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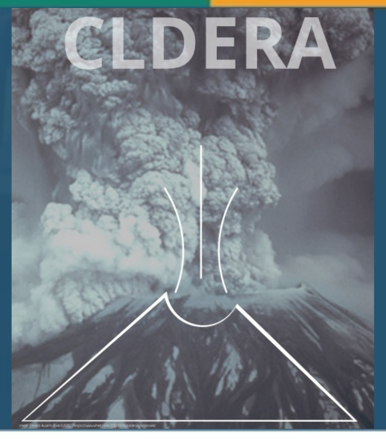

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A Simple Chemistry Approach to Prognostic Volcanic Aerosol in E3SM – Modeling the Mt. Pinatubo Eruption for CLDERA

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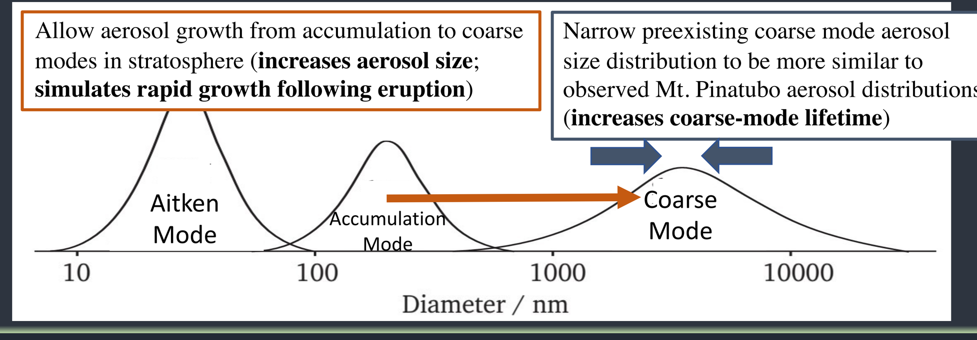
I. Motivation

- Modify the Energy Exascale Earth System Model (E3SMv2) to improve representation of stratospheric sulfate formation/evolution from the 1991 Mount Pinatubo eruption for the CLimate impact: Determining Etiology thRough pAthways (CLDERA) project.
- The modified E3SMv2 will provide data to the CLDERA project, which seeks to develop new methods for climate attribution built upon discovering and representing evolving chains of physical processes (see sandia.gov/cldera for more information).

II. Modifications to E3SM Volcanic Treatment

- Default E3SMv2 prescribes stratospheric sulfate from explosive volcanic eruptions. When configured to simulate sulfate formation and evolution, sulfate lifetime is too short.
- Improved model referred to as E3SMv2-PA (Prognostic [stratospheric sulfate] Aerosol). Major modifications to the Modal Aerosol Module (*Liu et al., 2012, 2016*) shown in Fig. 1.

Figure 1: Major changes made to E3SMv2-PA aerosol size modes in order to prognostically calculate stratospheric sulfate formed from the volcanic emission of sulfur dioxide in the stratosphere.



III. Model and observational datasets

- Model simulations
  - **E3SMv2, E3SMv2-PA**
    - Simple chemistry and prognostic stratospheric sulfate aerosol
  - Community Earth System Model with the Whole Atmosphere Chemistry Climate Model (**CESM2-WACCM**) (*Mills et al., 2016, 2017*)
    - Full-chemistry and prognostic stratospheric sulfate aerosol (*simulations run by Ziming Ke*)
- Observational datasets
  - Stratospheric mass burden – High Altitude Infrared Radiation Sounder (**HIRS**) (*Baran and Foot, 1994*)
  - Aerosol Optical Depth (AOD) – Advanced Very High Resolution Radiometer (**AVHRR**) (*Zhao et al., 2013*)
  - Stratospheric aerosol effective radius – Upper Atmosphere Research Satellite (**UARS**) instruments: Improved Stratospheric Mesospheric Sounder (ISAMS) and Cryogenic Limb Array Etalon Spectrometer (CLAES) (*Stenchikov et al., 1998*)

IV. Aerosol Stratospheric Burden

- **E3SMv2-PA improves the model representation of stratospheric burden when compared to HIRS** (Fig. 2).
- Differences in lifetime not only affect the burden but also the transport (spatial distribution) of the stratospheric aerosol (Fig. 3).

The 1991 Mount Pinatubo volcanic eruption is well represented in our stratospheric aerosol version of E3SM, showing improvements in aerosol lifetime, effective radius, and mass burden without the computational cost of a full-chemistry earth system model.

Figure 2 → Time series of stratospheric sulfate burden. Models and observations report mass in teragrams (=10^{12} g) sulfur. Models are validated against the HIRS with 1.4 Tg uncertainty bounds (black dashed lines). Select times noted by the letters "A" through "F" at the bottom of the figure are expanded into E3SMv2 and E3SMv2-PA global stratospheric burden in Fig. 3.

