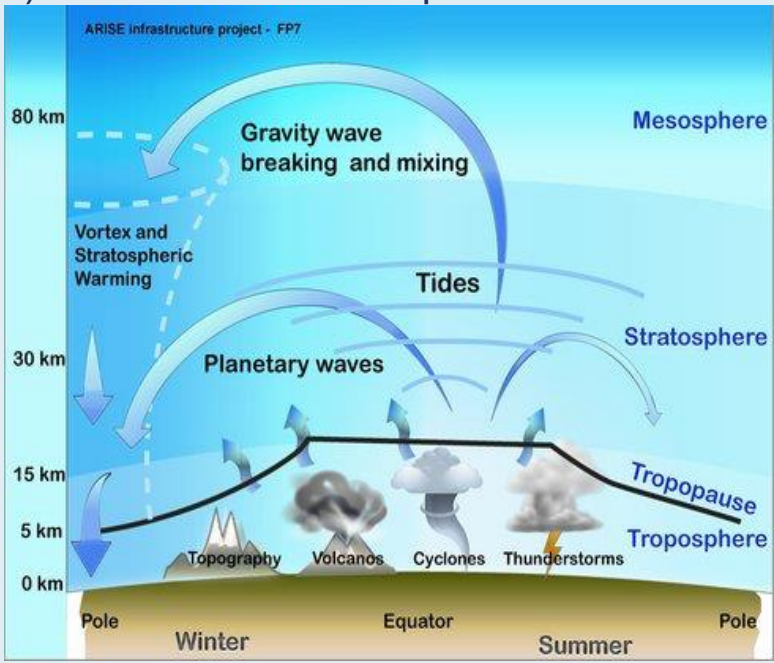
- Coupling of different components: atmosphere, ocean carbon cycle, sea-ice model, land model

Different Atmospheric configurations include:

- Whole Atmosphere Community Climate Model (WACCM) -> 140km model top
- CAMchem: 40km top

Default Aerosol Scheme: Modal Aerosol Model (MAM4)





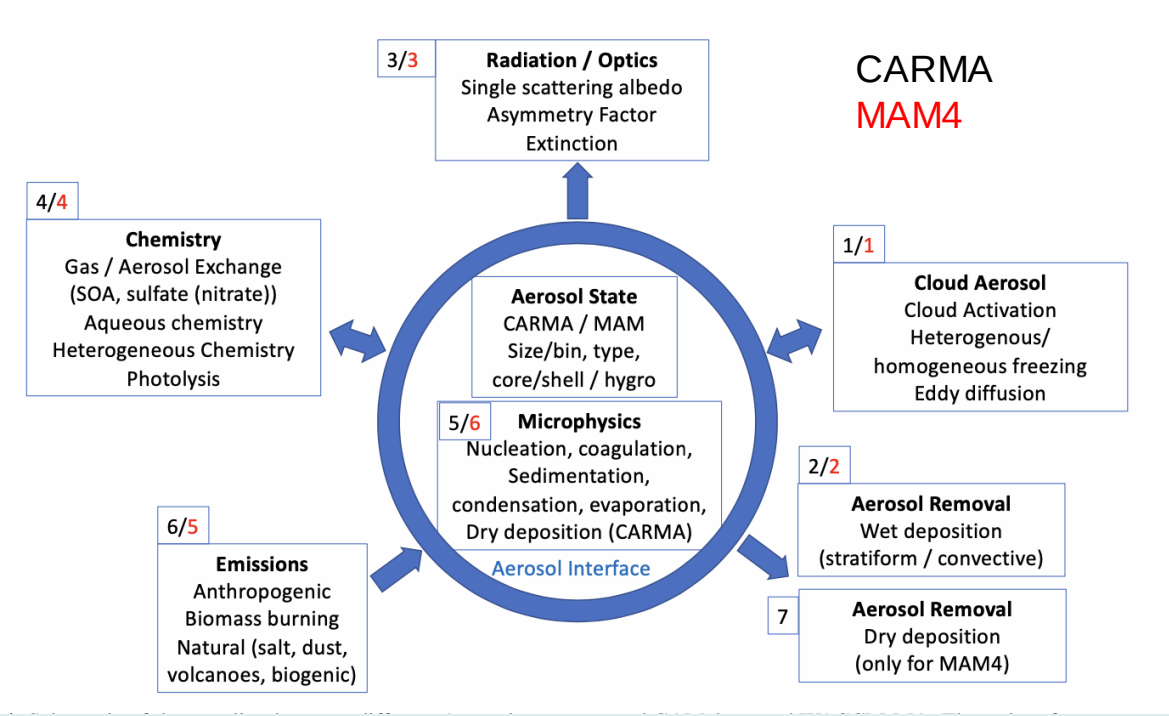
Coupling of CARMA to CESM2

- Default aerosol model: Modal Aerosol Model (MAM4)
- New aerosol model: Community Aerosol and Radiation Model for Atmospheres (CARMA)
- 2 groups: mixed aerosol and pure sulfate, 20 bins each adopted from Yu et al., 2015

➔ Sectional aerosol model for both troposphere and stratosphere

➔ Produce suitable model for Stratospheric Aerosol Injection experiments

Development of a new flexible aerosol interface in CESM at NCAR



Tilmes et al., 2023, GMD

CESM2 Implementation and Performance

CARMA implementation into CESM2

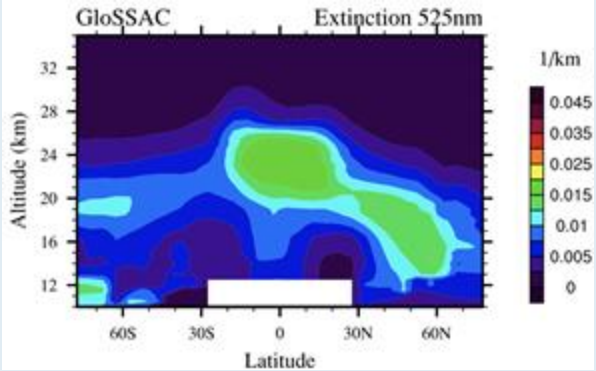
Two compsets have been developed and tested (nudged to MERRA2 and prescribed SSTs)

- WACCM-MA (with middle atmosphere chemistry) 1.9x2.5 horizontal resolution
- CAMchem (with troposphere/stratosphere (TS1) chemistry) 0.9x1.25 resolution

