CLDERA Tiered Verification: HSW++ Idealized Volcanic Aerosol Forcing

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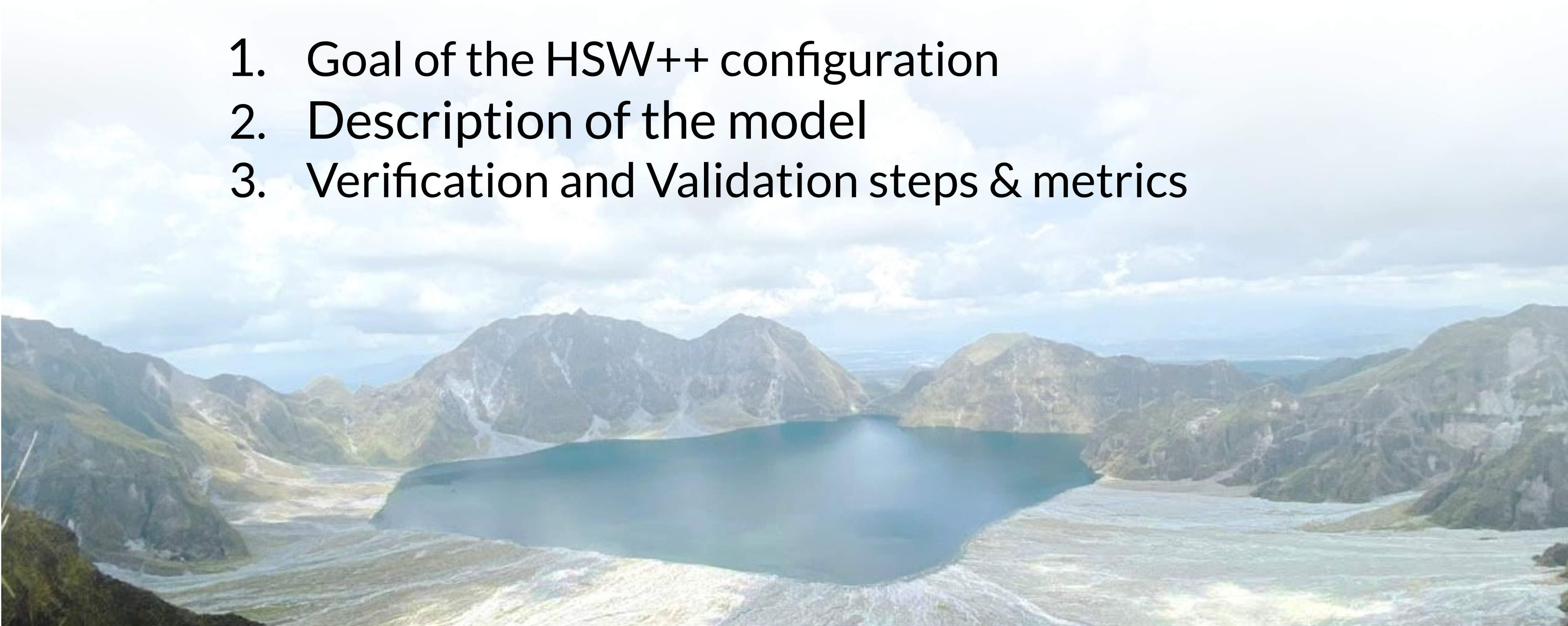
CLDERA All-Hands Meeting
Sandia National Laboratories, Albuquerque NM
July 27, 2022

Outline



1. Goal of the HSW++ configuration
2. Description of the model
3. Verification and Validation steps & metrics

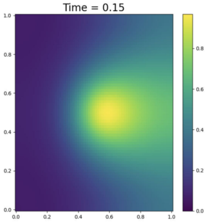
Tiered Verification & Validation

To answer the proposed science questions, CLDERA is pursuing a strategy of ***Tiered Verification & Validation***

- ***Verification***: Have we implemented what was intended to be implemented?
- ***Validation***: Do the implemented tools meet their target metrics?

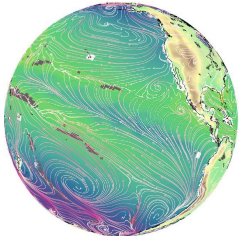
- Data products need to be designed for the testing of pathway-discovery and attribution methods; should be offered in ***tiers of increasing complexity***

Model complexity



2-D “Plume+” Tracer model

- 2-dimensional tracer model
- Prescribed winds
- Very simple and controlled environment



Full-complexity E3SM

- Active chemistry and radiation
- Fully-coupled climate model

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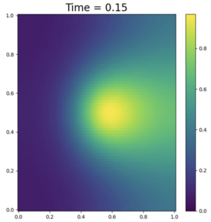
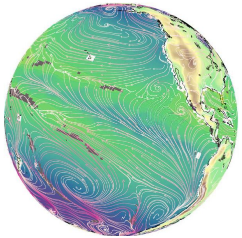


2-D “Plume+” Tracer model

- 2-dimensional tracer model
- Prescribed winds
- Very simple and controlled environment

Our “idealized model”

- Embedded in GCM
- Forcings terms are as few and as simple as possible



Full-complexity

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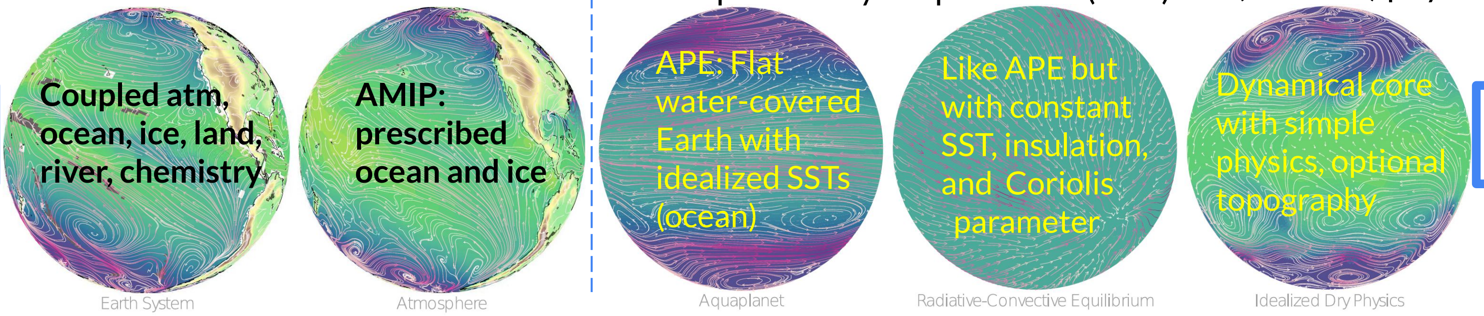
Building Bridges Across the GCM Model Hierarchy

Full complexity

Realistic climate configurations



Coupled System

Coupled atm, ocean, ice, land, river, chemistry

Atmosphere & Land

AMIP: prescribed ocean and ice

Aquaplanet: Atmosphere only

APE: Flat water-covered Earth with idealized SSTs (ocean)

Radiative-Convective Equilibrium (RCE)

Like APE but with constant SST, insulation, and Coriolis parameter

Dycore with idealized dry (or moist) physics

Dynamical core with simple physics, optional topography

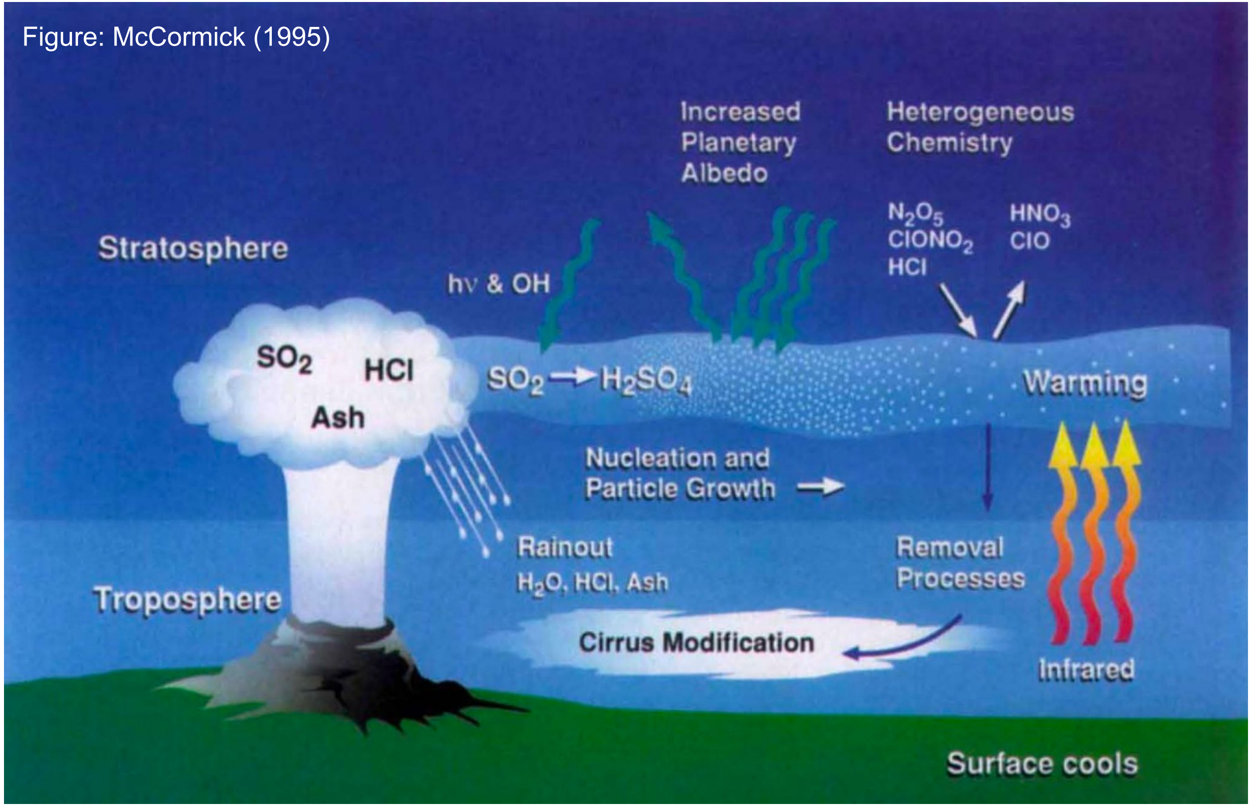
Reduced complexity

Modified from Maher et al. (2019), Fig. 7

Our work (dry)