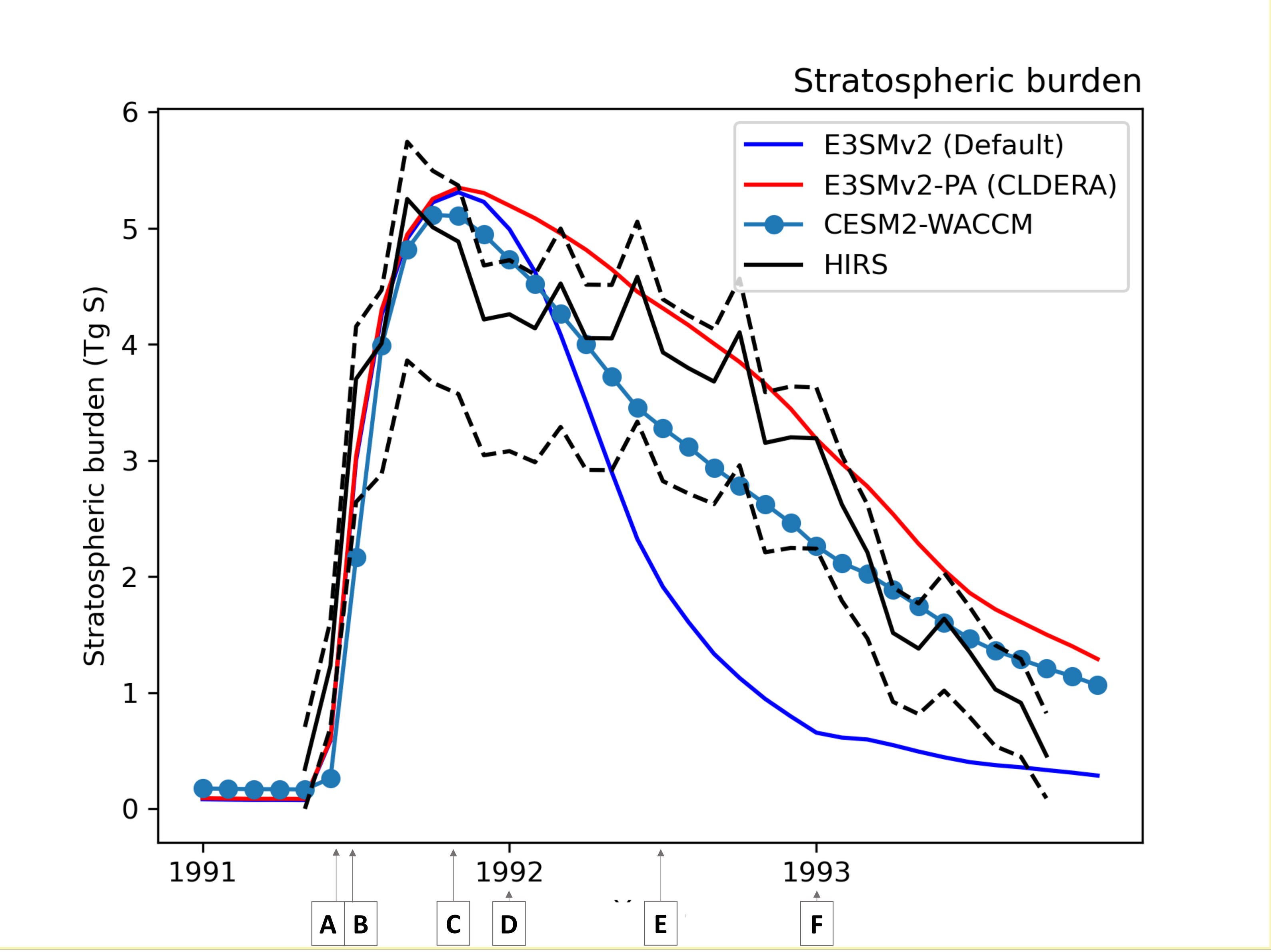
