Improving the E3SM Representation of the Stratospheric Aerosol Forcing Induced by Volcanic Eruptions

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Motivation

- The stratospheric sulfate aerosol cools down the troposphere by scattering incoming solar radiation and warms up the stratosphere by absorbing infrared light. Its interaction with oxides of nitrogen and halogen species has potential to cause ozone depletion.

- The E3SMv1-EAM has significantly increased model top height (~70 km) and vertical layers (72 layers) compared to E3SMv0 (~40km and 30 layers), while lefts the stratospheric aerosol prescribed.

- Having **prognostic** stratospheric aerosol is an important step to simulate the impact of volcanic eruptions and geoengineering injections on climate.

SO_2 gas, ashes and other species

SO_2 chemistry*

H_2SO_4 gas

Background OCS Chemistry

Nucleation

Condensation

Condensation

Coagulation growth

Coagulation growth

Cooling: Scattering Solar radiation

Stratosphere Aerosol Physics

Warming: Absorbing tropospheric radiation

Interact with Stratospheric Chemistry: O_3 depletion

Stratosphere and Troposphere Exchange: High Cloud Properties

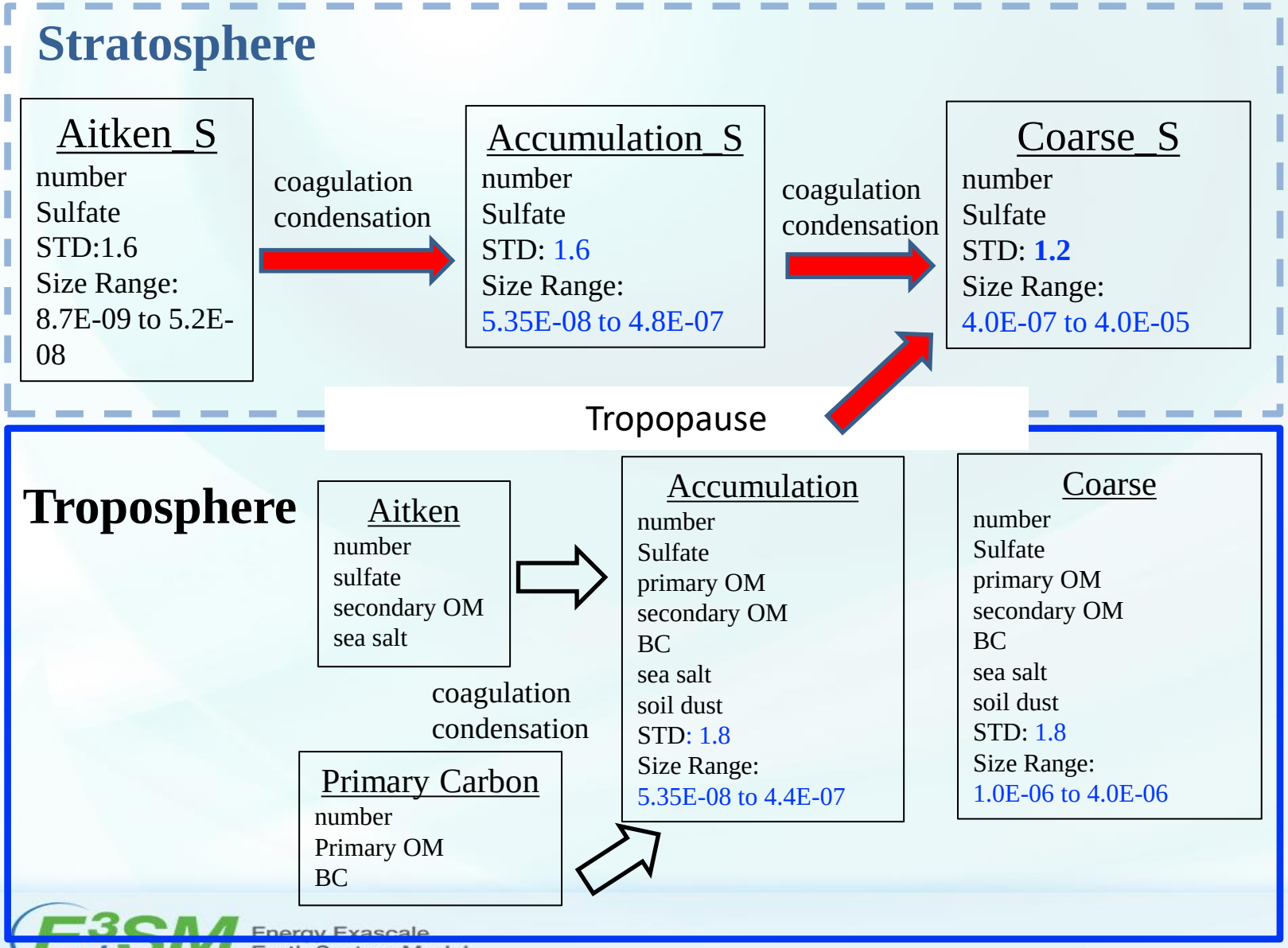
*SO_2 chemistry reactions

$SO_2 + OH \rightarrow SO_3 + HO_2$