Pont du Gard Aqueduct near Avignon, France

1991 Eruption of Mt. Pinatubo - Pathway Schematic



Schematic of immediate effects to local energy balance by stratospheric loading of SO_2 and sulfate aerosols

Absorption of upward-travelling longwave radiation causes net warming of stratosphere

Decrease of shortwave radiation reaching the surface due to increased aerosol optical depths (AOD) causes net cooling of surface

- The important nodes in the pathway are:
  SAI → secondary aerosols (sulfate) → radiation effects → temperature

1991 Eruption of Mt. Pinatubo - Pathway Schematic

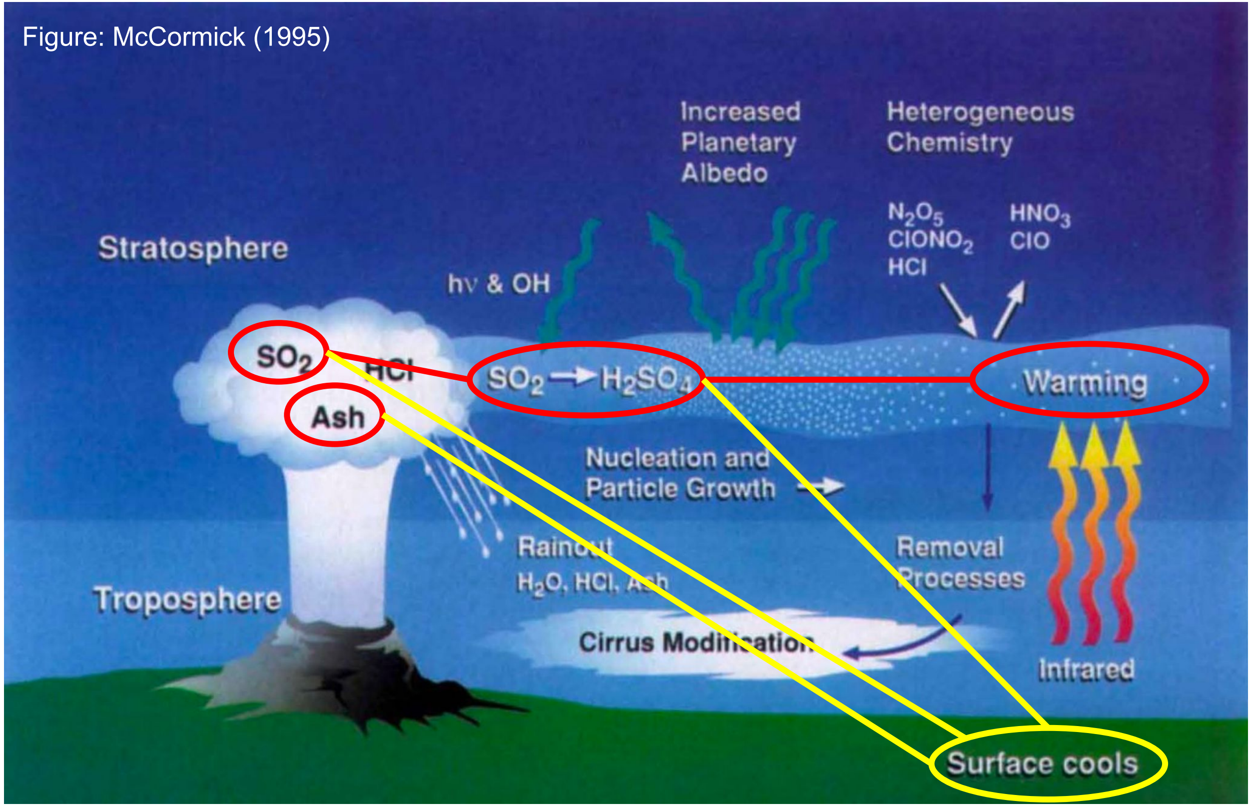


Figure: McCormick (1995)

In addition to simplifying the climatological forcing (HSW), we also simplify the relevant Pinatubo climate-impact *pathways*

Attempt to describe processes between source-impact pairs with *as few forcing terms as possible*

Straight lines (═) represent direct couplings by analytic functions

- The important nodes in the pathway are:
  SAI → secondary aerosols (sulfate) → radiation effects → temperature

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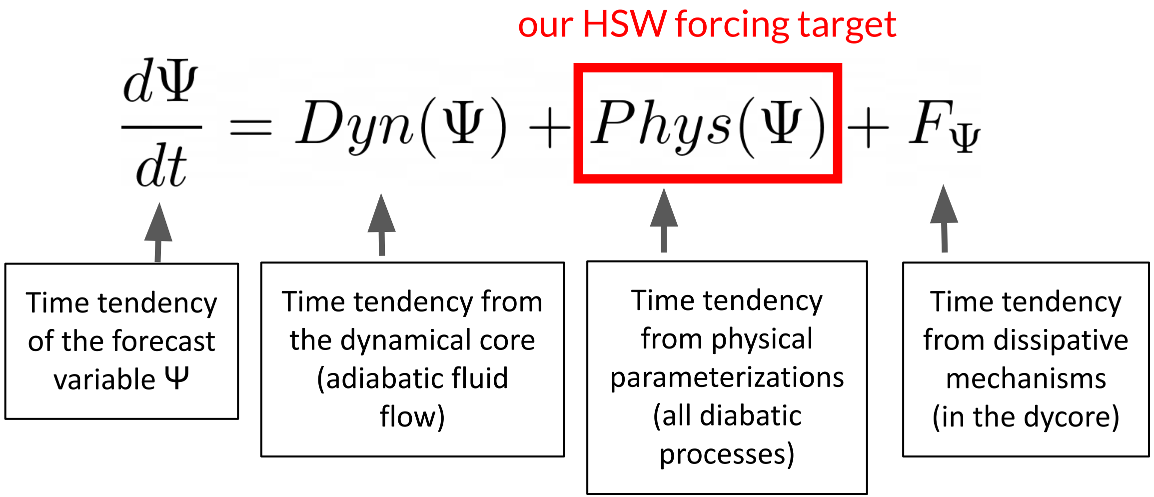
Idealized Held-Suarez-Williamson (HSW) Forcing

Main idea: replace the complex physics package with processes that are:

- just complex enough to allow simulations of an idealized ‘climate’ (resembling nature)
- simple enough to allow tractability of flow features embedded in this environment
    - “cleaner”, i.e. fewer couplings/feedbacks between processes
    - Lower *conceptual* and *computational* complexity

- The HSW forcing for **dry** dynamical cores mimics the **planetary boundary layer (PBL) mixing** via Rayleigh friction and replaces the **radiation** with a Newtonian temperature relaxation.



Prognostic GCM variables are forced by:

our HSW forcing target

$$\frac{d\Psi}{dt} = Dyn(\Psi) + \boxed{Phys(\Psi)} + F_\Psi$$

Time tendency of the forecast variable Ψ

Time tendency from the dynamical core (adiabatic fluid flow)

Time tendency from physical parameterizations (all diabatic processes)

Time tendency from dissipative mechanisms (in the dycore)

Idealized HSW Forcing plus Simple Pathway Mechanisms

Physical Parameterizations	Replaced by Idealized HSW Physics
Microphysics	none
Macrophysics	none
Deep convection	none
Shallow convection	none
Gravity wave drag	none
Radiation	Newtonian temperature relaxation
Surface fluxes	none
Planetary boundary layer turbulence	Rayleigh friction

Modules	Replaced by (for embedded pathways)
Chemistry module	none or ‘toy chemistry’
Aerosol module	none or ‘sulfate’ (via toy chemistry) & ‘AOD’ (via aerosol column burden) analogues

$\boxed{Phys(\Psi)}$ functions

$$\frac{\partial T}{\partial t} = -\frac{1}{k_T(\phi, p)}\left[T - T_{eq}(\phi, p)\right]$$

$$\frac{\vec{v}_h}{\partial t} = -\frac{1}{k_v(p)}\,\vec{v}_h$$

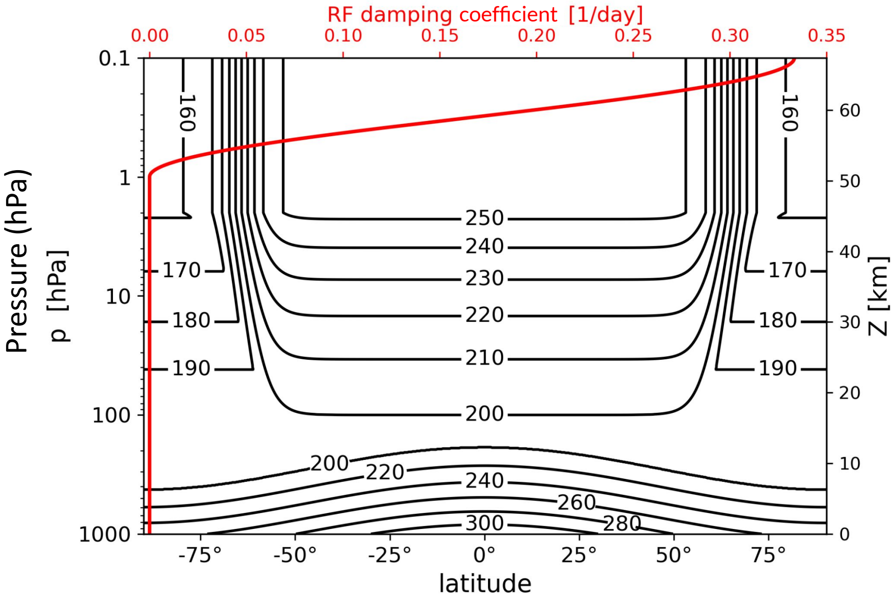
- k_v and k_T are spatially-dependent relaxation coefficients
- T_{eq} is a prescribed equilibrium temperature (see next slide)

See Held and Suarez (1994), Williamson et al. (1998)