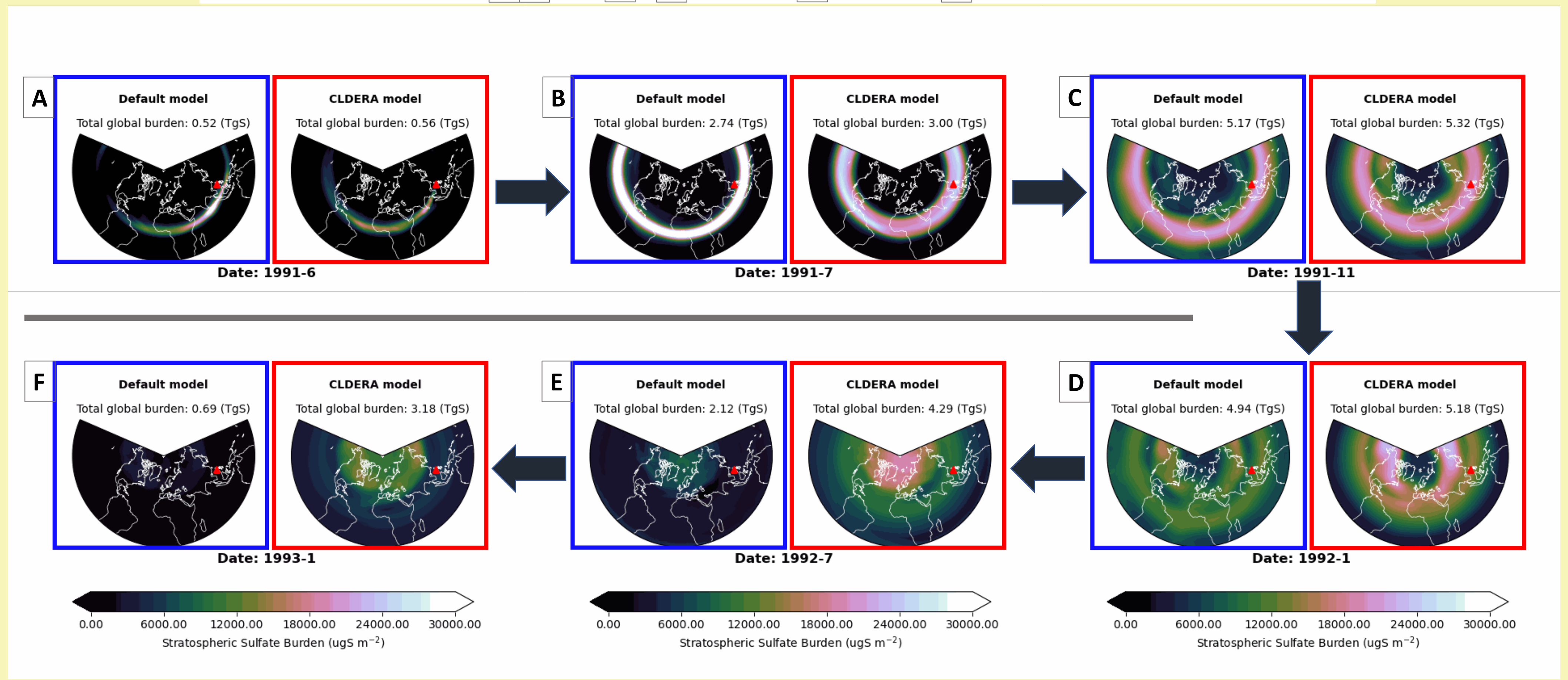


