Mt. Pinatubo-Inspired Idealized Climate Data Sets with Embedded Pathways

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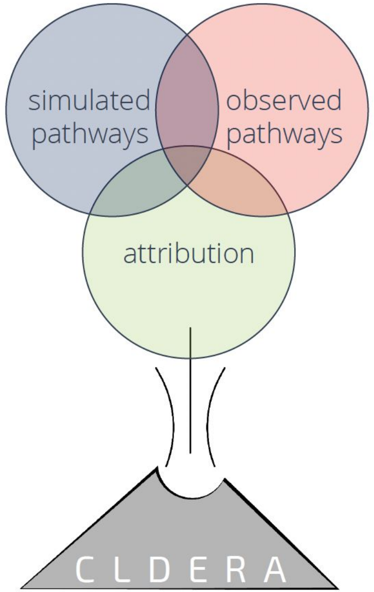


CLDERA All-Hands Meeting, 05/16/2022

Motivation

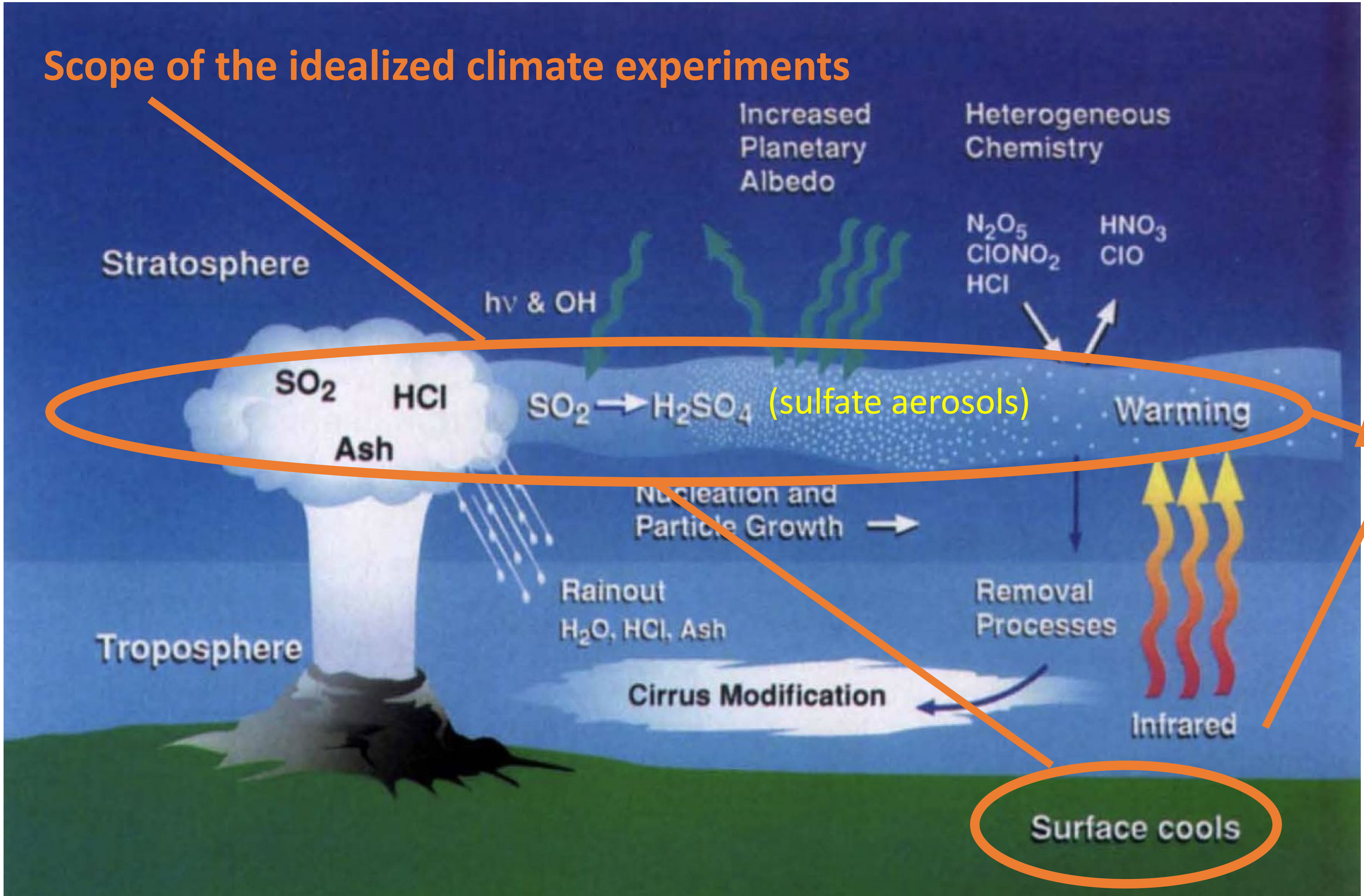
- Goal: Provide idealized climate data sets with prescribed pathways for a tiered verification of the CLDERA tools
- CLDERA exemplar: Selected Characteristics of the Mt. Pinatubo eruption
- Reminder of the first CLDERA science question: Temperature
- Principles behind idealized climate simulations
  - Climate model hierarchy: from simple to complex
  - Idealized Held-Suarez-Williamson (HSW) forcing with an active stratosphere
  - Baseline HSW climate
- Use of passive tracers to emulate the Mt. Pinatubo stratospheric aerosol injection (SAI)
  - Transported tracers: SO_2 and ash with sources and sinks
  - Embed prescribed pathways in the simulations, guided by the tracers
    - **2-node** pathway with a single radiative response in the stratosphere
    - **3-node** mixed pathway (via toy chemistry) with a single radiative response in the stratosphere
    - **3-node** mixed pathway with a dual radiative response: stratosphere & surface
- Discussion points