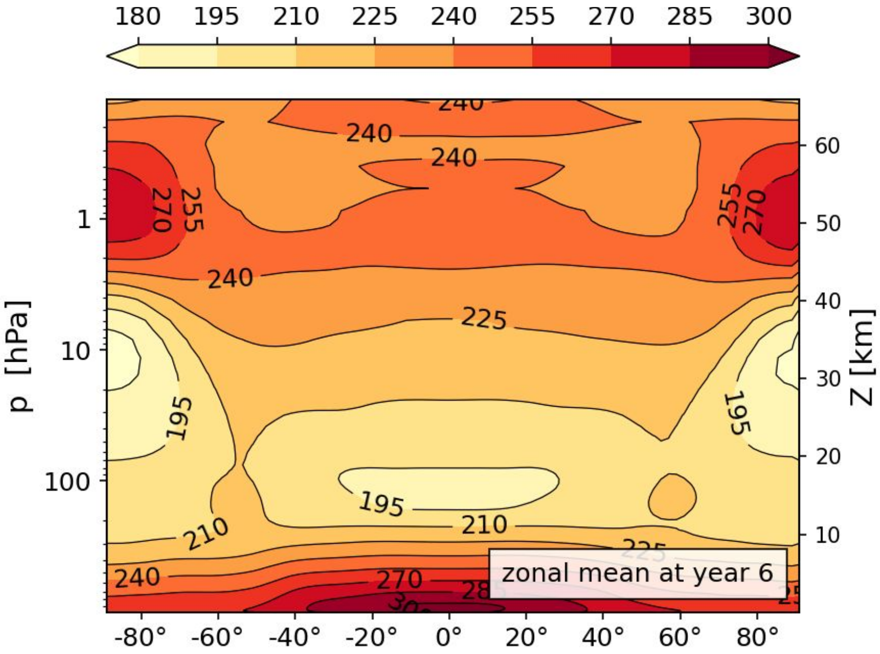
Description of the HSW forcing & Initial Conditions (IC)

- All radiation processes approximated by the relaxation to the HSW equilibrium temperature profile T_{eq}
- Two Rayleigh friction (RF) layers
  - at lower levels below 700 hPa mimicking the PBL turbulence/mixing
  - RF mixing above 1 hPa in the sponge layer to absorb upward propagating waves (up to E3SMv2 model top at >60km, ~0.1hPa

HSW Equilibrium Temperature T_{eq} (K) and strength of the RF sponge (red curve)

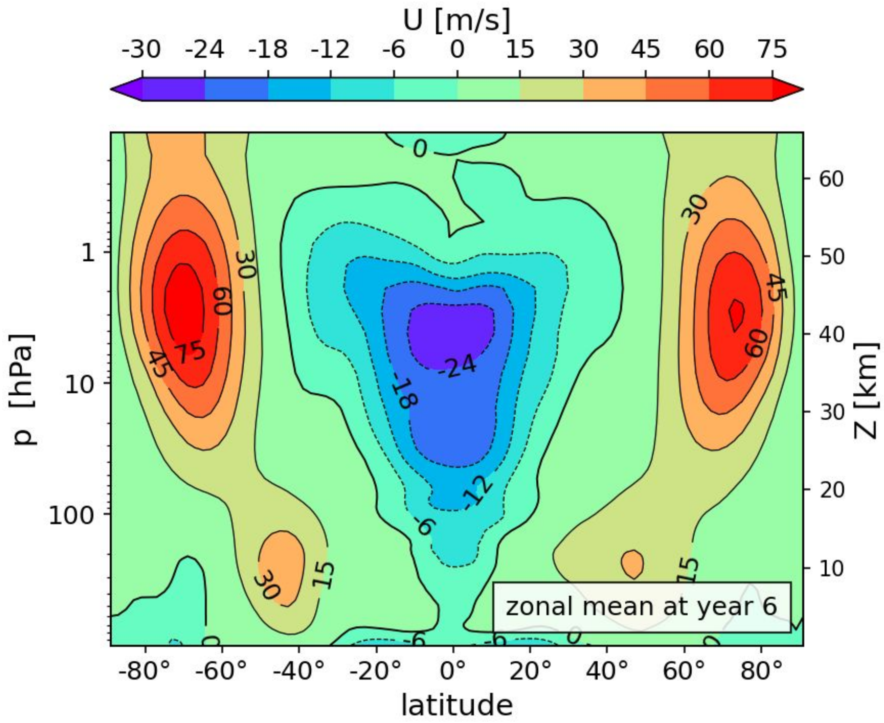


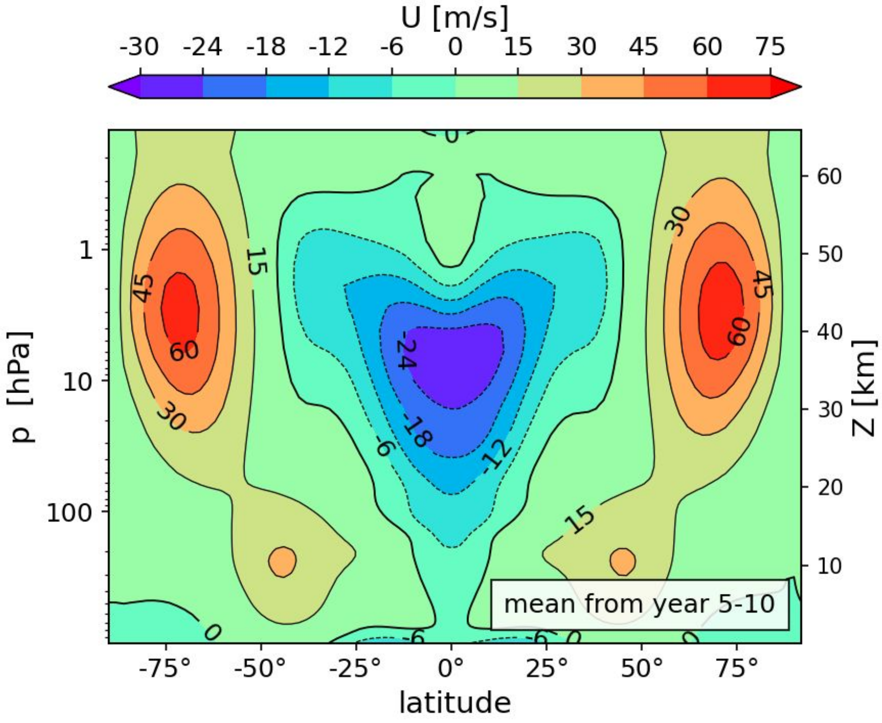
Initial state (after a 6-year spin-up from a state of rest): Temperature T (K), ne16L72 (200 km), E3SMv2



HSW Climate Response is Quasi-Realistic

- Time-mean zonal-mean zonal wind U (m/s) climatology mimics Earth
- Circulation is quasi-realistic with mid-latitudinal and polar jets caused by latitudinal T gradients



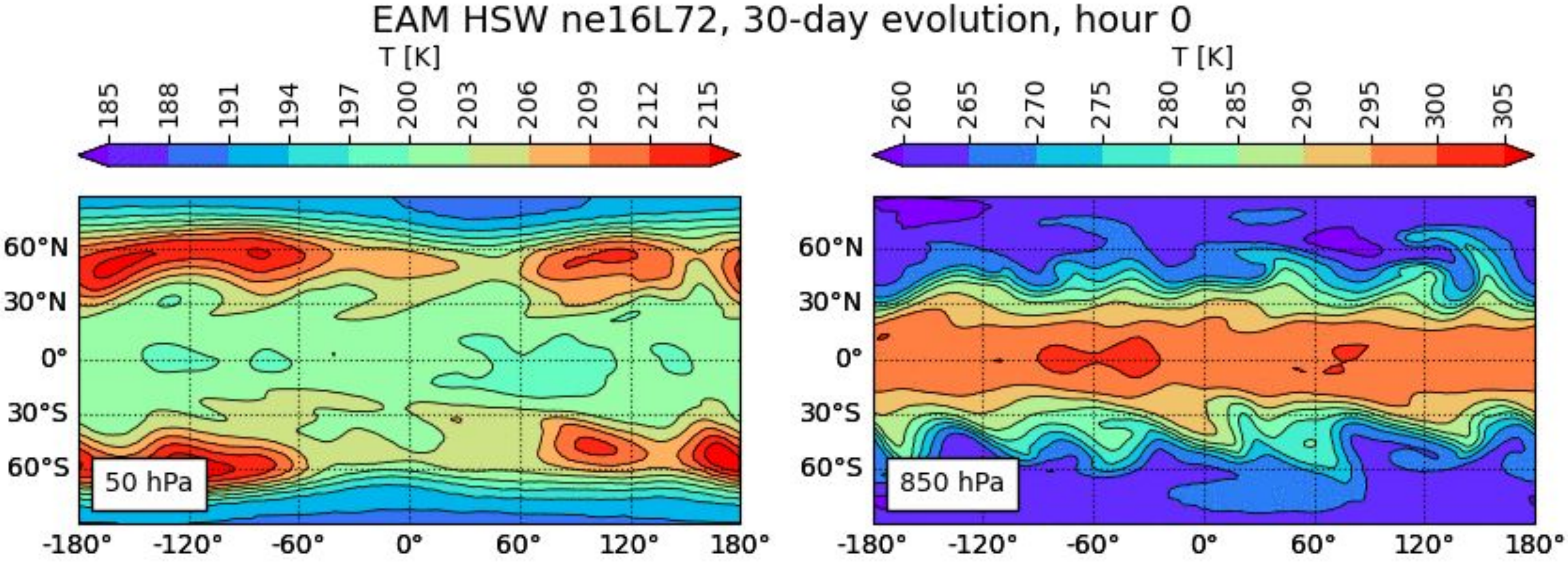


HSW: Snapshots of the Temperature are Quasi-Realistic

Though steady state is highly symmetric, small-scale motions and internal variability are quasi-realistic

Animations of the 30-day temperature (T) evolution in the:

- stratosphere (50 hPa, ~20 km, left)
- lower troposphere (850 hPa, ~1.5 km, right)



The Injection Model:

Idealized Etiological Pathways Triggered by Tracers

Simple *Stratospheric Aerosol Injection* (SAI) event modelled uniformly over a column, with prescribed time limit and vertical profile

- The *mass tendency for tracer j* (e.g. SO2) is a function of the injection source *f* and a linear sink *R* representing chemical removal:

$$\frac{\partial m_j}{\partial t} = R(m_j) + f$$

Sink:

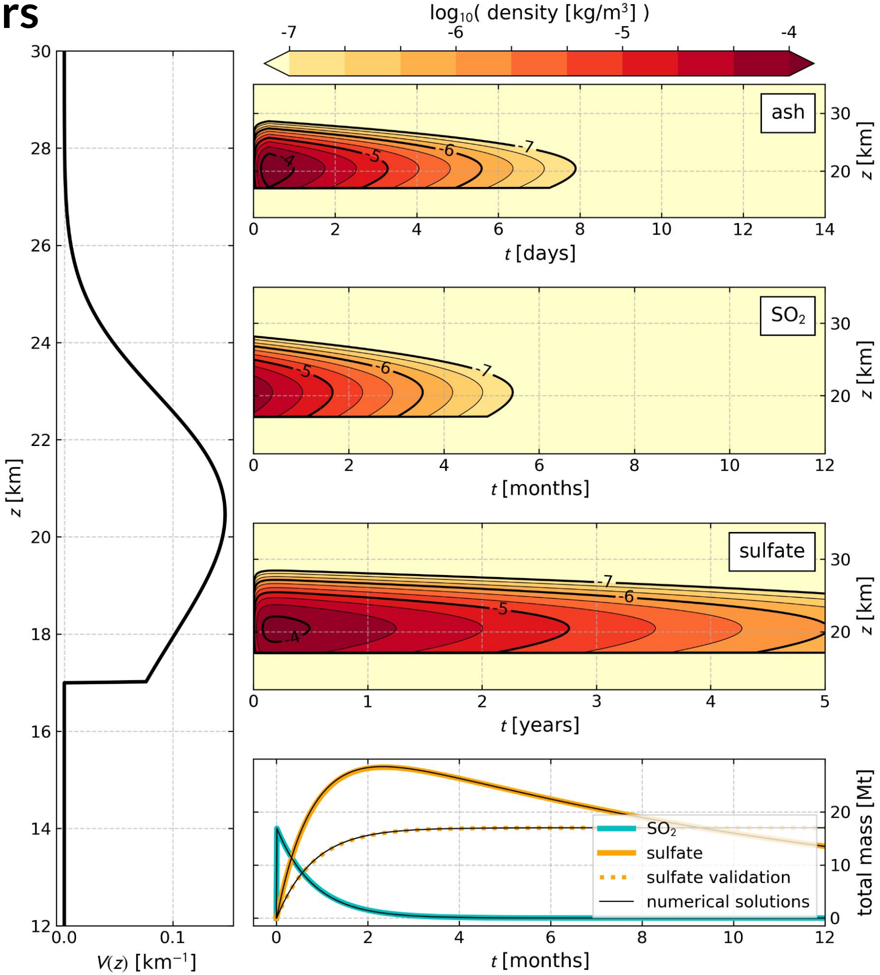
$$R(m_j) = -k_j m_j$$

Source:

$$f = \underset{\substack{\uparrow \\ \text{Amplitude}}}{A_j}\,\overset{\substack{\text{Vertical shape} \\ \downarrow}}{V(z)}\,\underset{\substack{\uparrow \\ \text{Time} \\ \text{dependency}}}{T(t)}\,\overset{\substack{\text{Selects} \\ \text{column} \\ \downarrow}}{\delta_{i,i^*}}$$

z: height
k: inverse removal time scale

Analytic advection-free solution for single column



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$$\frac{\partial m_j}{\partial t} = R(m_j) + f$$

Sink:

$$R(m_j) = -k_j m_j$$

Source:

Vertical shape

Selects column

$$f = A_j V(z) T(t) \delta_{i,i^*}$$

Amplitude

Time dependency

- Skew-normal vertical profile informed from Sheng et al. (2015) 2D Pinatubo ensemble studies:

$$f(z) = \frac{2}{\sqrt{2\pi}\sigma}\exp\left(-\frac{(z-\mu)^2}{2\sigma^2}\right)\int_{-\infty}^{\alpha\frac{z-\mu}{\sigma}}\frac{1}{\sqrt{2\pi}}e^{-\frac{x^2}{2}}\,dx$$

scale

location

skewness

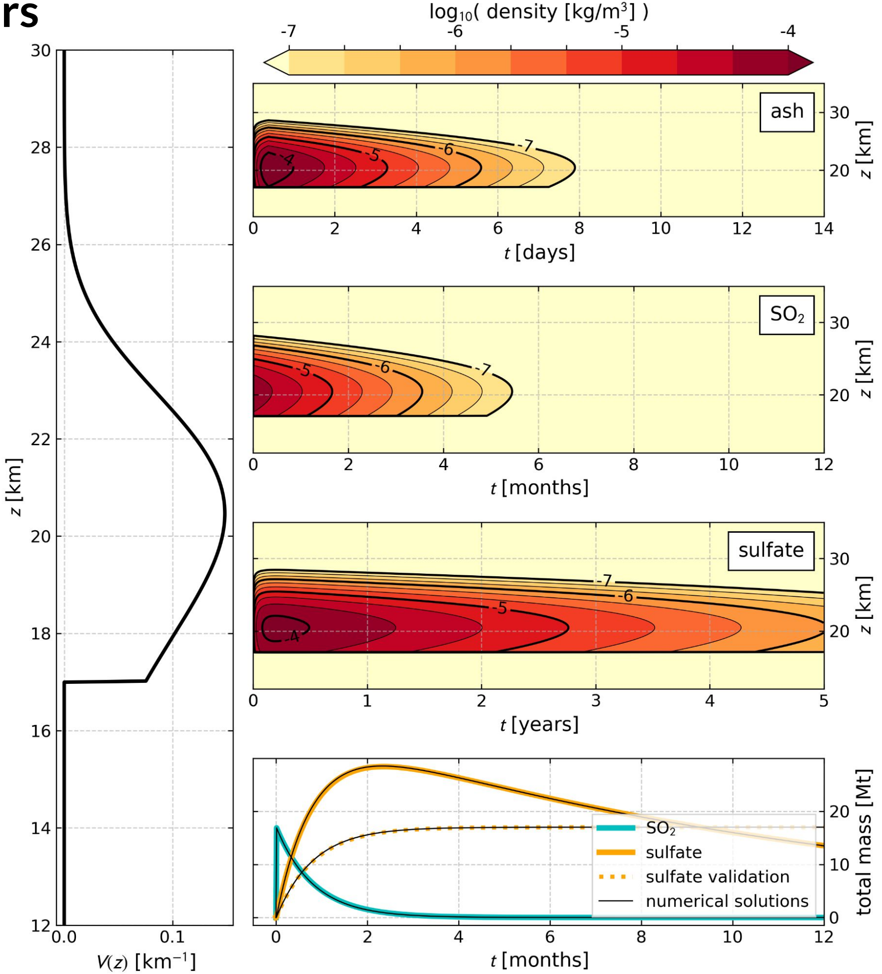
- Sulfate formation modeled directly with inverse SO2 removal term:

sulfate removal timescale

reaction mass weighting

$$\frac{\partial m_{\text{sulfate}}}{\partial t} = -k_{\text{sulfate}} m_{\text{sulfate}} + w k_{\text{SO2}} m_{\text{SO2}}$$

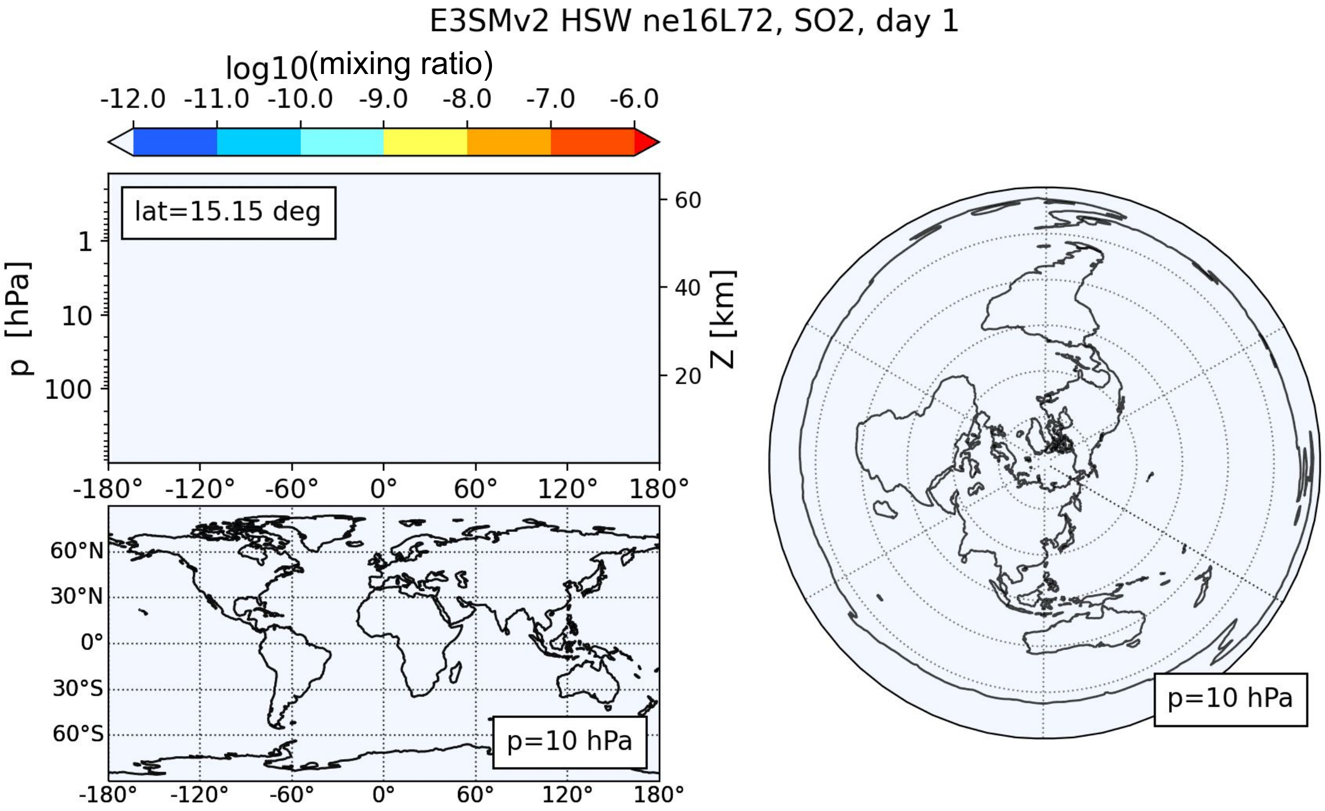
Analytic advection-free solution for single column



SO_2 Evolution in E3SMv2 HSW (over 30 days)

17 Mt SO_2 injected over 9-hour period near (15 N, 120 W)

Circulates the globe in ~15 days; quasi-realistic!