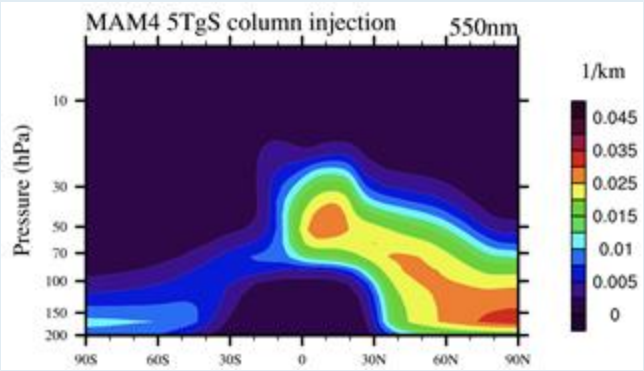
Model configuration	CAMchem	WACCM-MA	CAMchem	WACCM-MA
Horizontal Resolution	0.9x1.25	1.9x2.5	0.9x1.25	1.9x2.5
Top of Model	42km	150km	42km	150km
Chemistry	TS1	MA	TS1	MA
Aerosol	CARMA	CARMA	MAM4	MAM4
Number of Aerosol Tracers	220	140	27	19
Throughput	2.6 yrs/day	2.5 yrs/day	3.6 yrs/day	9.2 yrs/day
Model Cost (Core hours/yr)	31 K	11 K	7.5 K	2.3 K
Nucleation Scheme	Zhao	Zhao	Vehkamäki	Vehkamäki

WACCM-MA: Mt Pinatubo Period 1991-1995

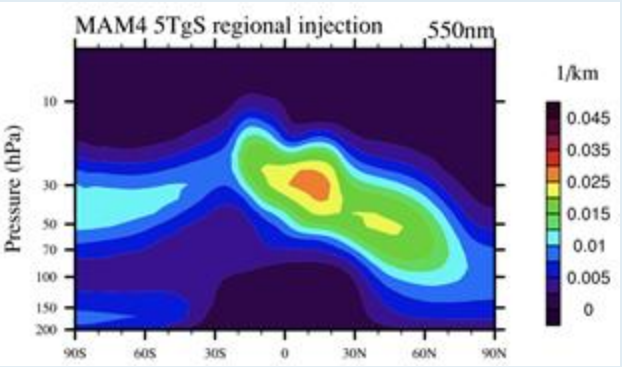
GloSSAC



MAM4 1-Column Inj.



MAM4 Regional Inj.

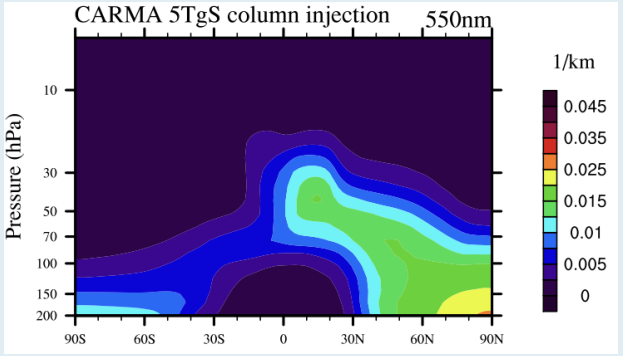


Default Injections in CESM2:

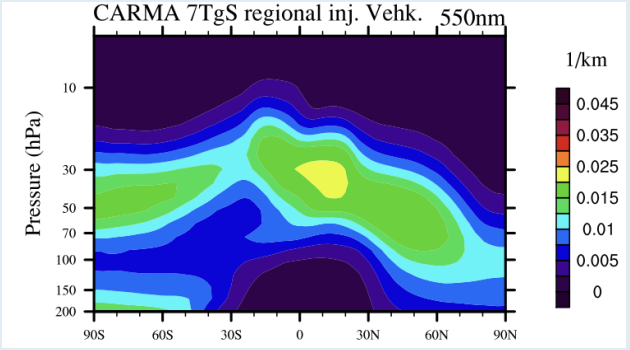
5TgS in one column. Jan-Mar 1992

- Regional injections of SO_2: *5°S-15°N, 19-27km (peak 22km), 9 hours*, improves distribution of both CARMA and MAM4
- CARMA reproduce observations best with higher injections (7TgS) (more in line with observations), due to differences in the bin resolution

CARMA 1-Column Inj.

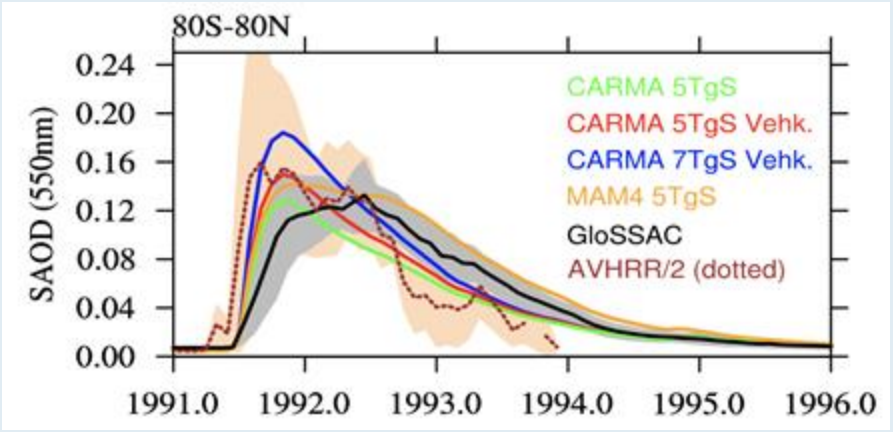


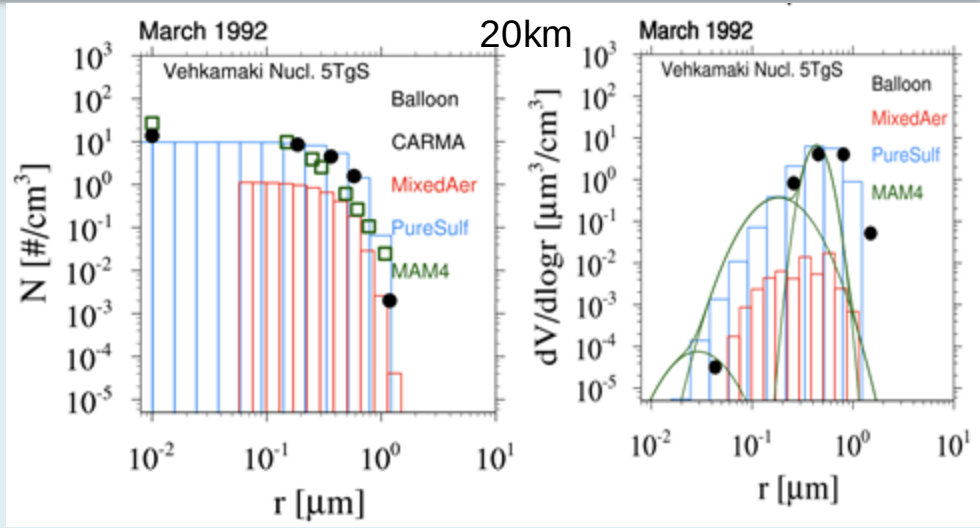
CARMA Regional Inj.



