A Simple Model of Volcanic Aerosol Forcing Against an Idealized Climatological Background in Support of the Sandia Labs CLDERA Project

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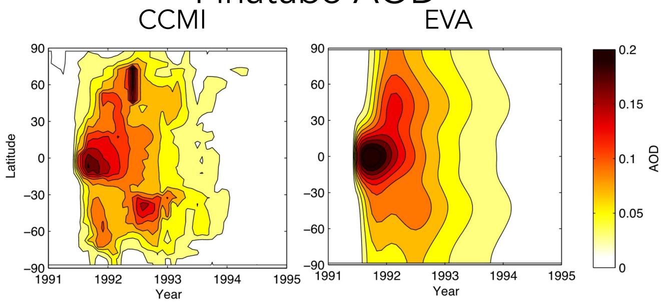
Idea: Finding Space in the Aerosol Model Hierarchy

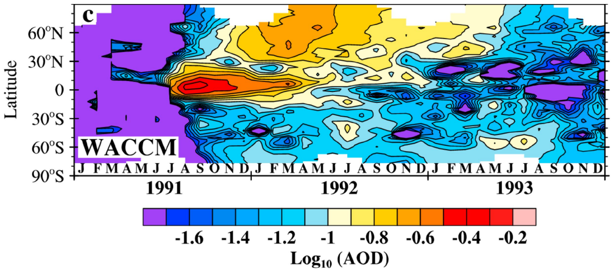
Aerosol Model Complexity

Pinatubo AOD



This work: intermediate complexity

Pinatubo log(AOD)



Prescribed forcings
e.g. CCMI, EVA

similar in structure
similar in simplicity/efficiency

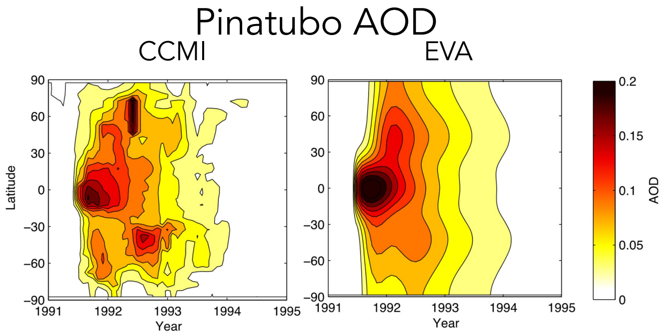
Prognostic aerosols
e.g. NCAR's WACCM model

EVA: Easy Volcanic Aerosol
Toohey et al. (2016)
CCMI: Chemistry Climate Model Initiative
Eyering et al. (2013)

WACCM: Whole Atmosphere Community Climate Model
Mills et al. (2016)

Idea: Finding Space in the Aerosol Model Hierarchy

Aerosol Model Complexity



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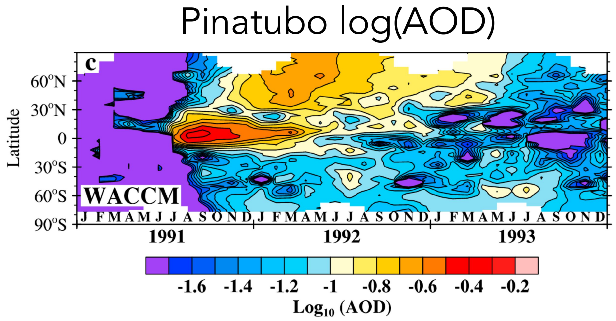

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EVA: Eas…
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- **Injection** and **transport** of aerosol tracers to the DOE E3SM model
- "Radiative heating" via **direct, analytic coupling** of aerosol mixing-ratios to temperature
- Heating parameters tuned for a **Pinatubo-like** climate response

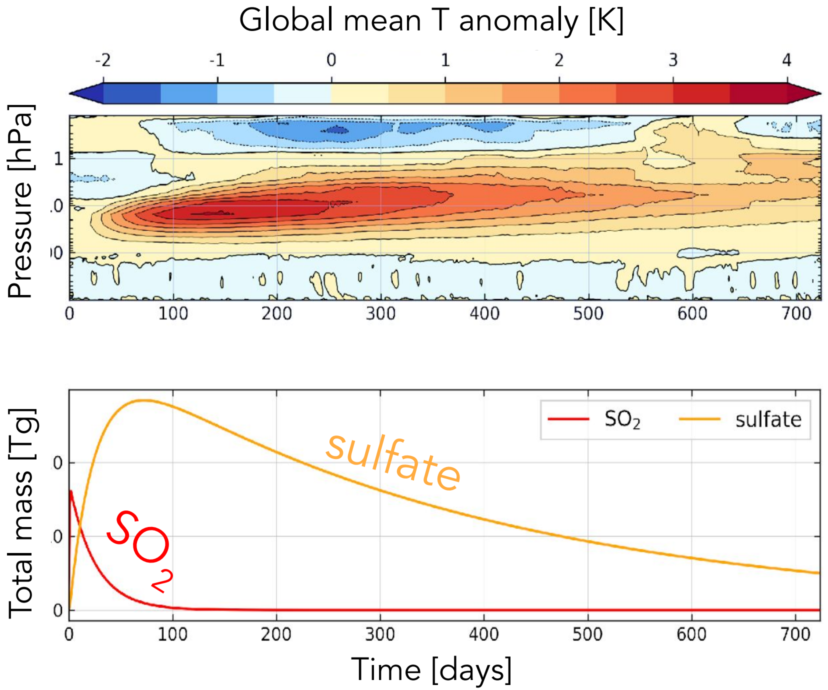
Preview: Idealized Forcing Mimics Pinatubo Observations