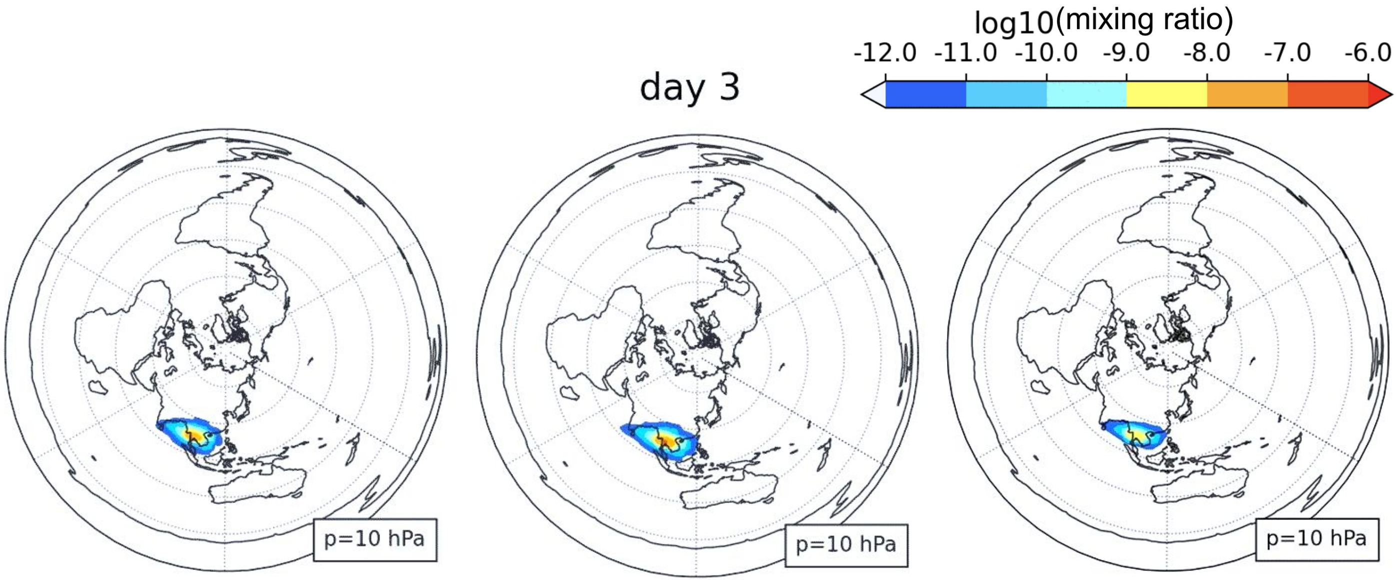
Tracer Evolution in E3SMv2 HSW (over 90 days)

17 Mt SO2, 50 Mt ash injected over 9-hour period near (15 N, 120 W)

SO_2 Circulates the globe in ~15 days. **Sulfate** mixing ratios are ~2 orders of magnitude higher than SO_2 by 3 months

Ash dissipates below 1e-12 by day ~15, reaching the west coast of North America (halfway around the globe)

SE ne30L72, HSW



ash
1-day removal

SO2
25-day removal

Sulfate aerosol
360-day removal

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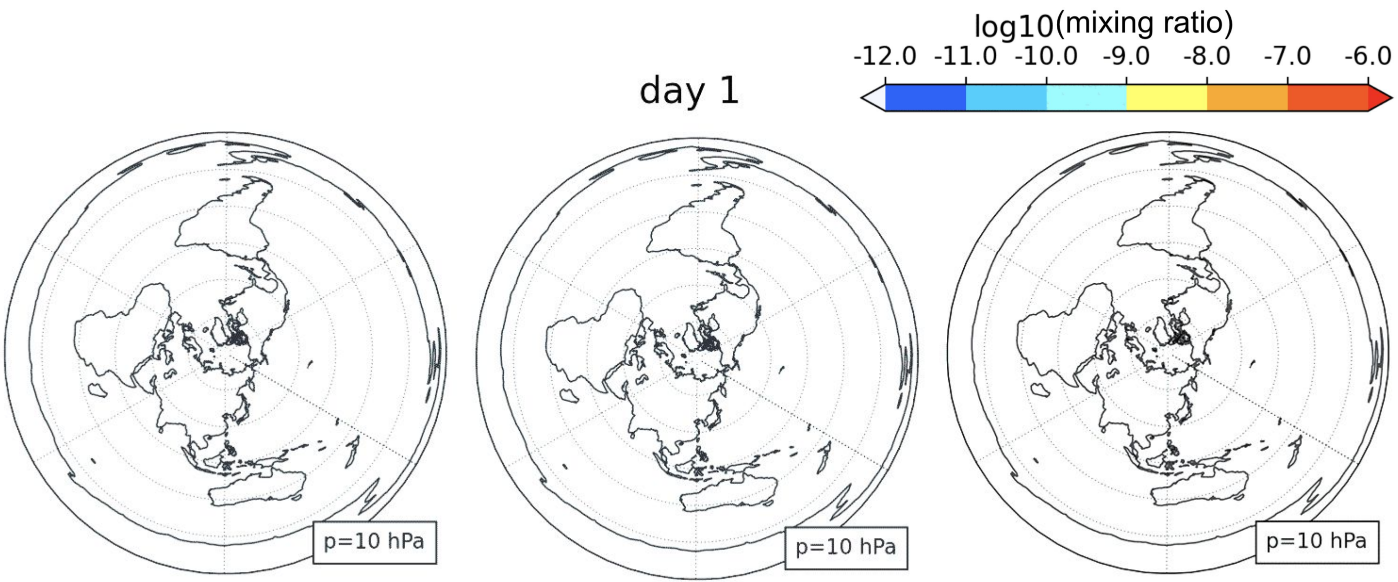


ash
1-day removal

SO2
25-day removal

Sulfate aerosol
360-day removal

Pathway 1: Local Diabatic Heating of the Stratosphere

- Stratospheric heating is directly connected to SO_2 and sulfate mixing ratios

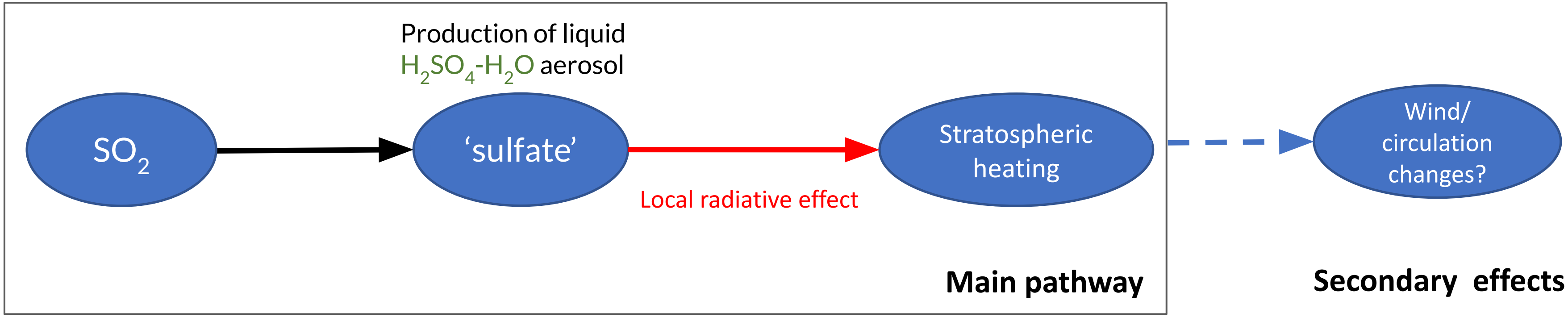
Model this via a heating rate per unit mass, influencing the temperature tendency

SO_2 , sulfate mixing ratio

$$s_{\text{strat}} \equiv \boxed{\frac{Q_{\text{strat}}}{m}} = \frac{q c_p \delta T_{\text{strat}}}{q^*} \qquad \boxed{\frac{\partial T}{\partial t}} = \ldots + \frac{q \delta T_{\text{strat}}}{q^*}$$

heating mag. = **0.3 K/day**

normalization



Production of liquid H_2SO_4-H_2O aerosol

SO_2

'sulfate'

Local radiative effect

Stratospheric heating

Wind/ circulation changes?

Main pathway

Secondary effects

Pathway 2: Local Remote Cooling of the Surface

- Surface cooling is directly connected to aerosol optical depth (AOD)

  Model this analogously to the stratospheric heating, after computing the AOD τ:

AOD at column i

Column burden of tracer j

$$\tau_i = \sum_j b_j M_{j,i}$$

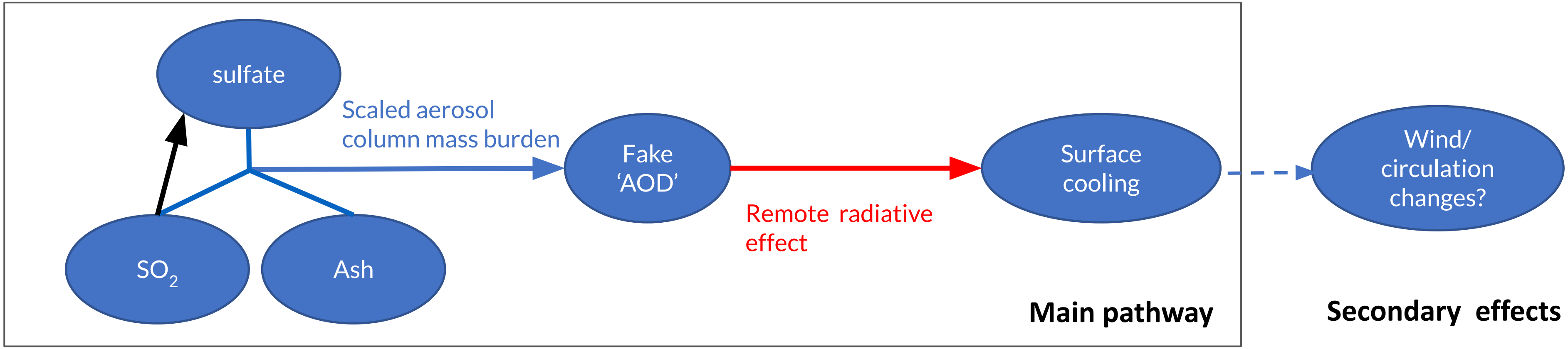
Mass-extinction coefficient

$$s_{\text{surf}} \equiv \frac{Q_{\text{surf}}}{m} = \frac{\tau c_p \delta T_{\text{surf}}}{\tau^*}$$

cooling mag. = 0.01 K/day

$$\frac{\partial T}{\partial t} = \ldots \frac{\tau \delta T_{\text{surf}}}{\tau^*}$$

normalization



sulfate

SO_2

Ash

Scaled aerosol column mass burden

Fake 'AOD'

Remote radiative effect

Surface cooling

Wind/ circulation changes?