WACCM-MA: Mt Pinatubo Period 1991-1995

Stratospheric Aerosol Optical Depth



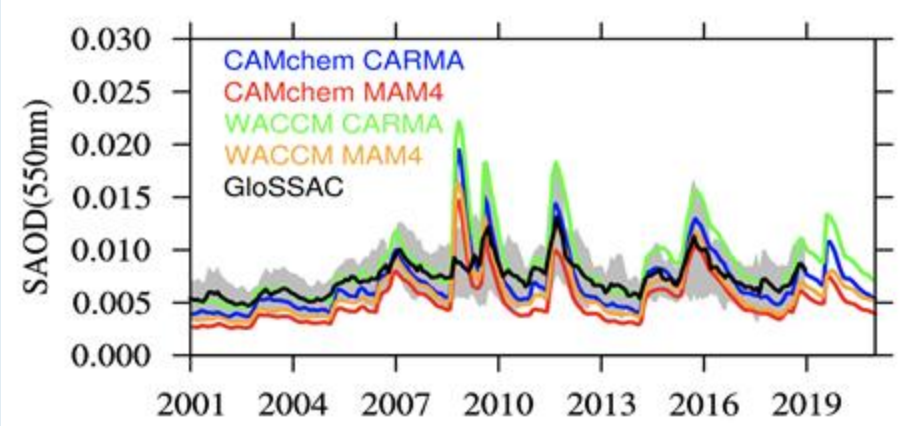


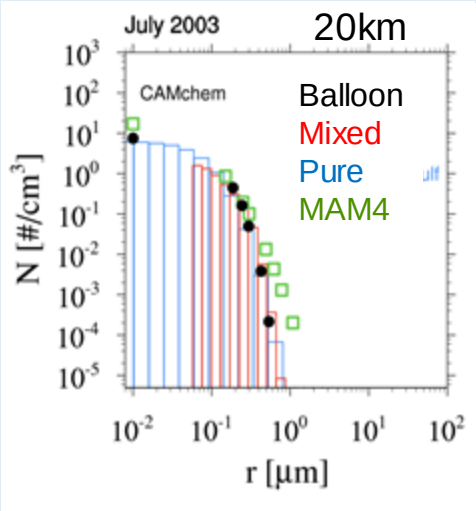
Comparisons to observations in the stratosphere

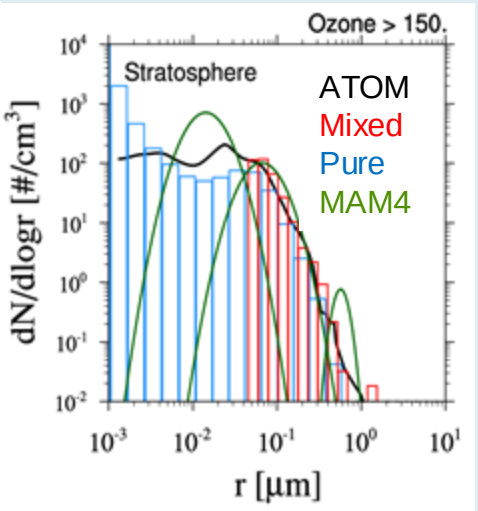
- Both aerosol models can reproduce Stratospheric AOD over the Mt Pinatubo period
- MAM4 bins are not able to reproduce the observed number distribution
- CARMA overestimates the number of the largest bin, may need larger bin size to simulate Mt Pinatubo
- Possible shortcomings for solar climate interventions

Stratospheric Background / Small Volcanoes 2001-2020

Stratospheric Aerosol Optical Depth



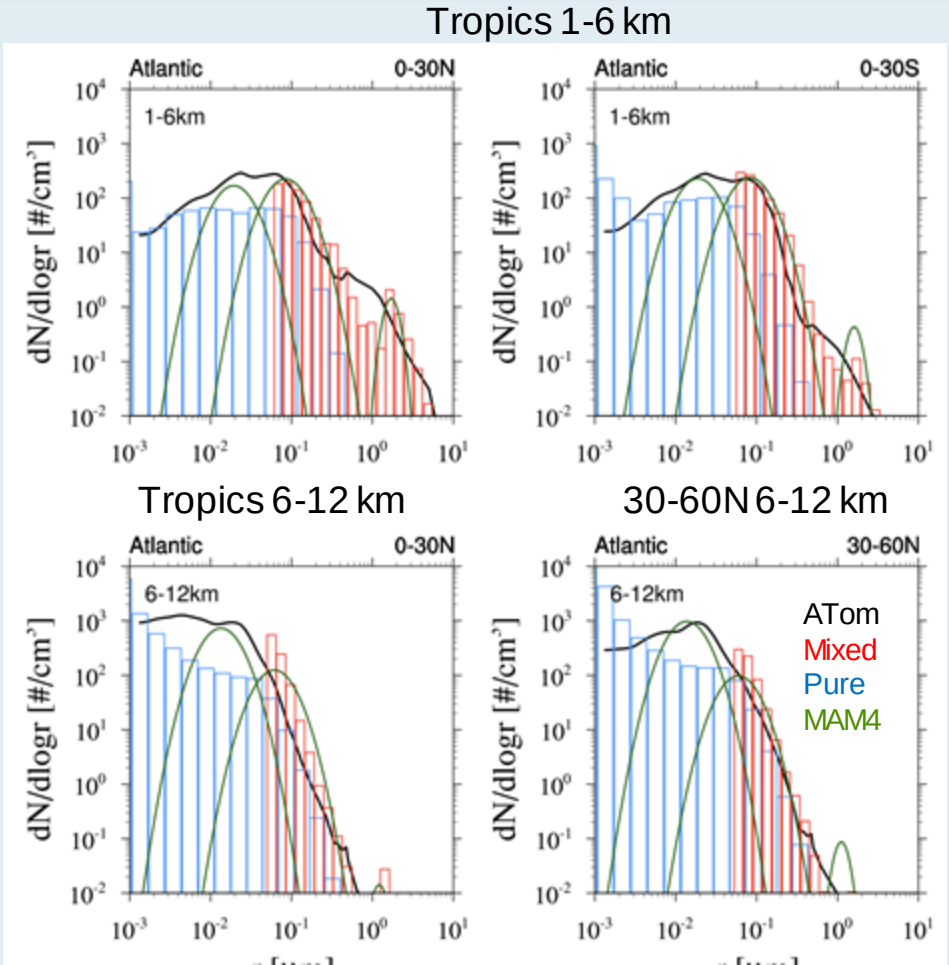




Comparisons to observations in the stratosphere (2001-2020)