$SO_3 + H_2O \rightarrow H_2SO_4$

- OH-HO_2 cycle is the essential for SO_2 oxidation.
- Stratospheric aerosol has longer lifetime than in the troposphere (months vs days).
- Aerosol surface area is important to heterogenous reactions

Schematic Diagram of Seven-Mode Version of the Modal Aerosol Model (MAM7S)



- MAM7S is based on default four-mode version MAM(MAM4), adding three additional stratospheric sulfate aerosol modes, **Aitken_S, Accumulation_S,** and **Coarse S**, with smaller STD values and modified size ranges compared to tropospheric modes.
- In the Stratosphere, the Accumulation and Accumulation_S modes sulfate aerosols could grow into Coarse_S mode due to size growth.
- MOZART gas chemistry is modified and updated to handle fast OH depletion after volcano eruption.

Experiments to Evaluate MAM7S Performance

- To investigate the EAMv1 capability to simulate atmospheric response to major volcano eruptions. M4-MC is control run and WACCM6 is benchmark.
- Nudging simulations from 1991 to 1993.
- Volcanic eruptions are considered as elevated SO_2 emissions.
- Analyze model performance under different aerosol module and chemistry configurations.

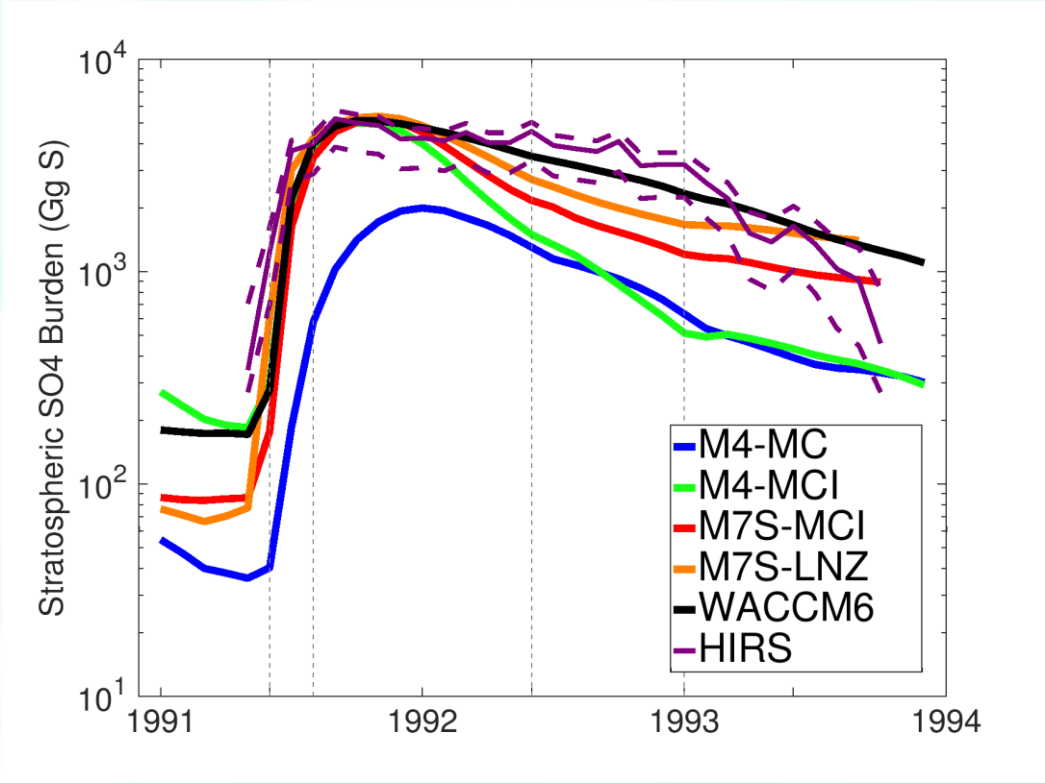
Table1. Experiment configurations.