Main pathway

Secondary effects

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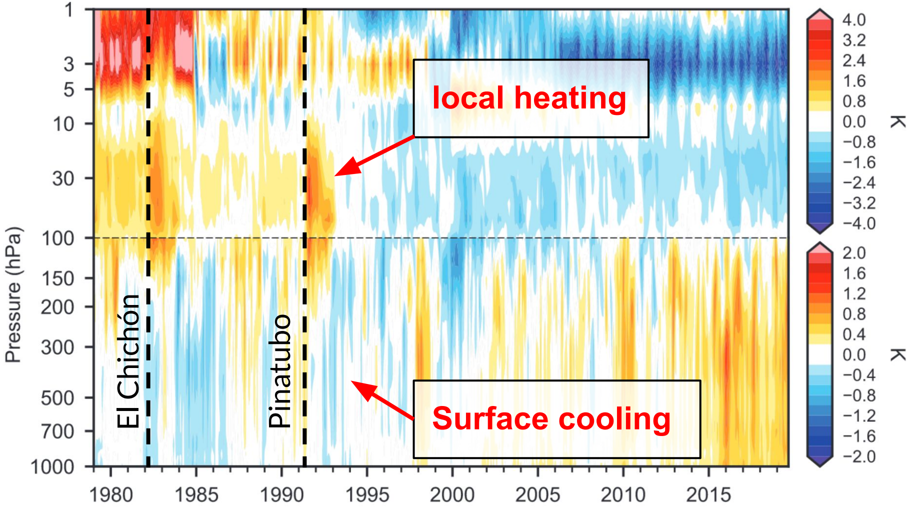
Climate Response to Pinatubo

Global response post-eruption:

- Negative anomaly in global mean surface temperature by up to 2-5 °C through 1993
- Positive temperature anomalies at the 30 hPa level (stratosphere) of up to ~3.5K

Global mean temp. anomaly

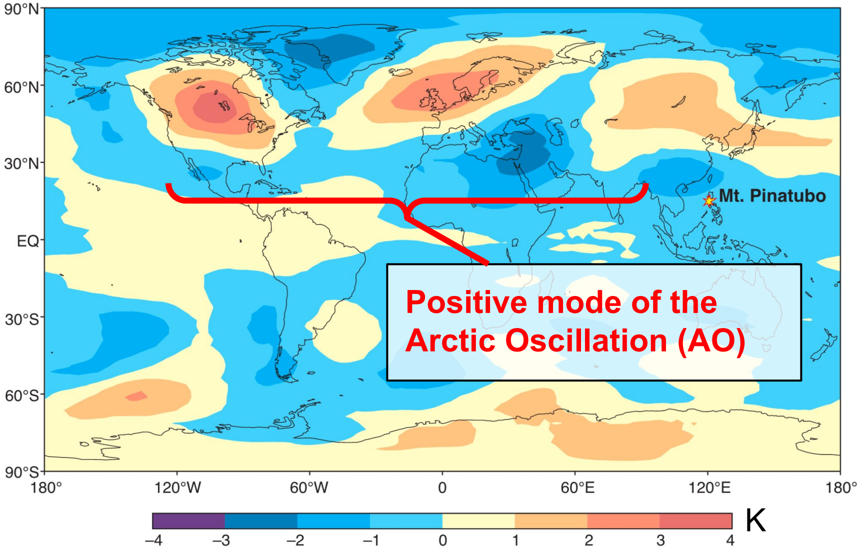


Data from ERA5 global reanalysis, Hersbach et al. (2020)

Zonally-asymmetric tropospheric response post-eruption:

- Positive temperature anomalies in North America, Europe, Siberia
- Negative temperature anomalies in Alaska, Greenland, the Middle East, China
- Follows all large, sulfate-rich explosive erruptions
- Pattern known as the **Positive Mode of the Arctic Oscillation**, associated with **strong polar vortex**

Lower tropospheric temp. anomaly (12/1991-2/1992)

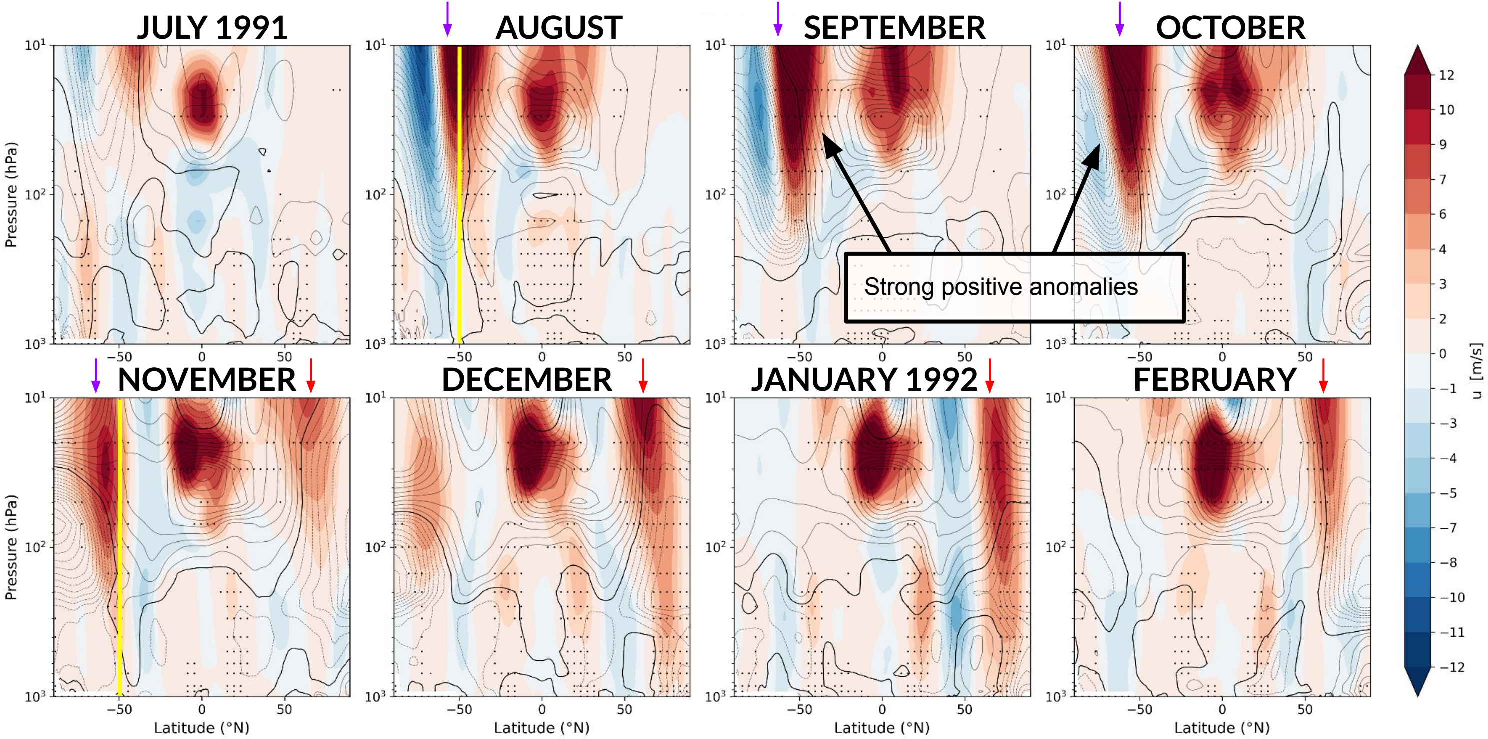


Data from Microwave Sounding Unit, Robock (2002)

Pinatubo Climate Response in E3SM CMIP5 Ensemble

Zonal wind anomalies following the Pinatubo eruption with respect to a 25-year climatological base period (1980-2004) in E3SMv1 CMIP5 AMIP (atmosphere-only) 3-member ensemble mean

- Initial response is the poleward shift of a strengthened southern polar jet (August-November 1991)
- Strengthening of northern polar jet during the winter following the eruption (November-February 1991)



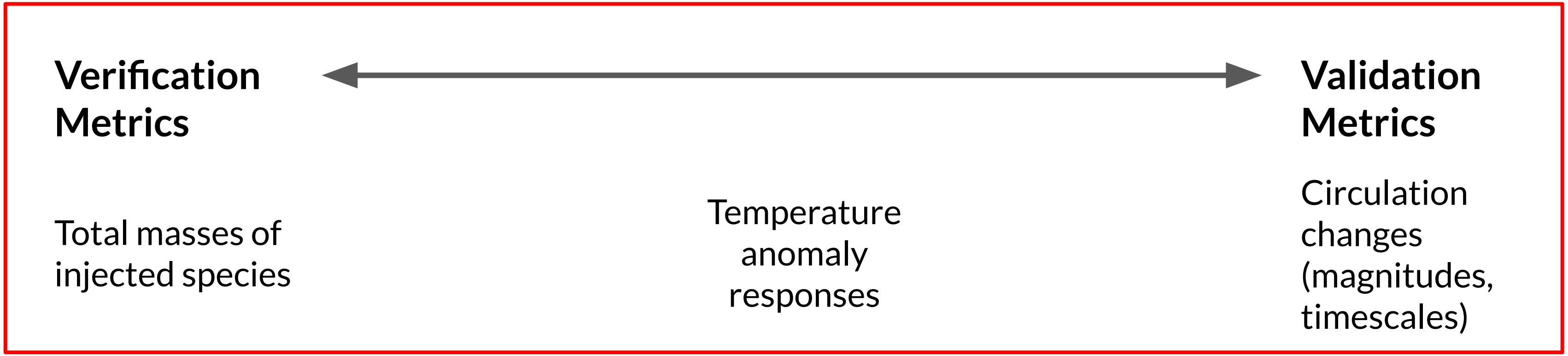
*Data is **ensemble mean** of **zonal-mean** zonal-wind*

Stippling gives locations where all ensemble members agree on the sign of the anomaly

All 3 ensemble members are in a positive QBO phase at 30 hPa

Yellow lines guide eye to see poleward shift of the anomaly

Verification & Validation of the HSW++ implementation



Verification Metrics

Validation Metrics

Total masses of injected species

Temperature anomaly responses

Circulation changes (magnitudes, timescales)