- Both aerosol models can reproduce Stratospheric AOD during the last 20 years
- MAM4 has slightly lower values, mostly within the error bar, CARMA shows larger peaks of small volcanoes
- CARMA size distribution captures observations in the stratosphere very well

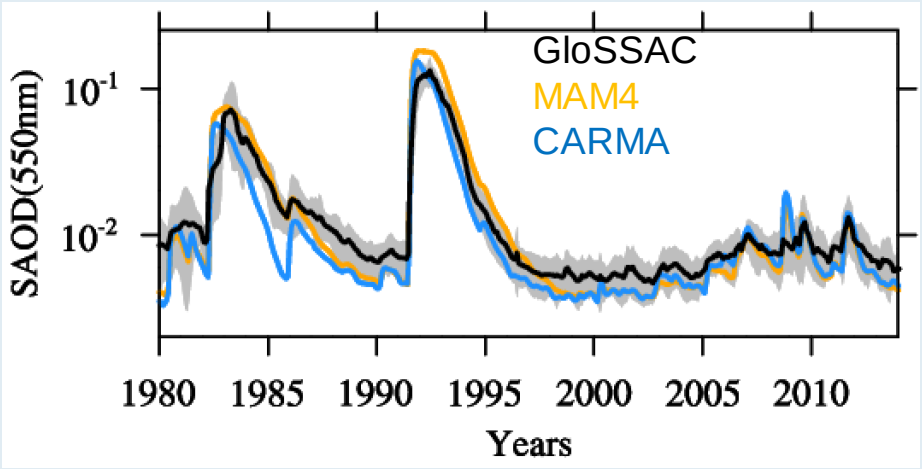
ATom Tropospheric Evaluation: Aerosol Size distribution

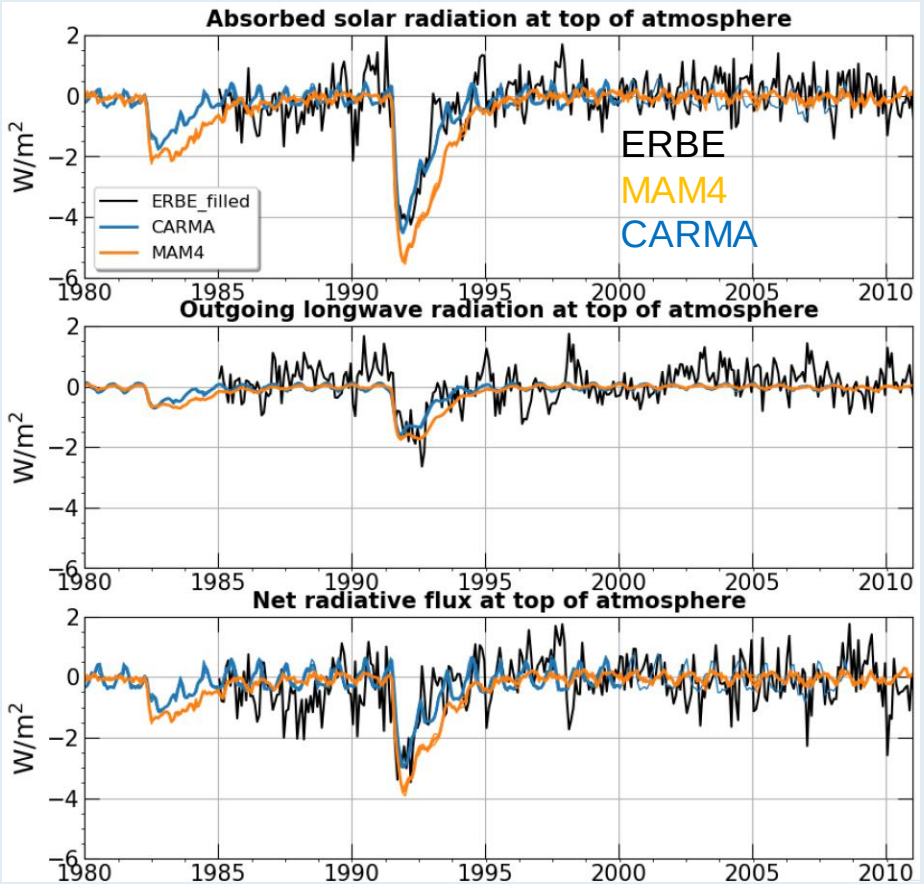


- **Tropics 1-6km:** CARMA reproduces larger bins (dust, sea-salt) better than MAM4 (mode width is too small)
- **Upper troposphere:** CARMA has shortcomings in reproducing Aitken mode mixed aerosol sizes. Mixed group from CARMA does not reach to small enough sizes