Mt. Pinatubo (June/15/1991) Fact Sheet

- Source/SAI: Main volcanic eruption released about 17-20 Tg of sulfur dioxide (SO_2) and 50 Tg of ash into the stratosphere (20-27 km) in the tropics (Guo et al. (2004a,b), Mills et al. (2016))
- Sink: E-folding (removal) time is around 25 days for SO_2 and 1 day for ash
- 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
- 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
- Forcing: Aerosols control radiative forcing, **aerosol optical depth (AOD)** is an indicator
  - 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
- The important nodes in the pathway are:

  gas/SAI injection → secondary aerosols (sulfate) → radiation effects → temperature
- The elements in red are simplified in the idealized climate experiments

CLDERA Mt. Pinatubo Exemplar: Nodes in the Pathways



Plus:
Secondary pathways related to changes in the wind and circulation (caused by the heating/cooling). Are these detectable?

Modified from McCormick et al. (Nature, 1995)

Relationship to the CLDERA Science Question:
What are the spatio-temporal signatures of the temperature change due to the Mt. Pinatubo eruption?

Primary use of the idealized data	• Can known pathways be recovered and new pathways discovered in both simulated and observed 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)
Not covered in idealized data	• Can pathways be used to resolve debate surrounding NH winter warming?

Building Bridges across the GCM Model Hierarchy

Full complexity

Realistic climate configurations

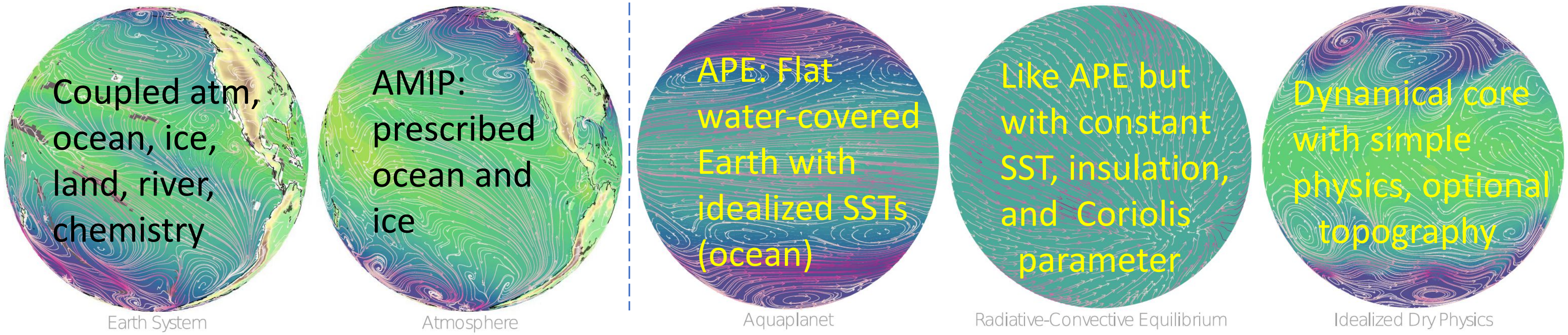
Coupled System

Atmosphere & Land

Aquaplanet: Atmosphere only

Radiative-Convective Equilibrium (RCE)