Verify that the injection implementation is correct

- Total masses at injection, over time
- Local heating, cooling rates

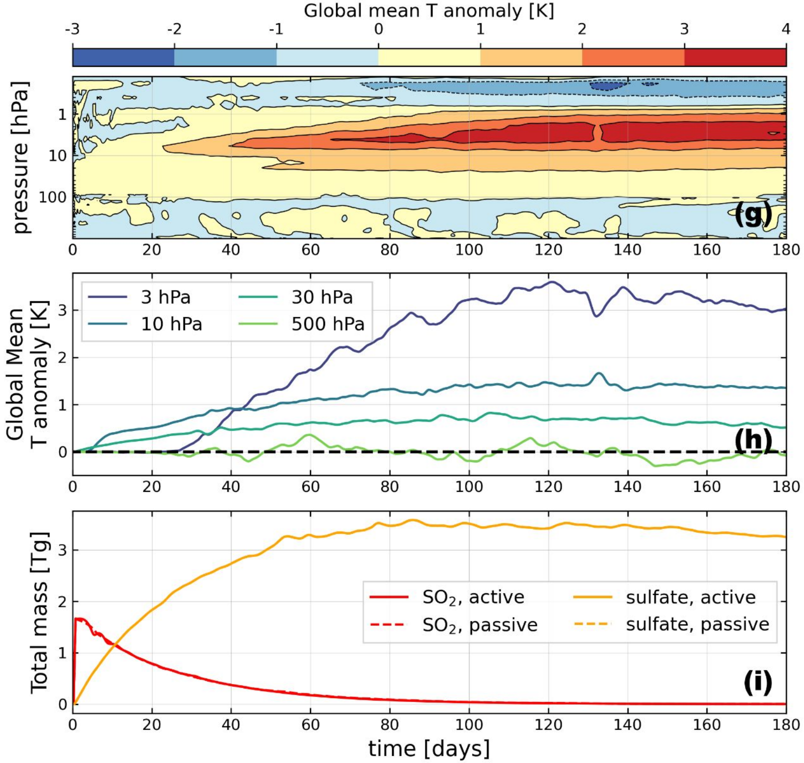
Validate that the model gives rise to a quasi-realistic climate response

- Global temperature anomalies
- Modifications to polar jets (magnitudes, timescales)

Preliminary Results from E3SMv2

180-day run subject to the **HSW forcing set**, with an **active idealized SAI** including SO2, sulfate, ash tracers (“anomalies” plotted = difference between run with/without heating terms, otherwise identical initial conditions)

- Realistic heating rates in the stratosphere of 3-4 K in the global mean ✓
- Realistic max local heating rates of 0.3 K/day ✓
- Realistic strengthening of the polar jets ✓
- Realistic timescales of SO2 decay and sulfate production ✓
- Normalization issue in the total tracer masses ✘
- Surface heating very weak - tuning required ✘
- Plume localization at unrealistically low pressures ✘



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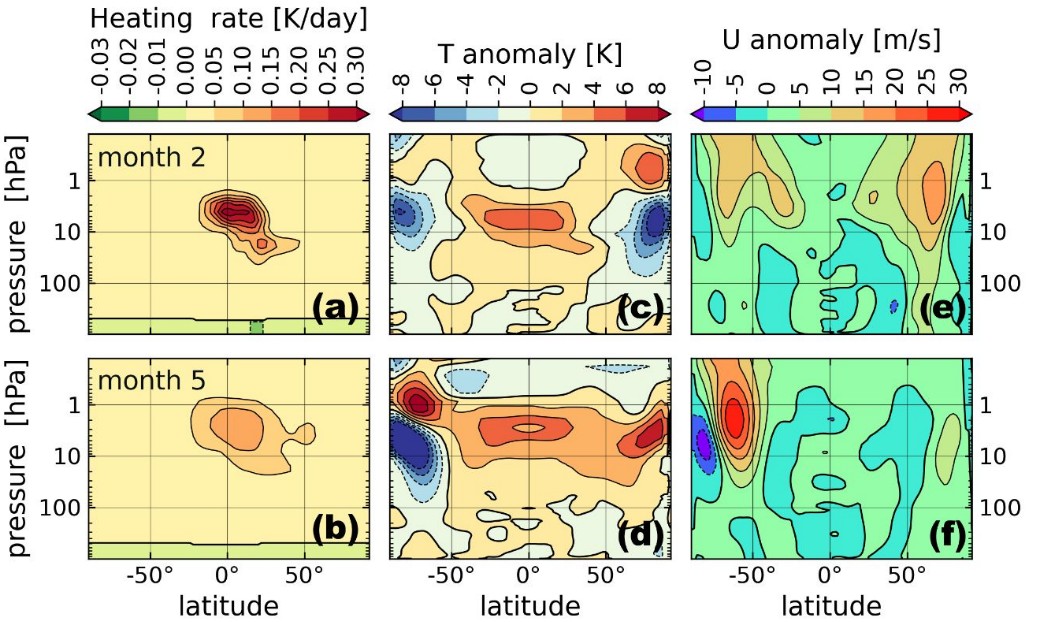


Next Steps

- Identify cause of total mass errors

- Iterate on tuning of the heating parameters

- Understand cause of rapid upward motion of tracer plume
    - May involve a more general investigation of the general and stratospheric circulation of HSW in E3SM; supported by other activities in the tracer sub-group (e.g. E90)

- Enable flexible usage of the configuration for the CLDERA Profiling Tools
    - (near completion; see Jerry's talk next)

Thank you!

1991 Eruption of Mt. Pinatubo - Fact Sheet

- Source: Main volcanic eruption released about 17-20 Tg of sulfur dioxide (SO_2) and 50 Tg of ash into the stratosphere (20-27 km)
- Sink: E-folding (removal) time is around 25 days for SO_2 and 1 day for ash
- Chemistry: SO_2 chemically interacts with other species (like OH, H_2O) to form sulfuric acid gas H_2SO_4 and liquid H_2SO_4-H_20 sulfate aerosols

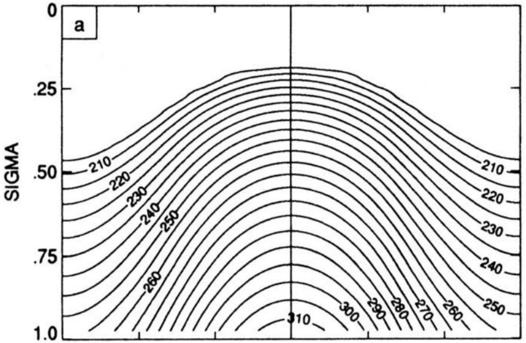
- Tracer advection & atmospheric circulation:
    - SO_2 circled the Earth within 3 weeks
    - Injected particles (and their radiative forcing) are initially confined within the tropics and subtropics before the aerosols reach the midlatitudes and poles after 3-4 months

- Forcing: Aerosols control radiative forcing
    - **Stratospheric heating** due to **absorption** of **long wave (LW)** and near-infrared **radiation** (SO_2 and H_2SO_4)
    - Surface/Troposphere cooling: sulfate scatters incoming short-wave (SW) solar radiation, overall cools the surface and troposphere, cooling dominates the overall response of the climate system for ≈ 2 years

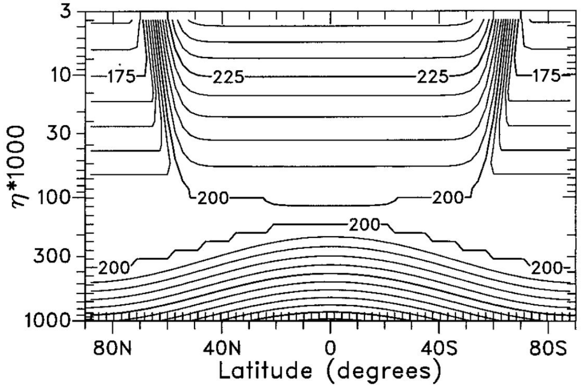
Any event of this nature is referred to as a *Stratospheric Aerosol Injection* (***SAI***) Event

Temperature Relaxation Profile

- Original T_{eq} from **Held and Suarez (1994)** one of the first standardized dycore benchmarks; designed with forcing toward a warmer equator and cooler poles, and high static stability in the tropics



- Modified T_{eq} from **Williamson et al. (1998)**; required "active" stratosphere while maintaining simplicity of original HS94 configuration, for their assessment of tropopause dynamics across model implementations



- This idealized configuration has evolved over the years in response to an increasing understanding of the importance of troposphere-stratosphere coupling, and therefore higher GCM model tops

Idealized configuration publications in context of stratospheric dynamics research

Boville & Baumhefner (**1990**)

"Tropospheric error growth rates increase with stratosphere degradation"

Held & Suarez (**1994**)

Williamson + (**1998**)

Baldwin & Dunkerton (**2001**)

"Stratosphere anomalies propagate to the troposphere within 1 week, impact circulation for up to 2 months"

Charlton+ (**2004**)

"Tropospheric forecast skill falls off when stratosphere ICs intentionally misspecified"

Future Work, Specific Aim 1: Validation of CLDERA Pathway Discovery Tools

Goal: Work with the pathway discovery and attribution tool developers to ingest HSW SAI datasets, serve as effective verification & validation for the methods

Primary use of the idealized data

- Can known pathways be recovered and new pathways discovered in our simulated data sets? How well do the simulated and observed pathways align? (magnitude, lag, extent, …)

Secondary use when using different ICs

- How does the QBO, ENSO, and / or NAO (a 'varying background state') impact the relationship between the eruption and temperature perturbation?

Another potential secondary use

- Can CLDERA identify the location and magnitude of the Mt. Pinatubo eruption from the temperature perturbation? How does the attribution change as a function of eruption characteristics and lag from eruption time? *(traditional inverse problem)*

(The elements in red are simplified in the idealized climate experiments)

Future Work, Specific Aim 1: Validation of CLDERA Pathway Discovery Tools

Specific tool examples from the Simulated Pathways working group:

Global Sensitivity Analysis (***GSA***):

- Studies sensitivity of the climate to the injection source terms
- Establish "anomaly threshold", below which causal pathways no longer discernible, which are most dominant in impact strength

Random Forest (***RF***) *Regression*:

- Create predictive models for climate impact
- Determine most important features along pathway
- Narrow search space for subsequent attribution efforts

Software Profiling:

- Traces a "simulations path"through a code
- Detects changes in global or local physical tendencies in-situ

How the HSW SAI simulations can support the verification & validation of these tracers:

Generation of **ensembles**, which vary:

- Injection source terms (localization, amplitude)
- Initial conditions of background state
- Active pathway components (heating, cooling)
- Heating term strengths, rates

In all any such runs: "Ground truth" is known (analytic forms of all pathway steps are known)