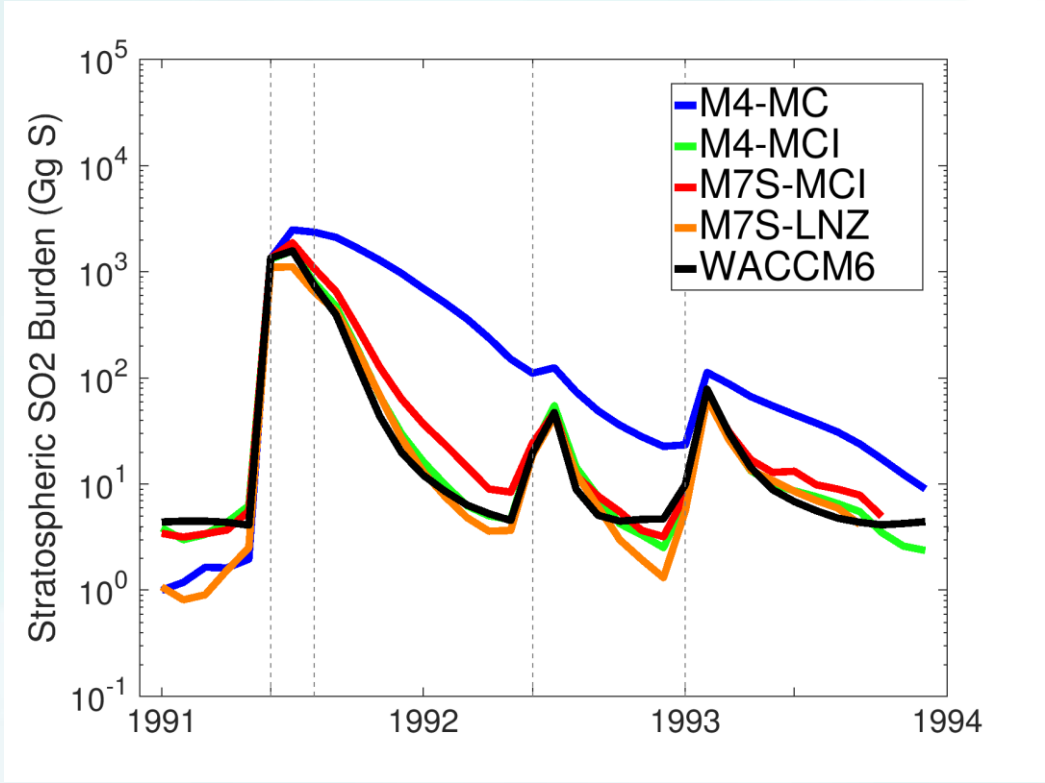
Acronym	Aerosol Module	Chemistry
M4-MC	MAM4	MOZART
M4-MCI	MAM4	MOZART_I
M7S-MCI	MAM7S	MOZART_I
M7S-LNZ	MAM7S	Linoz
WACCM6	MAM4*	TSMLT

Volcano	Date	SO_2 (Tg)	Alt (km)	Lat	Lon
Mount Pinatubo	1991.06.15	10	18-20	15.130	120.350
Cerro Hudson	1991.08.15	1.5	11-16	-45.900	287.030
Spurr	1992.06.27	0.6	9-14.5	61.300	207.750
Lascar	1993.01.30	0.4	15-23	-23.370	292.270