Free-running (fixed SST) WACCM-MA, MAM4 and CARMA

WACCM-MA, 1.9x2.5degrees horizontal resolution: Mt Pinatubo 7TgS injections

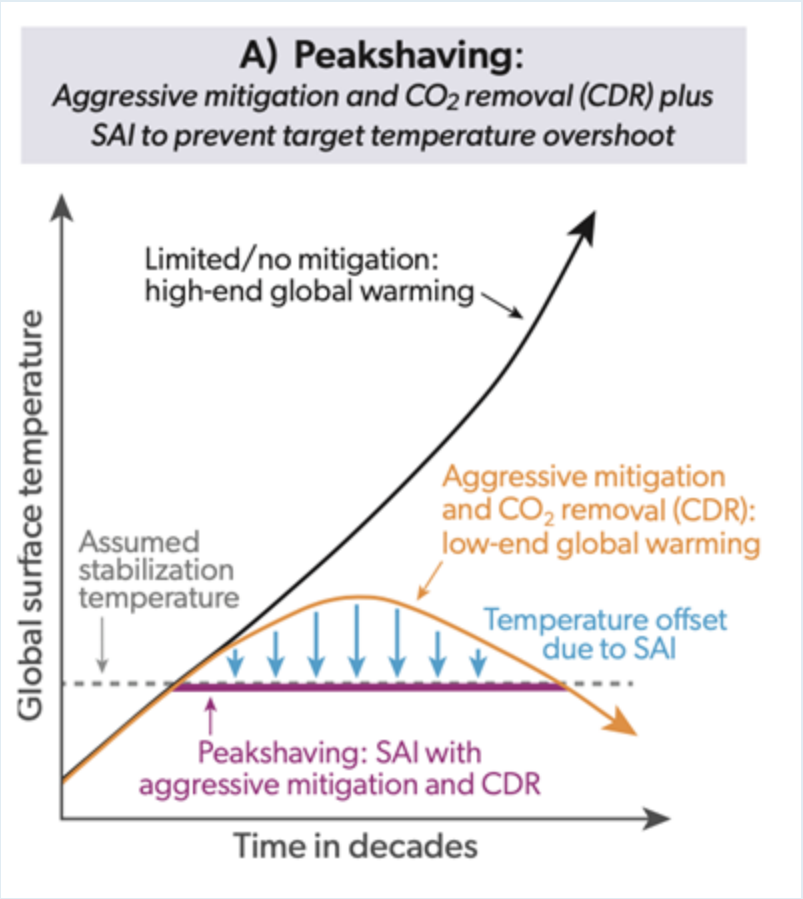




Both CARMA and MAM can reproduce AOD observations after Mt Pinatubo

- CARMA shows closer agreement of SAOD and radiative fluxes after the Mt Pinatubo eruption for the same injection amount
- SAI injection experiments to compare MAM4 and CARMA

Motivation for Stratospheric Aerosol Intervention (SAI) Research



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

Peakshaving Scenario: Uses Stratospheric Aerosol Intervention (Injection) (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.

Requirement

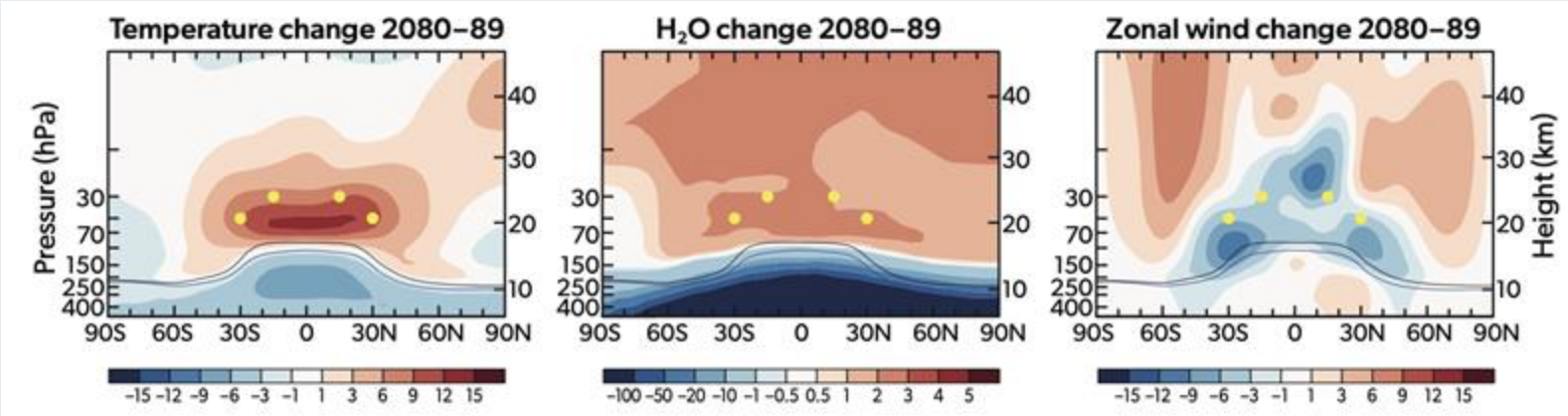
- ***Strong Decarbonization*** is required to keep GHG and surface temperatures towards a minimal increase
- ***Governance and Ethical requirement***: cooperative, representative, legitimate and just applications -> UNEP report, AGU ethical framework development
- ***Comprehensive understanding of benefits,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

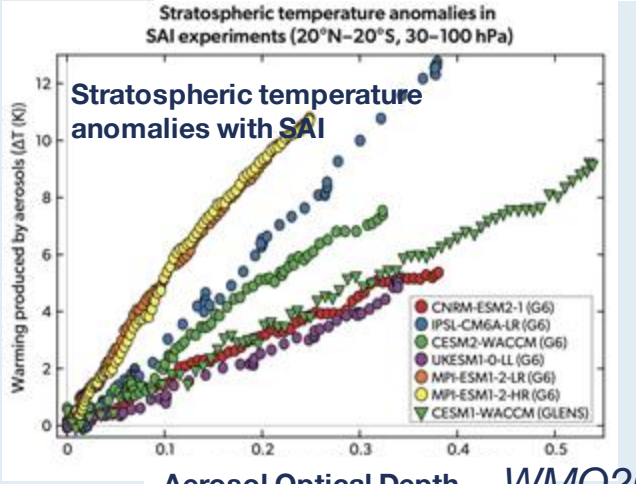
Questions

- How well can current model simulate effects of SAI on the climate system? What are the uncertainties?
- What can we do to reduce uncertainties?
- What are the most important impacts on societies and ecosystems?