Dycore with idealized dry (or moist) physics



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

AMIP: prescribed ocean and ice

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

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

Dynamical core with simple physics, optional topography

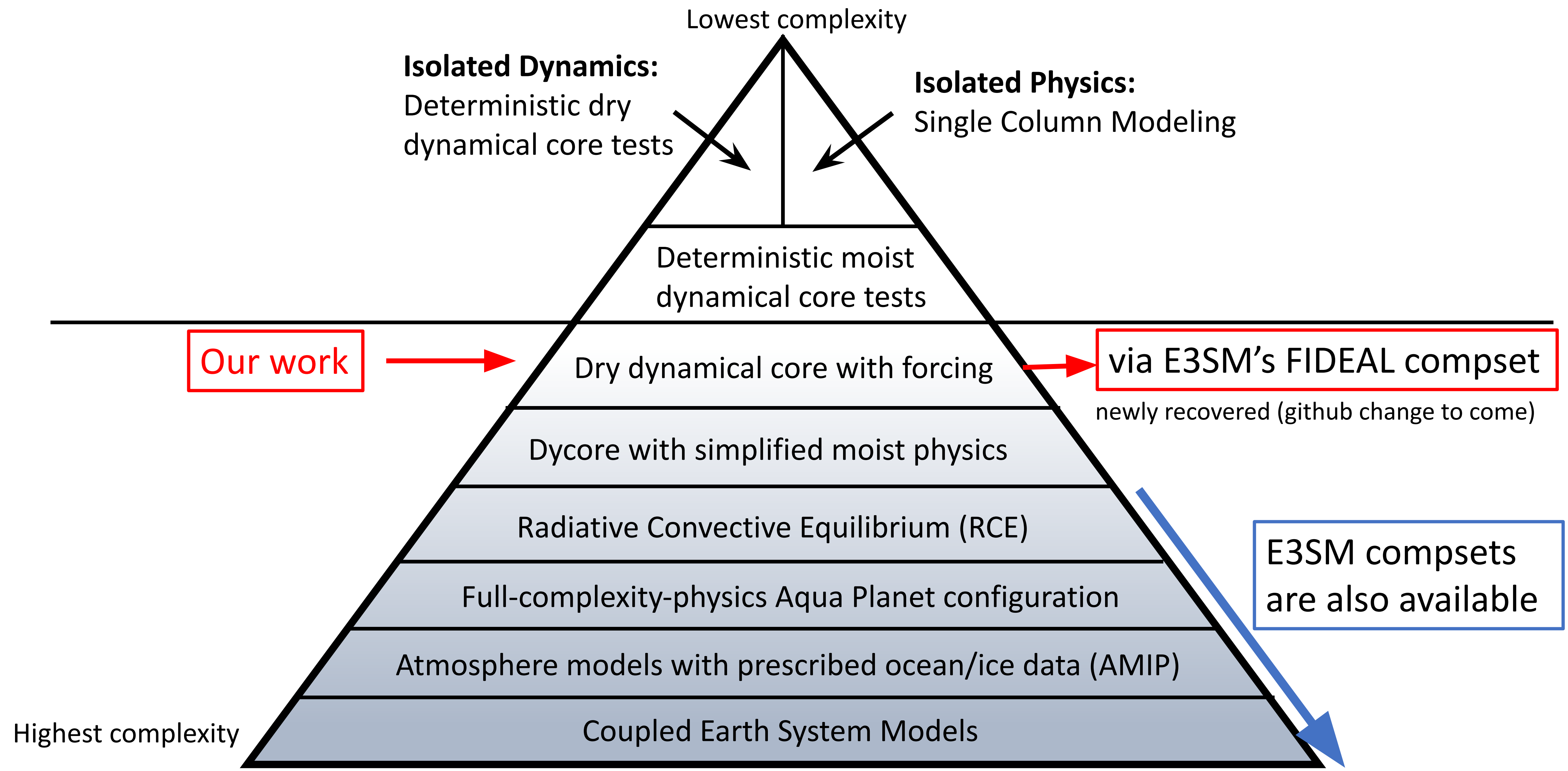
Reduced complexity

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

Our work (dry)

Pont du Gard Aqueduct near Avignon, France

GCM Model Hierarchy



Lowest complexity

Isolated Dynamics:
Deterministic dry dynamical core tests

Isolated Physics:
Single Column Modeling

Deterministic moist dynamical core tests

Our work

Dry dynamical core with forcing

via E3SM's FIDEAL compset

newly recovered (github change to come)