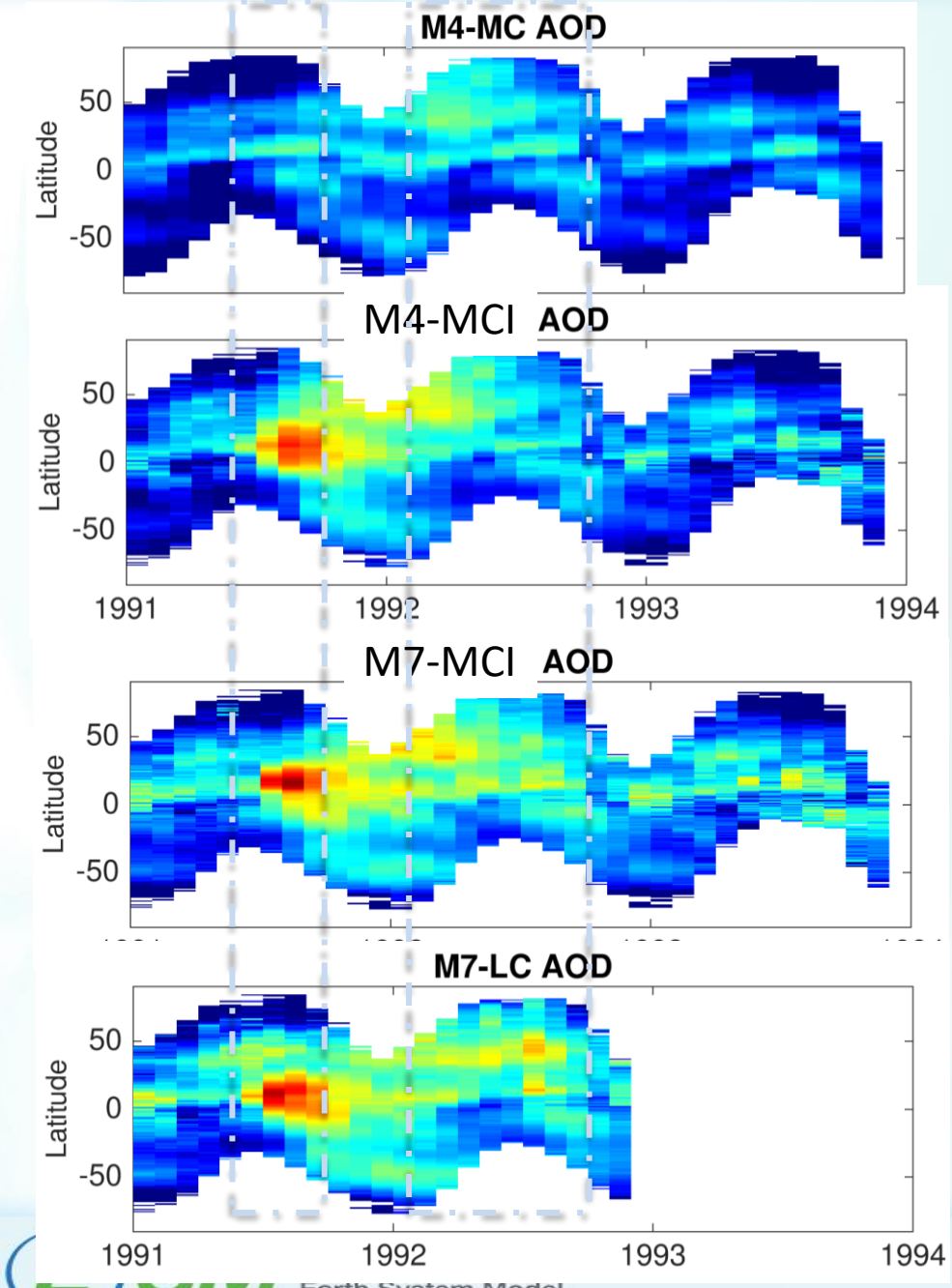
Table2. Major volcanos during 1991 to 1993.