SAI Impacts Stratospheric Composition and Dynamics

Tilmes et al., 2021

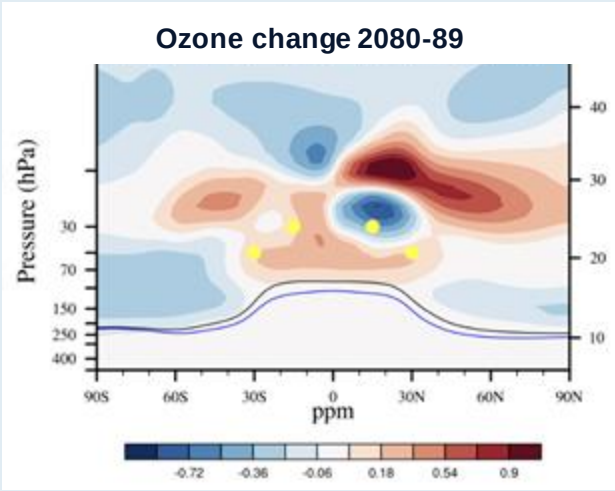




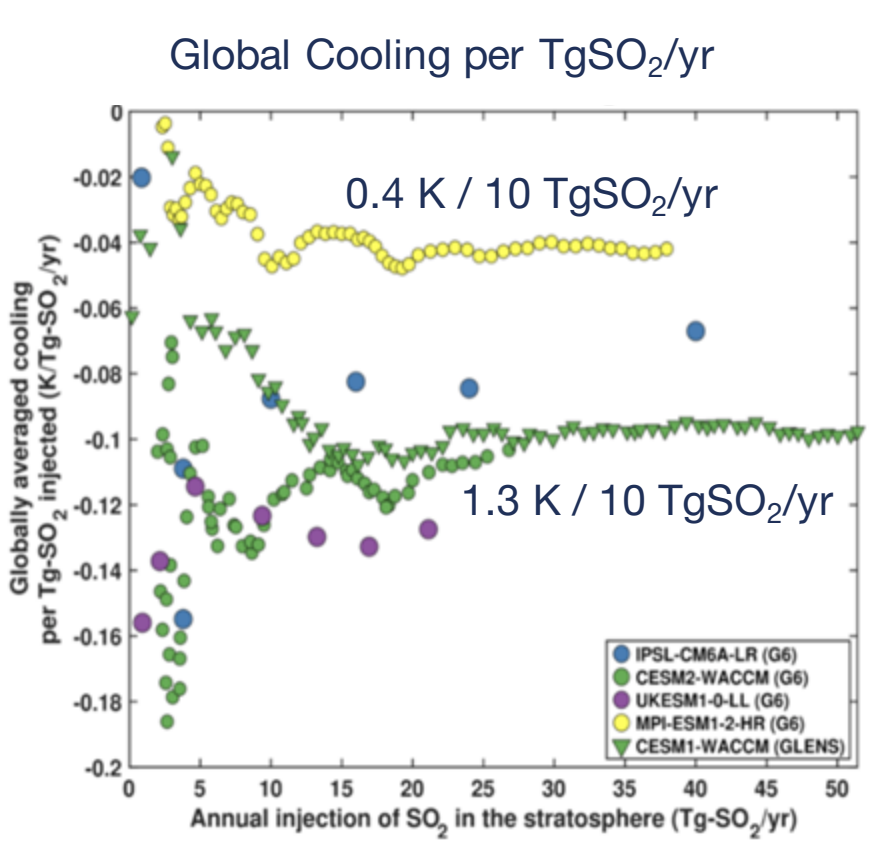
WMO2022

Large uncertainty in Stratospheric Heating per AOD increase due to

- Differences in needed amount of aerosol injections
- Differences in the aerosol distribution
- Model differences in radiation, resolution, chemistry etc.



SAI Effects on Surface Temperature



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

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

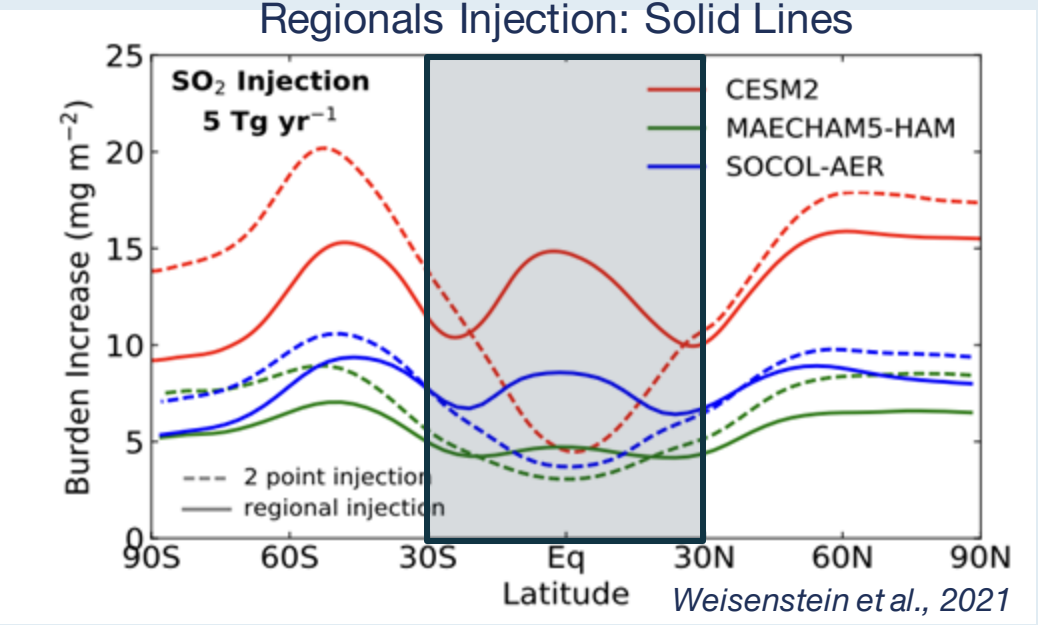
Implications for uncertainties in the required injection amount :

- More sulfur injections result in more impacts (climate and ozone)
- Economical uncertainties on costs and technical aspects

What are the reasons for the differences between models?

WMO2022

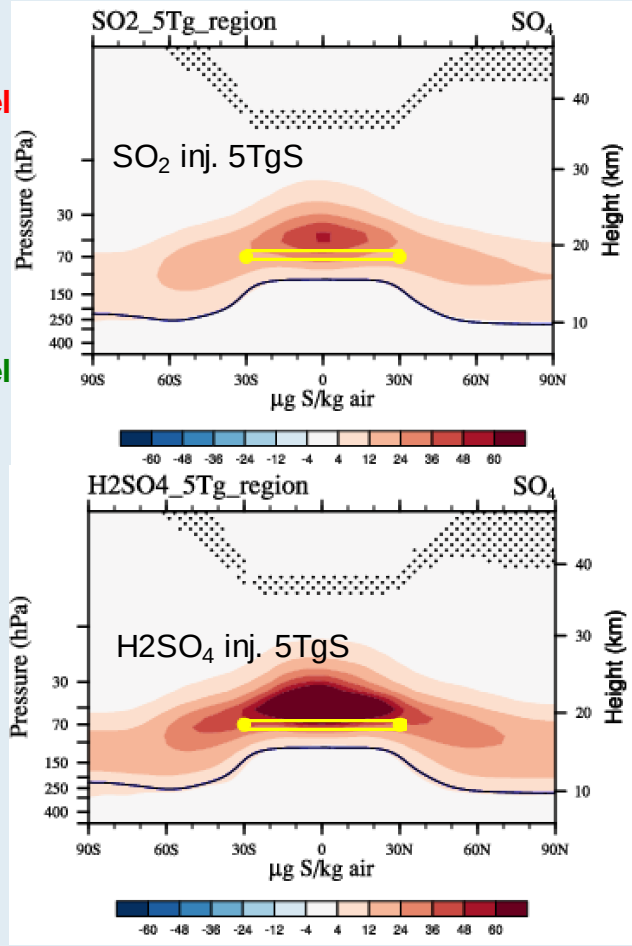
SAI Injection Experiments (Different Models)



Modal Model 1deg res.