Dycore with simplified moist physics

Radiative Convective Equilibrium (RCE)

Full-complexity-physics Aqua Planet configuration

Atmosphere models with prescribed ocean/ice data (AMIP)

Coupled Earth System Models

Highest complexity

E3SM compsets are also available

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.

our HSW forcing target

Prognostic GCM variables are forced by:

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

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

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

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

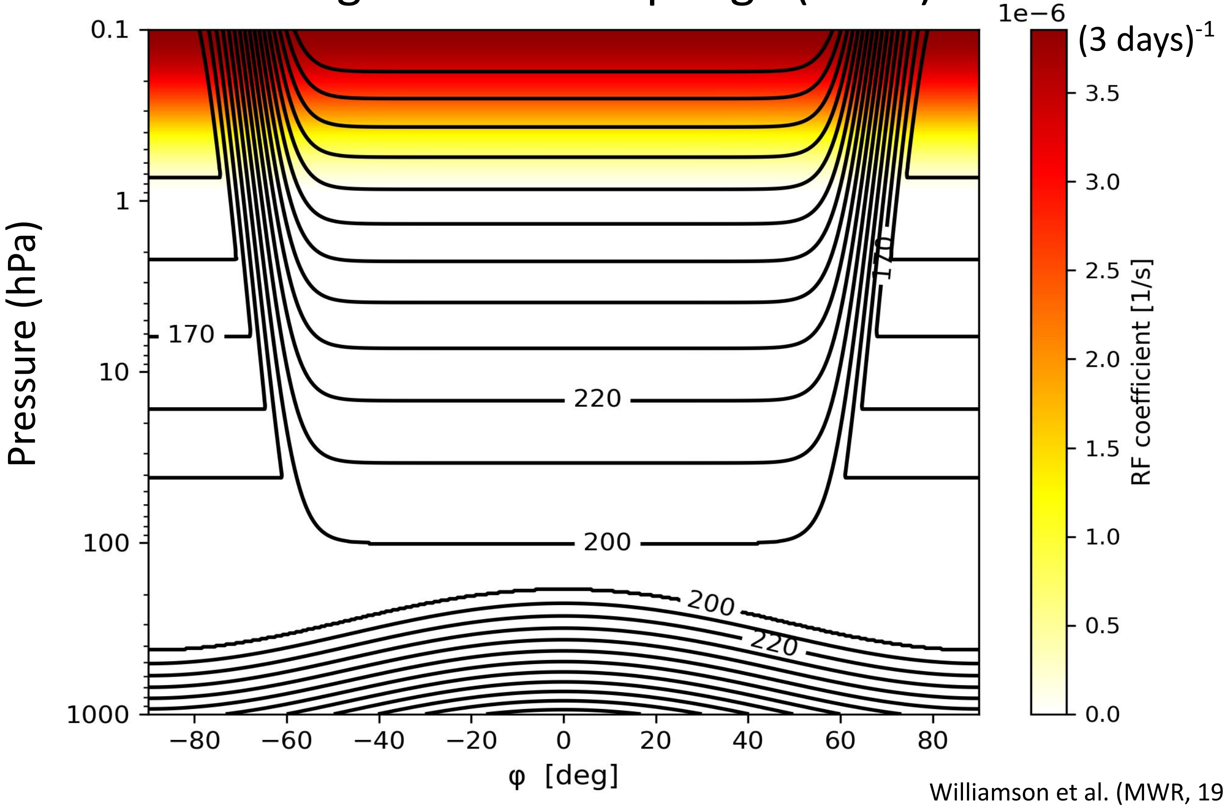
- k_v and k_T are spatially-dependent relaxation coefficients
- T_{eq} is a thermal equilibrium temperature (shown on next slide)