In this talk:
- Injection and transport of aerosol tracers to E3SM
- "Radiative heating" via direct, analytic coupling of aerosol mixing-ratios to temperature
- Heating parameters tuned for a Pinatubo-like climate response

Done in a way that provides:
- The spatial detail of a prognostic aerosol model
- The efficiency of applying a prescribed forcing set

Intended application:
- Embed in an idealized atmosphere with minimal forcings
- Generating CLDERA climate attribution validation datasets

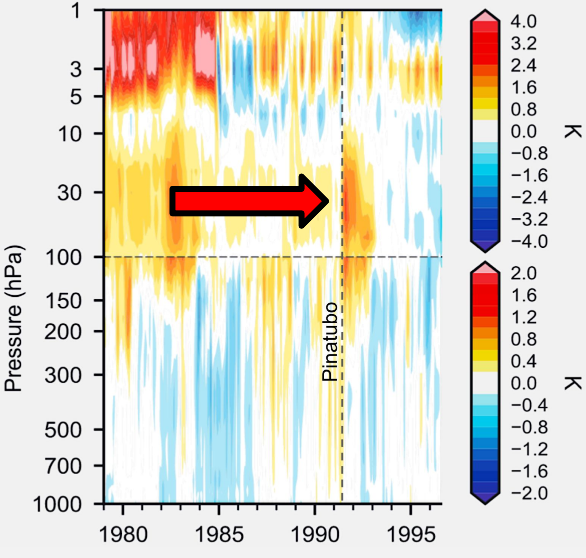
Teaser: Pinatubo aerosol forcing-induced temperature anomalies for 5-member ensemble



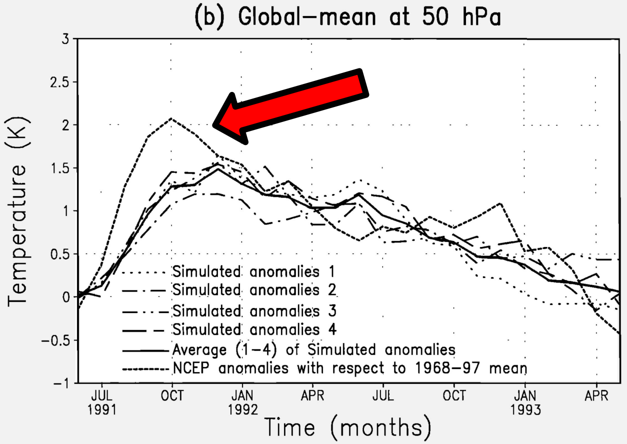
Pinatubo Observations Inspire Model Design

observation source

ERA5 reanalysis data	NCEP reanalysis data,
Global T anomalies up to ~3K peaking at 30-50 hPa	Global T anomalies peaking after ~3 months, vanishing by 18 months



Hersbach et al. (2020)



Ramachandran et al. (2000)

Model parameters from Pinatubo observations:

***e*-folding** for SO2, sulfate
Guo et al. (2004)
Barnes + Hofman et al. (1997)

Initial SO2 **mass loading**
Guo et al. (2004)

Initial **vertical distribution**
Sheng et al. (2015)

.....