Sectional Model 2.8deg res.

Modal Model 2.8deg. res.



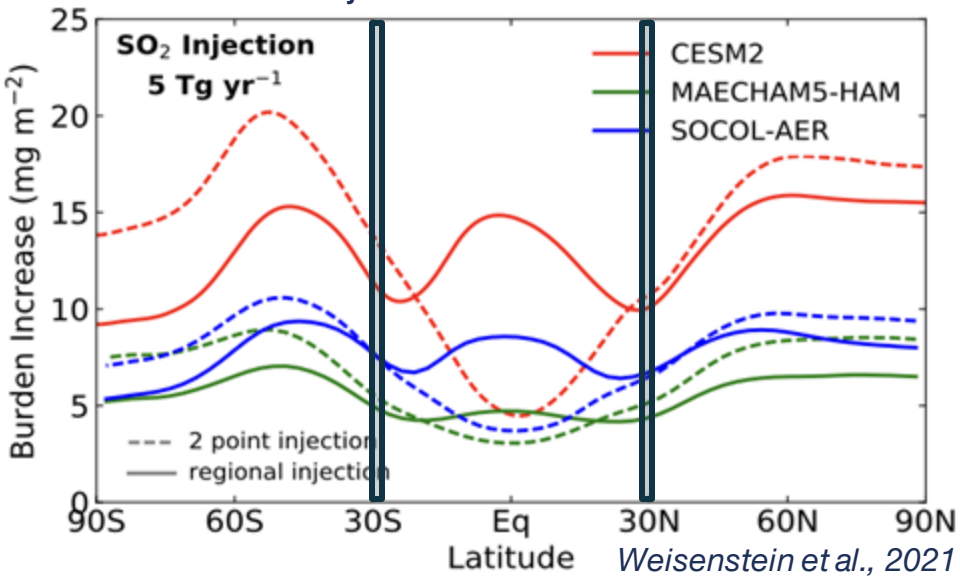
Injections of SO_2 over 10 years in the stratosphere: Goal, identify best injection strategies for cooling efficiency, *identify model differences.*

- SO_2 injections -> formation of aerosol from precursors
- H_2SO_4 injections -> injections in the accumulation mode 0.1microns

Regional injections (solid) between 30°N and 30°S, 19-21 km altitude

SAI Injection Experiments (Different Models)

Point Injection: Solid Lines

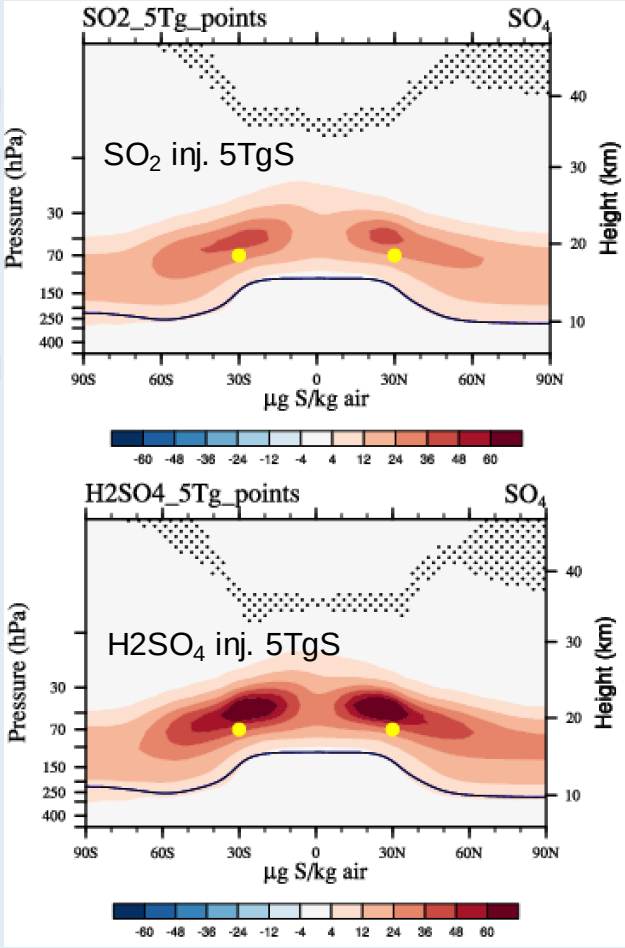


Weisenstein et al., 2021

Modal Model 1deg res.

Sectional Model 2.8deg res.

Modal Model 2.8deg. res.