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

Description of the HSW forcing & Initial Conditions (IC)

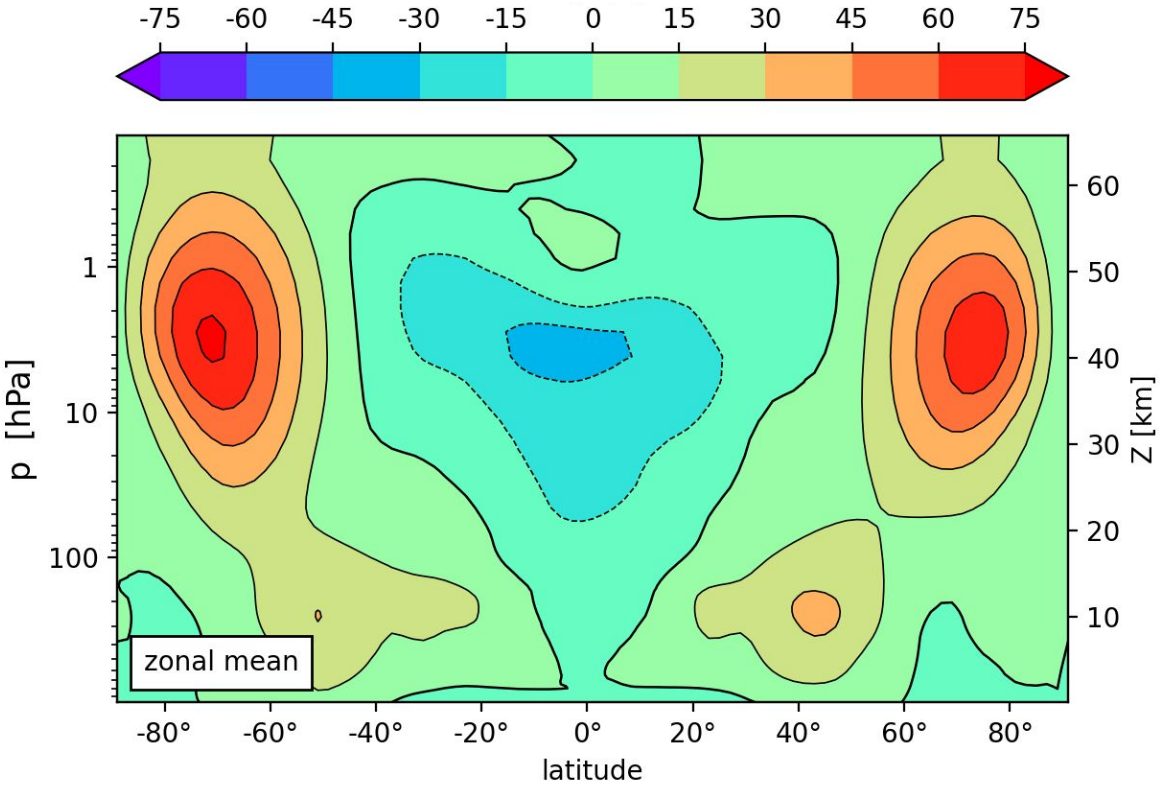
- All radiation processes approximated by the relaxation to the HSW equilibrium temperature profile T_{eq}
- Two Rayleigh friction (RF) layers
  - at lower levels below 700 hPa mimicking the PBL turbulence/mixing
  - RF mixing above 1 hPa in the sponge layer to absorb upward propagating waves