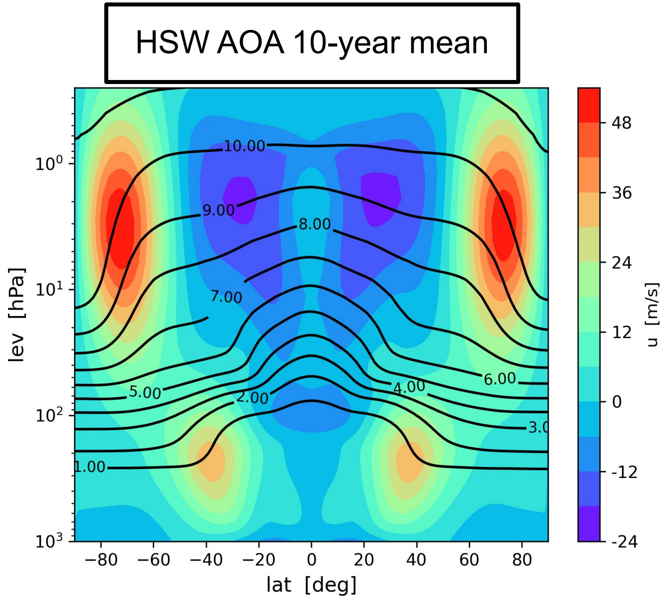
Future Work, Specific Aim 2: Assessment of E3SMv2 Stratospheric Circulation & Stratosphere-Troposphere Exchange

Done in part via metrics of the **realism of stratospheric structures**:

- Period of the *Quasi-Biennial Oscillation* (***QBO***)
- Frequency and strength of *Sudden Stratospheric Warmings* (***SSW***)
- *Brewer Dobson Circulation*

Also by implementation of **new *passive* tracer species** designed to return quantities which express features of the general circulation:

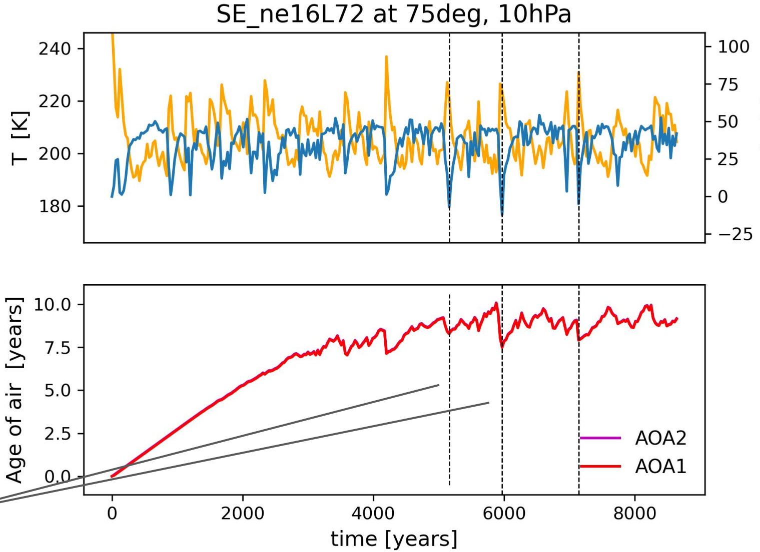
- *Age-of-air* (***AOA***): tracers which act as “clocks”, giving the mean time since last boundary-layer contact (strongly dependent on wave activity, SSWs, and other encouragements of stratospheric mixing)
- **E90**: tracer emitted from the surface with an e-folding decay timescale of 90 days (can assist in identification of the dynamical tropopause)



HSW AOA 10-year mean

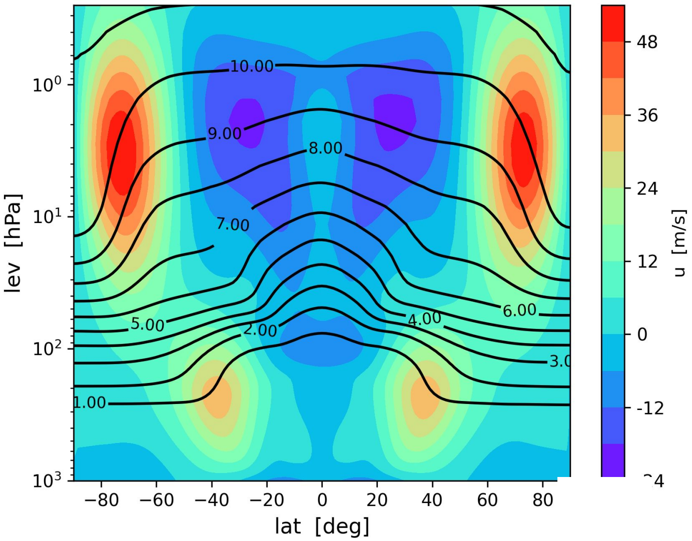
Future Work, Specific Aim 2: Assessment of E3SMv2 Stratospheric Circulation & Stratosphere-Troposphere Exchange

- Age-of-air (AOA) has a long spinup time (time to reach steady state) of at least 10 years
- This time is shortened (i.e. the oldest age contours are smaller in value) in the presence of more **stratospheric variability**
- This effect demonstrated by sharp drops in mean age at the position of the polar jet during a SSW event


SE_ne16L72 at 75deg, 10hPa

SSWs lower mean AOA at 10 hPa, as breakdown of polar jet allows mixing of younger air

AOA 10-year mean



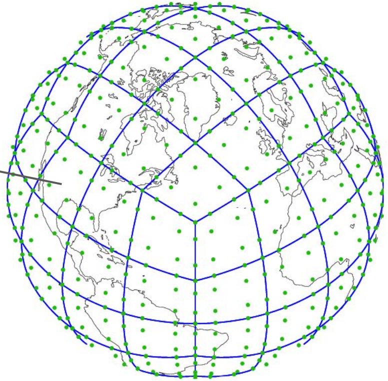
HSW: Scaling of the Problem on the “ne16pg2” grid

This idealized configuration scales well, but imperfectly

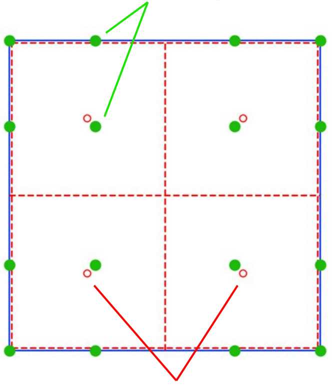
- Model runs presented here use cubed sphere with 16 cells (or “elements”) per side of each cubed sphere face (“**ne16**”) (16^2 = 256 elements per face, 256×6 = 1536 elements total)

- Subgrid physics are computed on a 2x2 grid (red open circles) internal to each element (“pg2”)
- Quantities are “remapped” back to the dynamics grid (green points) on each timestep

Example cubed-sphere **ne4** arrangement



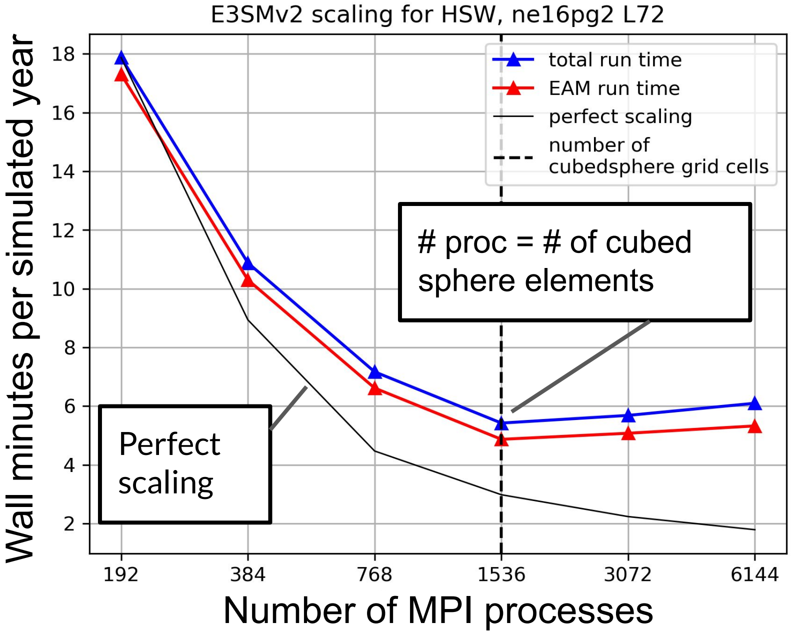
dynamics grid points



Physics grid points

Scaling on NERSC Cori KNL nodes with:

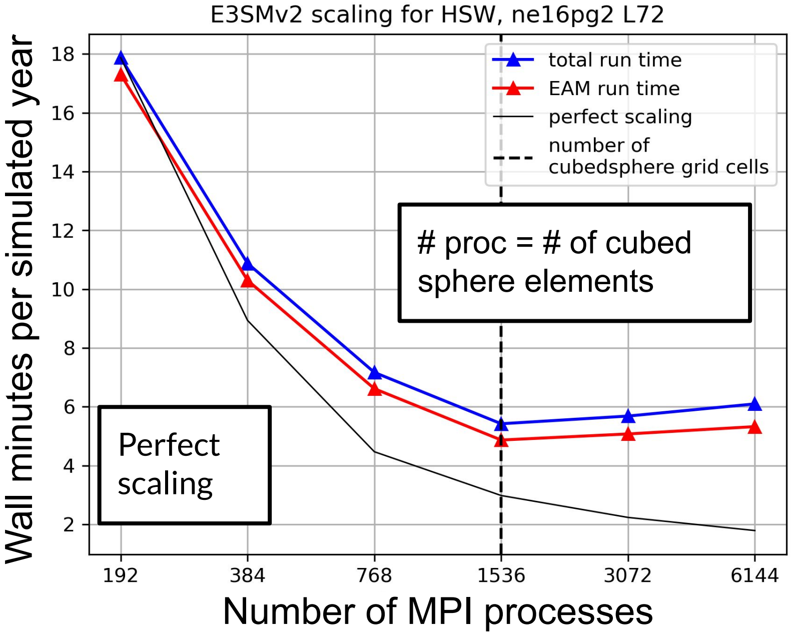
- **Dynamics** timestep of **15 minutes** **(**3rd order Runge-Kutte method**)**
- **Physics** timestep of **30 minutes** (1st order explicit scheme)



proc = # of cubed sphere elements

Perfect scaling

NERSC usage



proc = # of cubed sphere elements

Perfect scaling

- Cori KNL: **68 cores/node**
- With 384 processes (6 nodes):
  - 1 simulated year ~ 11 wall minutes ~ **1 node hour**
  - 10 years = 10 node-hours
- With 768 processes (12 nodes):
  - 1 simulated year ~ 7 wall minutes ~ **1.4 node hours**
  - 10 years = 14 node-hours
- Total consumption over development since January 2022 (6 months): **~1400 node-hours**
- **Note**, scaling test on right reports:
  - runtimes for HSW only; no active tracers
  - Runtimes for ne16pg2 only; was previously using ne16np4