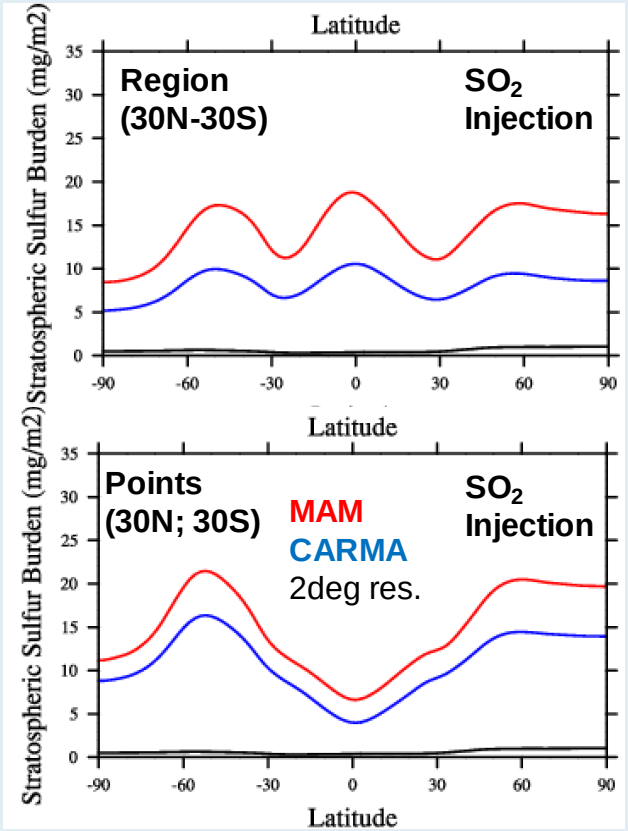


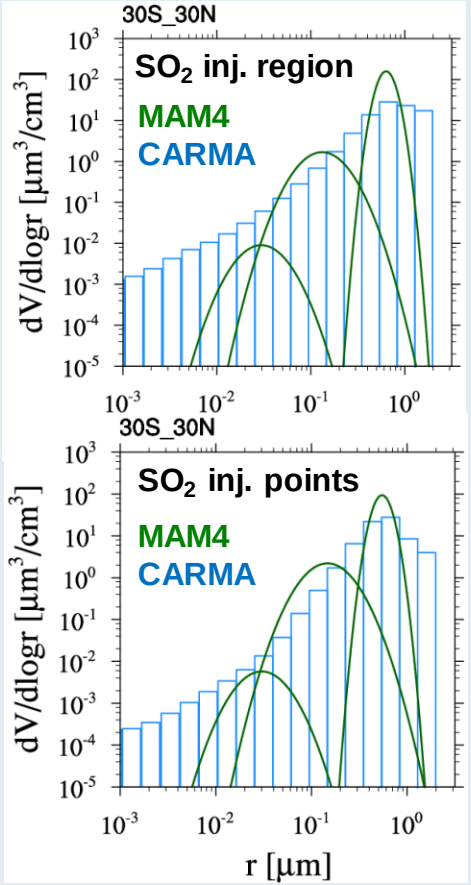
Injections of SO_2 over 10 years in the stratosphereGoal, identify best injection strategies for cooling efficiency, *identify model differences.*

Point injections (dashed) at 30°N and 30°S, 180°E, 20 km altitude

CESM2 (MAM4) shows larger burden than SOCOL (Sectional Model)

SAI Injection Experiments (MAM4 vs CARMA)





CARMA vs MAM4

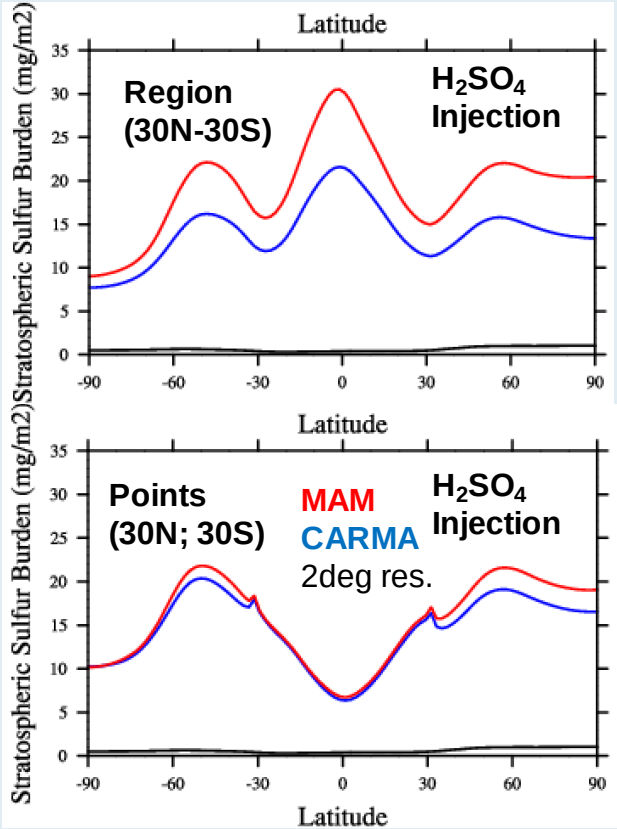
SO_2 injections

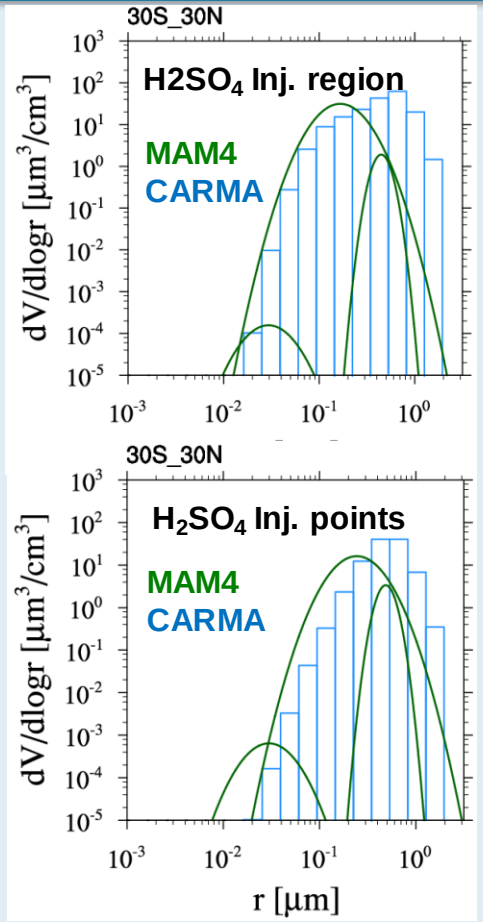
- MAM4 derives significantly larger sulfur burden for both point and regional injections for both regional and point injections

30N-30S Average Volume Distribution:

- Increased nucleation (CARMA) and coagulation (slightly larger sizes) in the regional injections
- More mass in larger bins in CARMA results in more removal (smaller burden)

SAI Injection Experiments (MAM4 vs CARMA)





CARMA vs MAM4

H_2SO_4 injections:

- MAM4 derives significantly larger sulfur burden for regional injections. More coagulation in CARMA and larger mass in largest size bins
- Point injections show very similar burden in the tropics, but still different size distribution

➔ Largest differences in the nucleation process between CARMA and MAM4

➔ Saturation of largest bin in CARMA may require extended size for climate intervention studies

➔ Choices of injection location and material changes outcomes, depends on the aerosol scheme used

Conclusions / Next Steps

New model implementation allows comparisons between a modal and sectional aerosol model in one model framework (CESM2)

- Sectional models can be used as a benchmark, with improved performance of aerosol size distribution in both troposphere and stratosphere

- Improvements and further developments of CARMA are planned, including exploring expanded bin ranges for both troposphere and stratosphere, more complicated aerosols composition

- CARMA produces significantly reduced aerosol burden than MAM4 for the same stratospheric sulfur injections. More comprehensive aerosol model may reduce the uncertainty in the cooling potential of stratospheric aerosols for climate intervention studies

Global Cooling per $TgSO_2/yr$