Design of the Simple Aerosol Injection

Strategy:
Inject initial tracer mass uniformly over single model column

SO_2 tracer mass tendency:

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

vertical profile, column selection, tracer mass

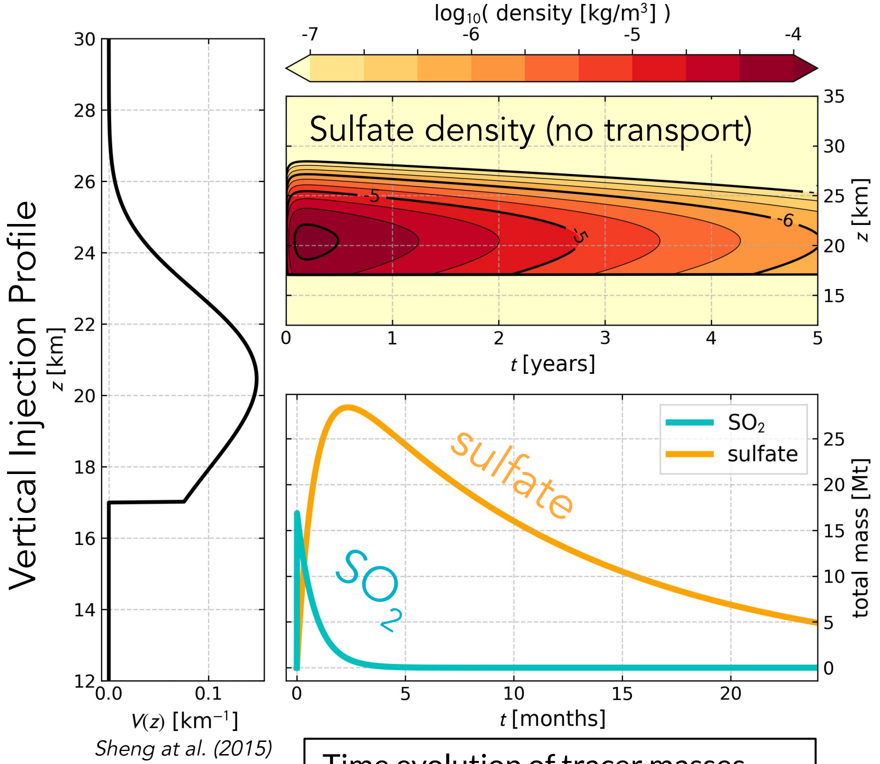
source: $f = A_j V(z) T(t) \delta_{i,i^*}$ sink: $R(m_j) = -k_j m_j$

amplitude, time dependency, removal timescale

Sulfate produced directly from SO2:

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

Analytic tracer injection time evolution for offline single column



Time evolution of tracer masses

Feedback from Analytically Defined Aerosol Forcings

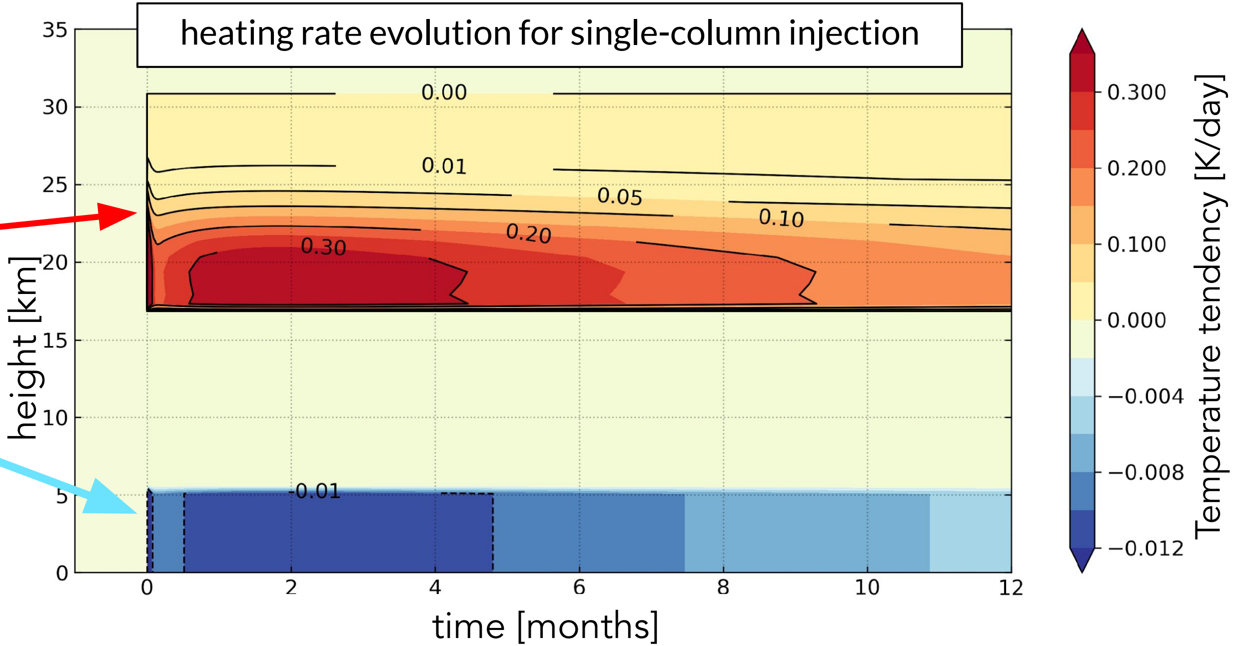
Diabatic effects of aerosols implemented as direct couplings to temperature field:

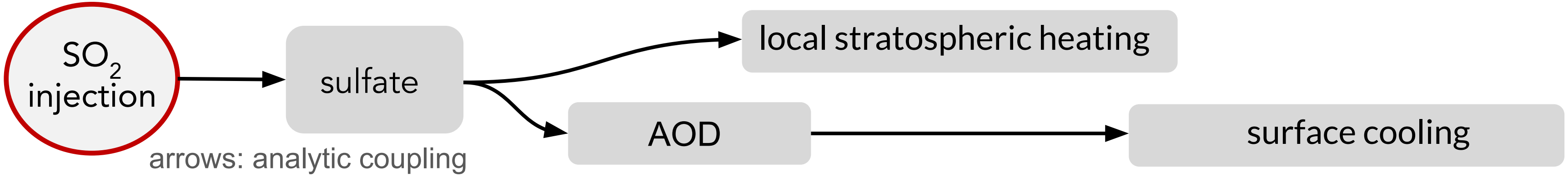
Local stratospheric heating

- heating rate ∝ log(mixing ratio)

Remote surface cooling

- AOD ∝ (column burden)
- cooling rate ∝ log(AOD)





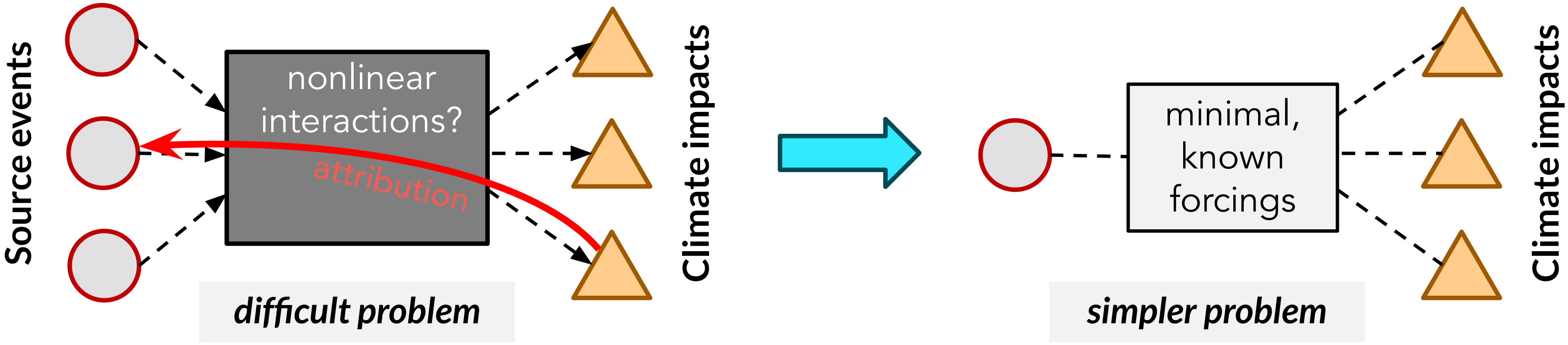
Why Idealize? Validation Datasets for Climate Attribution

Model has been produced in collaboration with Sandia National Labs:
***CLDERA*: CLimate impact: Determining Etiology thRough pAthways**

https://www.sandia.gov/cldera/

- **Ultimate goal:**
  develop new methods to confidently attribute climate impacts to localized sources

- Our model supports this effort by offering *validation datasets* of *controlled* source-impact pairs



HSW climate forcing minimizes complexity
(Held-Suarez-Williamson)

Main idea:

Replace complex physics suite with processes that are:

- just complex enough to allow simulations of quasi-realistic climate
- simple enough to assess diabatic effects

time tendency of forecast variable Ψ	Adiabatic fluid flow from the dycore	Dissipative mechanisms from the dycore

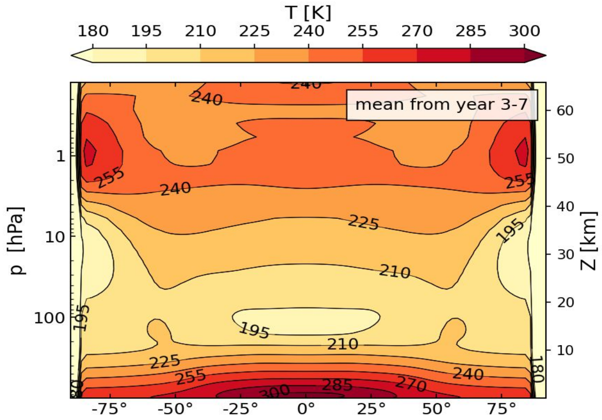
$$\frac{d\Psi}{dt} = Dyn(\Psi) + \boxed{Phys(\Psi)} + F_{\Psi}$$