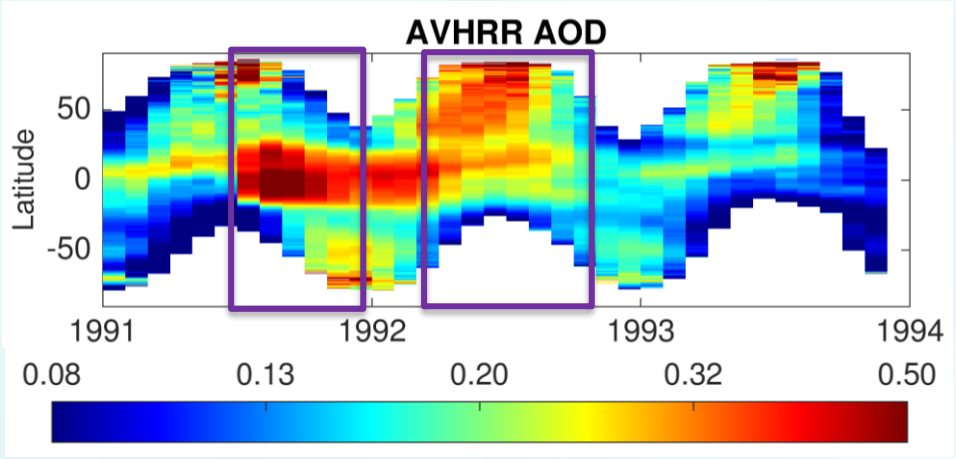
Highlight of the Progress: Long-term SO_4 and SO_2 burden





- The MAM7S and improved Mozart chemistry produced reasonable SO4 burden compared to HIRS observations.
- The SO2 burden suggests that the improved Mozart chemistry oxidized SO2 gas as good as TSMLT chemistry.
- There is internal variability in the stratosphere, suggesting more simulations are needed.





- AVHRR tends to overestimate AOD, especially at high latitudes.
- During 1991.6-1991.12, after Pinatubo eruption, there is a peak over tropic area. The default Mozart Chemistry run (M4-MC) did not the capture AOD peak while MODIFIED chemistry runs did better job (M7-MCI).
- The M7-LC and M7-MCI prolonged high AOD attribute to MAM7S aerosol scheme.