Figure 3 ↓ Global stratospheric mass burden from E3SMv2 and E3SMv2-PA from select times (A-F) in Fig. 2. The blue boxes denote E3SMv2 and the red boxes denote E3SMv2-PA.



V. Aerosol Optical Depth (AOD)

- **E3SMv2-PA improves modeled AOD compared to AVHRR data in the first ~6 months following the Mt. Pinatubo eruption.**
- E3SMv2-PA displays a greater seasonality than CESM2-WACCM and AVHRR, due in part to contributions to global AOD from dust and sea salt.

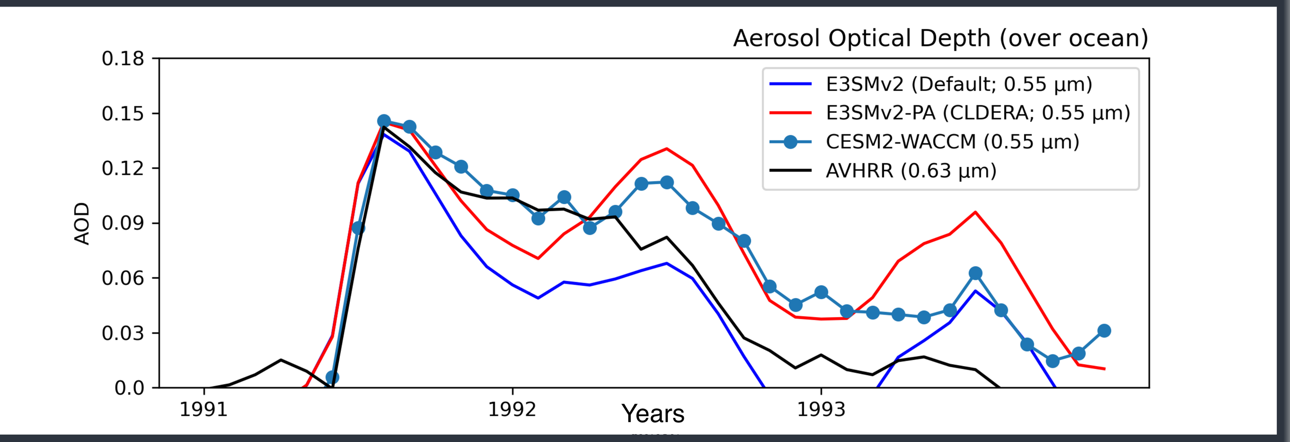


Figure 4: Aerosol optical depth (AOD) over the ocean. Models report AOD at 0.55 μm wavelengths, while AVHRR reports AOD at 0.63 μm. The respective annual averages from 1990 are subtracted from the models and AVHRR (hence the negative values in E3SMv2). Model data has been masked to reflect the same temporal and spatial data sampling as AVHRR.

VI. Aerosol Stratospheric Effective Radius

- **Aerosol effective radius from E3SMv2-PA is much closer to UARS derived values than E3SMv2 or CESM2-WACCM.**
- Future work will look aerosol size distributions to understand multi-modal behavior and aerosol number influence on E3SMv2-PA improvement

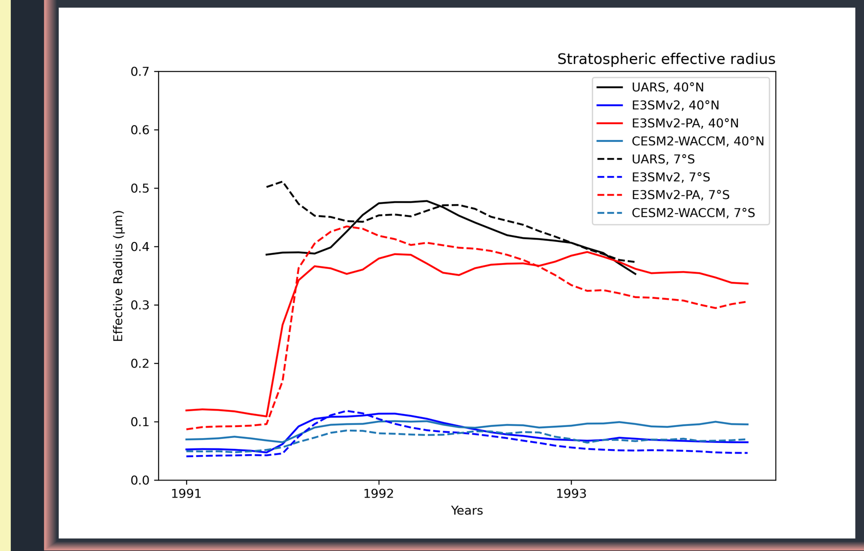
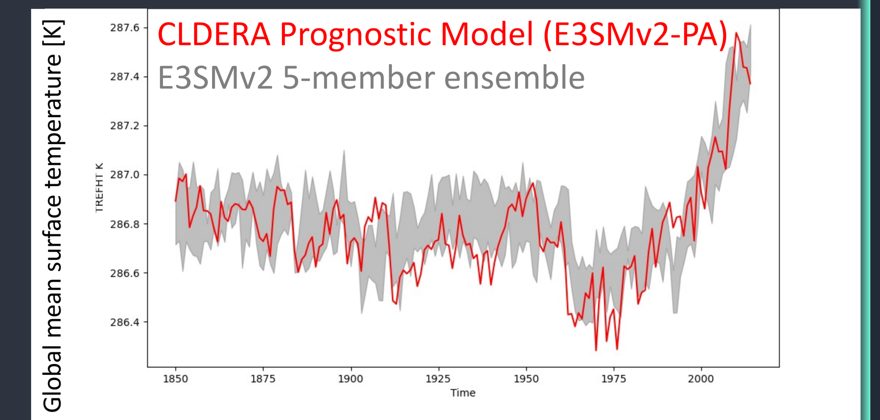


Figure 5: Stratospheric aerosol effective radius from models and UARS observations, averaged over 40˚N (solid lines) and 7˚S (dashed lines) latitude bands. Effective radius is derived from the ratio of total aerosol volume to total aerosol cross-sectional area. In the model simulations, these quantities are calculated from Aitken, accumulation, and coarse size modes. Due to 100 hPa limit on UARS measurements, all data are column averaged at pressures below 100 hPa.

VII. Historical Simulation with E3SMv2-PA

- Historical simulation with E3SMv2-PA is similar to default E3SMv2.
- Anomalously weak E3SMv2-PA global cooling after 1991 Mt. Pinatubo eruption in attributed to a positive simulated ENSO from 1990 to mid-1992.

Figure 5: Historical simulations (1850-2014) of global mean 2m reference height temperature from E3SMv2-PA and the 5 ensemble range from the E3SMv2 DECK historical simulations (*Golaz et al., 2022*).



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