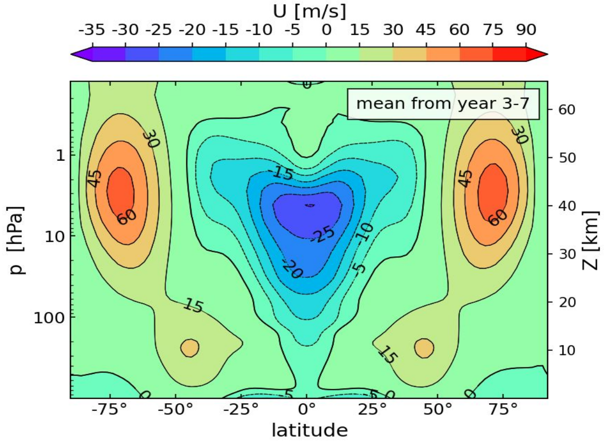
HSW forcing target

All diabatic time tendencies from physical parameterizations replaced with:

1. Mimic **PBL mixing** by Rayleigh friction
2. Mimic **radiation** by prescribed **temperature relaxation**
3. Sponge layer Rayleigh friction

Resulting mean steady-state
(5-year mean after 3-year spin up)



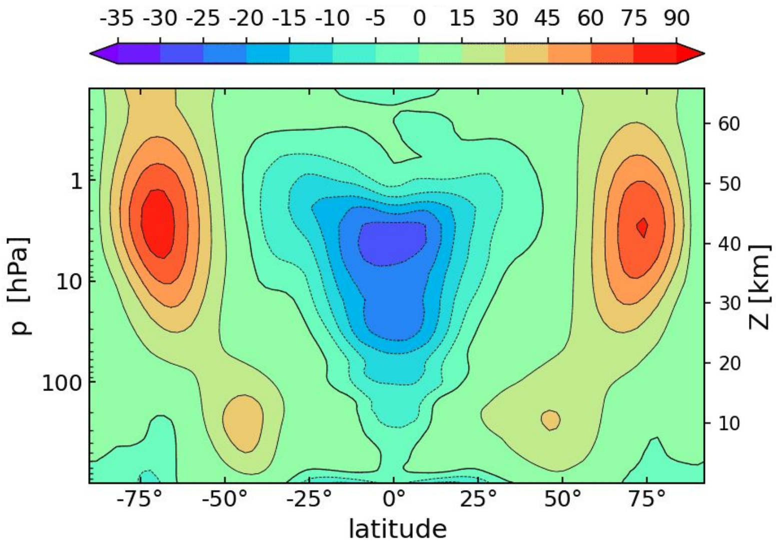


HSW climate forcing minimizes complexity

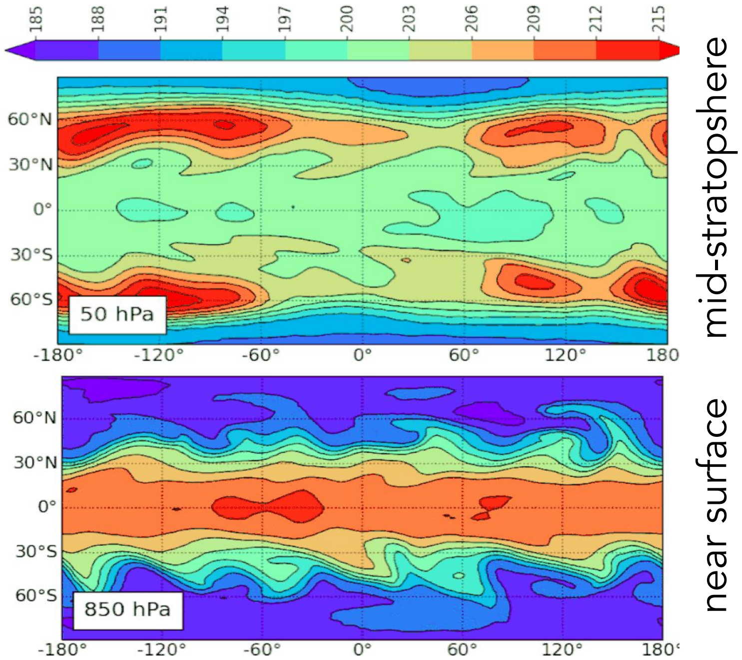
Though the HSW steady-state is eternal and symmetric, atmosphere is quasi-realistic:

- Low-frequency variability: latitudinal vacillations of the extratropical jets, timescale of ~25 days
- Horizontal mixing in midlatitudes