Highlight of the Progress: 15 days after eruption

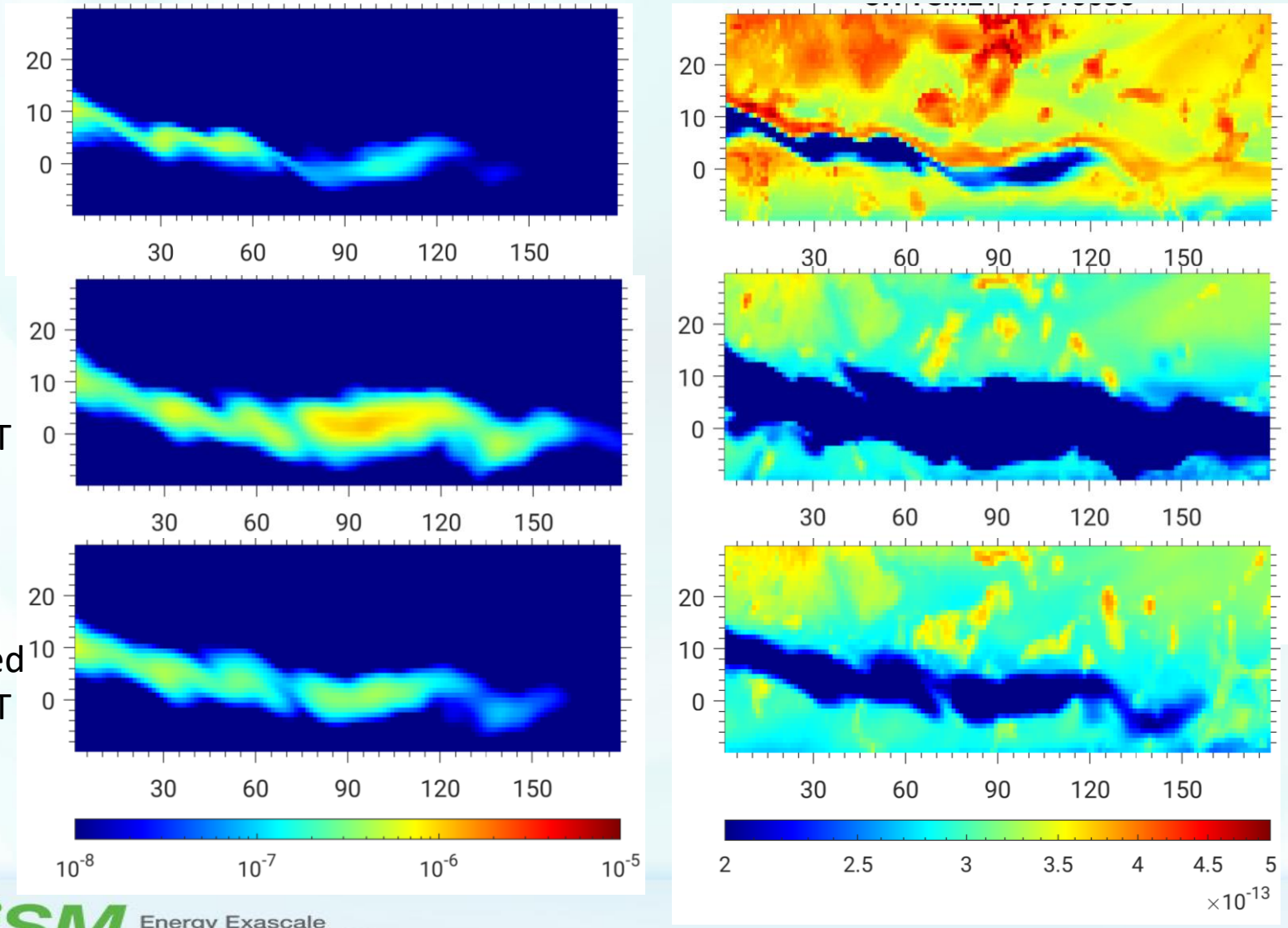
SO2 ctr at 61 hpa

OH ctr at 61 hpa

TSMLT

Default MOZART

Improved MOZART



- SO2 and OH concentration after 15 days of Mt. Pinatubo eruption.
- Default MOZART chemistry can not produce enough OH after eruption, result in more SO2 remained in the stratosphere.
- The improved MOZART chemistry greatly improved the OH and SO2 concentration

Simple gas-phase chemistry

1, DMS oxidation

DMS + OH -> SO2

DMS + OH -> .5 * SO2 + .5 * HO2

DMS + NO3 -> SO2 + HNO3

2, SO2 oxidation

SO2 + OH -> H2SO4

3, H2O2 production and loss

HO2 + HO2 -> H2O2

H2O2 + OH -> H2O + HO2

Oxidant concentrations (O3, OH, HO2, and NO3) are temporally interpolated from monthly averages taken from simulations by a chemistry-climate model (CAM-Chem) (Lamarque et al., 2010). **The Oxidant concentrations keep unchanged in every time step**.

MOZART gas-phase chemistry

1, Full chemistry in troposphere and Stratosphere (Lamarque et al., 2013).

MOZART Improvement

1, Replace SO2 oxidation

SO2 + OH -> SO3 + HO2

SO3 + H2O -> H2SO4

2, update reaction rate (Odd Nitrate Reacton)

NO2 + NO3 + M -> N2O5 + M

NO2 + HO2 + M -> HO2NO2 + M

3, update stratospheric heterogeneous reaction rates

4, use prognostic SAD in the stratosphere (in progress)

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Summary and Future Plan

- New aerosol module MAM7S and improved MOZART chemistry are implemented into E3SMv1 to enable model to simulate stratospheric aerosol evolution after major volcano eruptions.
- Simulated results agreed well with satellite measurements and WACCM6-TSMLT results. The chemistry affects the SO2 oxidation in the first 3 months after the Mt. Pinatubo eruption. The aerosol treatment impacts on the long-term stratospheric aerosol burden.
- The future work is to add the OCS chemistry and volcanic ash treatment in the stratosphere and to analyze the impact of stratospheric aerosol and chemistry on the climate in the troposphere.