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



Williamson et al. (MWR, 199

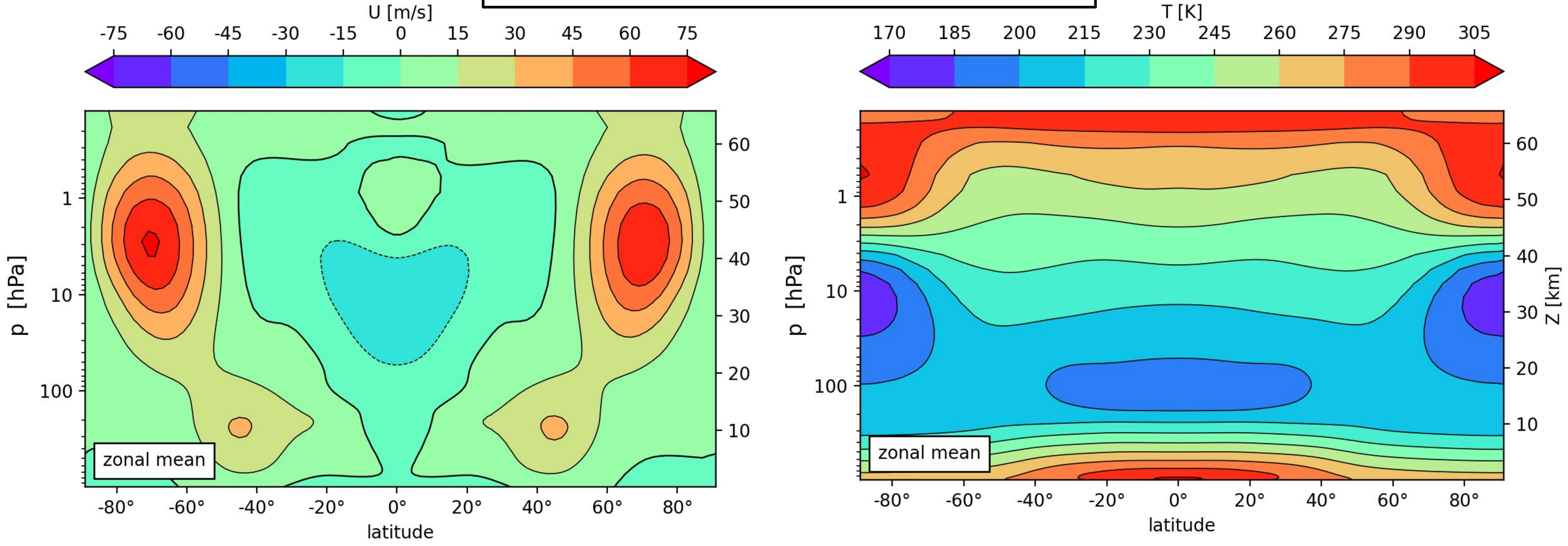
Initial state (after a 6-year spin-up from a state of rest):
Zonal-mean zonal wind U (m/s), ne16L72 (200 km), E3SMv2