Zonal-mean zonal wind [m/s]
30-day evolution



Temperature [K] 30-day evolution



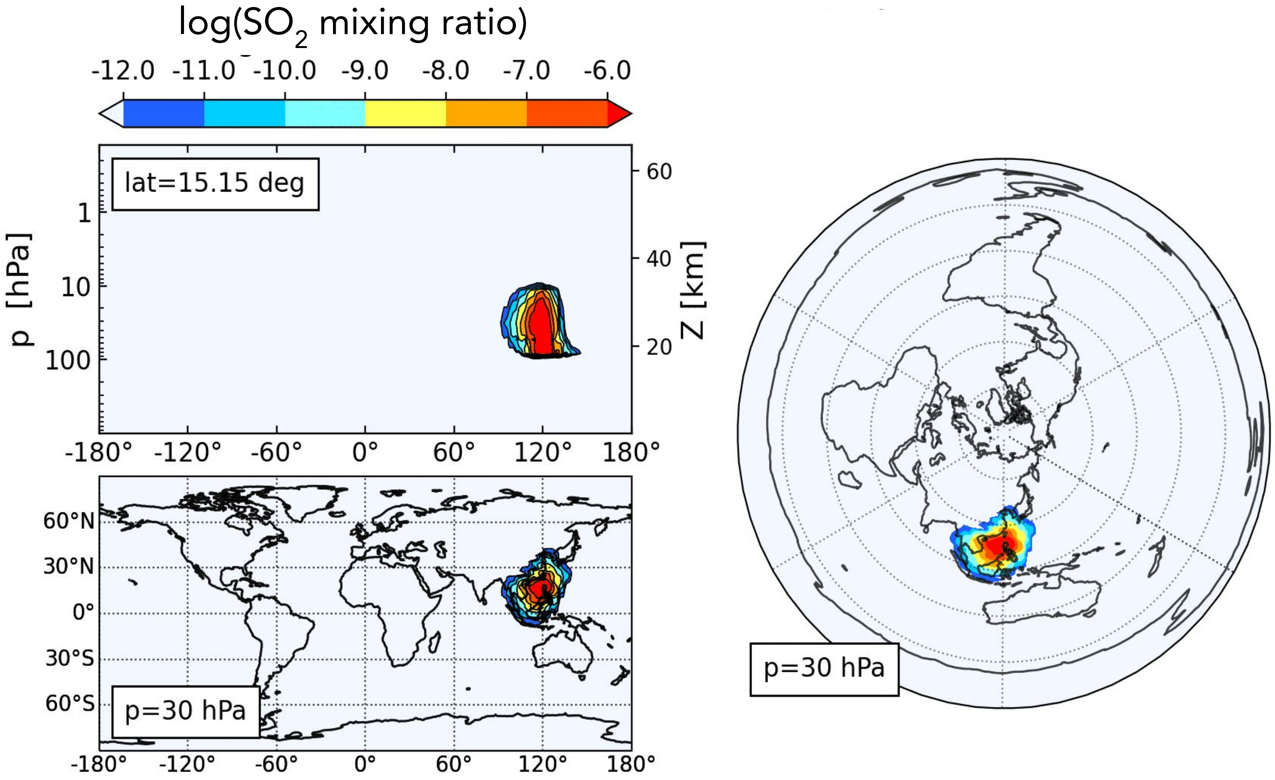
Post-Injection Tracer Transport in the HSW Atmosphere

Model: E3SMv2
Resolution: 2-degree (ne16)
Vertical grid: 72 levels to ~80 km

Pinatubo-like parameters:

SO_2 Loading: 17 Tg
Injection period: 9-hours Near
Location: (15 N, 120 W)

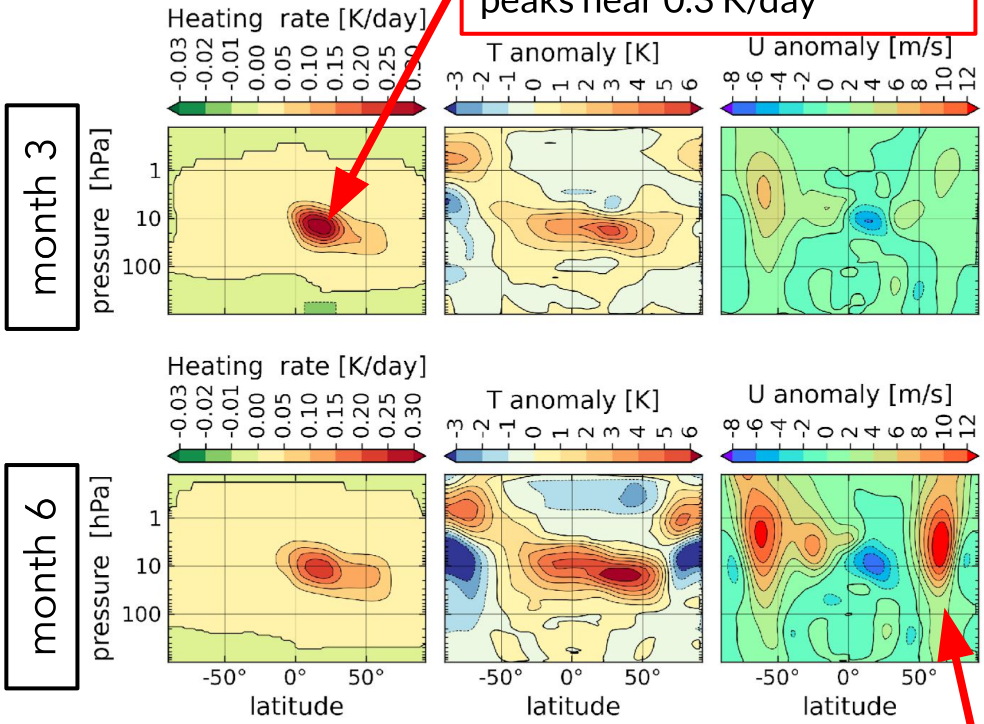
- Circulates the globe in ~15 days
- Density peak lowers to ~1% of injected values by month 3

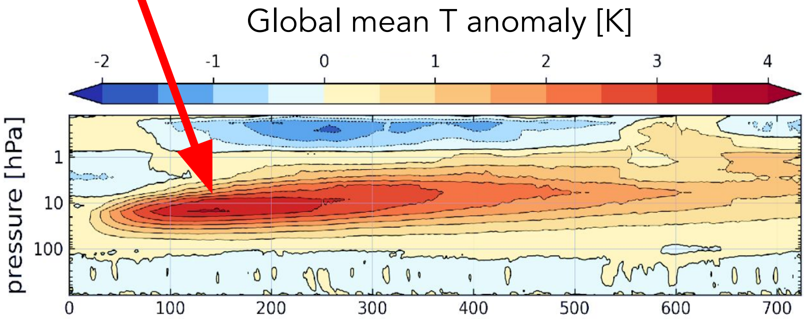


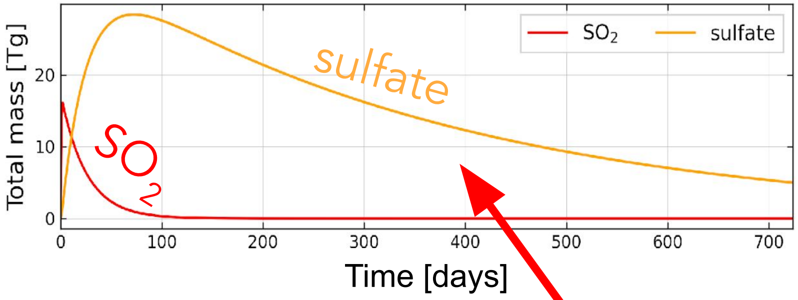
Forcing Applied to HSW Climate Gives Pinatubo-Like Impacts

Stratospheric heating rates peaks near 0.3 K/day

Temp anomalies of 3-4 K in global mean at ~30-50 hPa







Increased T-gradient at midlatitudes give strengthening of polar jets

Realistic timescales of SO2, sulfate production, decay

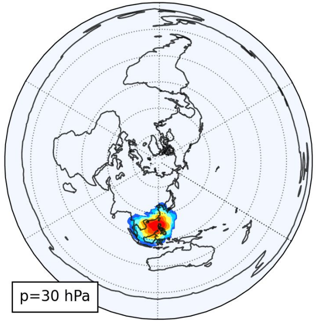
Closing Thoughts

Model design was specifically motivated to:

- Provide validation datasets for **climate attribution tools**
- Forcings lying between the volcanic event and climate impact are **minimal and controlled**; ideal first-step for new attribution methods

This **intermediate-complexity** implementation may be generally useful for idealized assessments of volcanic eruptions on climate:

- Injection, forcing model can be included with **any** dynamical core configuration from dry idealized to complex



Questions?

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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

$Phys(\Psi)$ functions

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

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

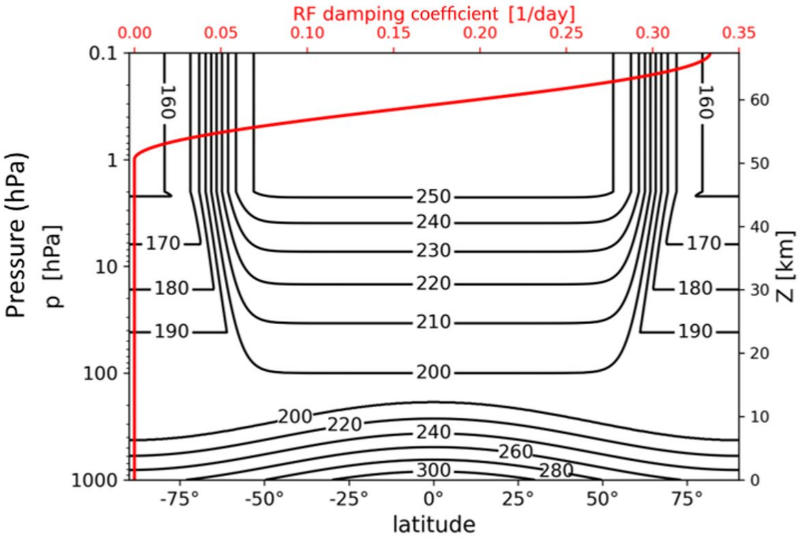
- k_v and k_T are spatially-dependent relaxation coefficients
- T_{eq} is a prescribed equilibrium temperature (see next slide)

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

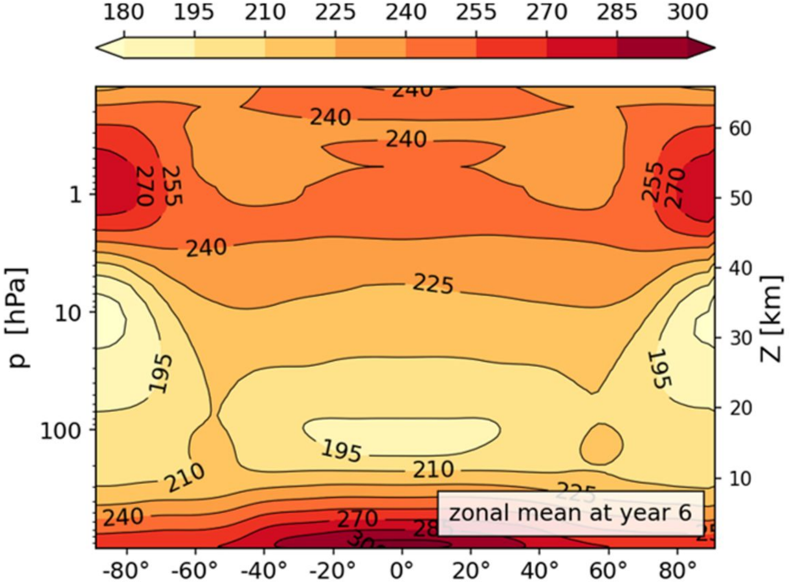
Description of the HSW forcing & Initial Conditions (IC)

- 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)

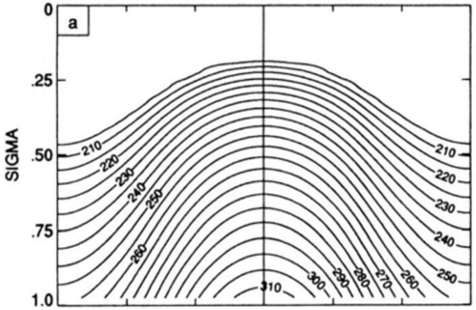


Initial state (after a 6-year spin-up from a state of rest): Temperature T (K), ne16L72 (200 km), E3SMv2

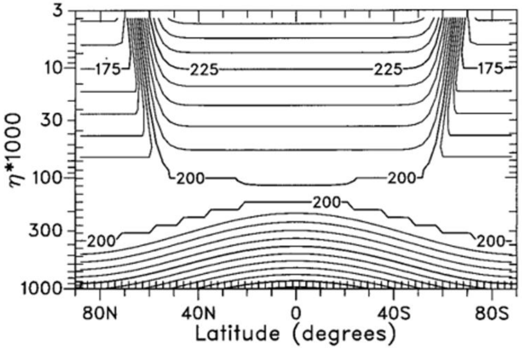


Temperature Relaxation Profile

- 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"

Feedback from Analytically Defined Aerosol Forcings

Local stratospheric heating

- Heating rate per unit mass *s*
- Directly coupled to aerosol mixing ratios *q*

$$s = c_p \delta T_{\text{strat}} \left[1 - \frac{\log(q/q^*)}{\log(q_0/q^*)}\right]^{\gamma_q} \quad \frac{\text{J}}{\text{kg s}}$$

Remote surface cooling by AOD

- AOD τ defined as a scaled sum of column burdens
- Directly connected to aerosol optical depth (AOD)

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

$$s = c_p \delta T_{\text{surf}} \left[1 - \frac{\log(\tau/\tau^*)}{\log(\tau_0/\tau^*)}\right]^{\gamma_\tau} \quad \frac{\text{J}}{\text{kg s}}$$

AOD ”updates” surface temp, outgoing LW