HSW Climate Response is Quasi-Realistic

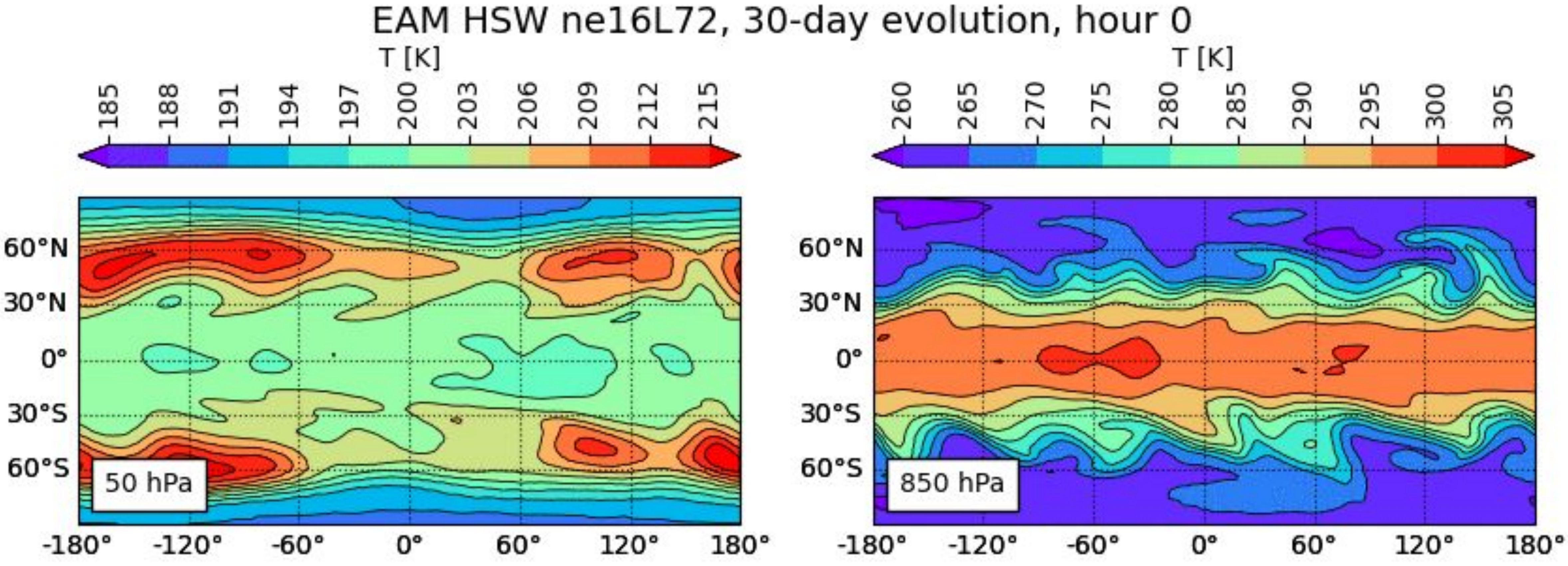
- Time-mean zonal-mean zonal wind U (m/s) and temperature T (K) climatology mimics Earth
- Circulation is quasi-realistic with midlatitudinal and polar jets caused by latitudinal T gradients

E3SM HSW ne16L72, mean from years 5-10



HSW: Snapshots of the Temperature are Quasi-Realistic

- Animations of the T evolution in the lower troposphere (850 hPa) & stratosphere (50 hPa)



Idealized Etiological Pathways Triggered by Tracers

Simple *Stratospheric Aerosol Injection (SAI)* modelled as a 3D Gaussian ellipsoid, injection has a prescribed time limit and profile

- The *tracer tendency* $\frac{\partial \rho}{\partial t} = R(\rho) + f$ for e.g. the SO_2 density ϱ is a function of the injection source f and a linear sink R representing chemical removal:

Source:

Horizontal shape

Time dependency

$$f = AH(r)V(z)T(t)$$

Amplitude

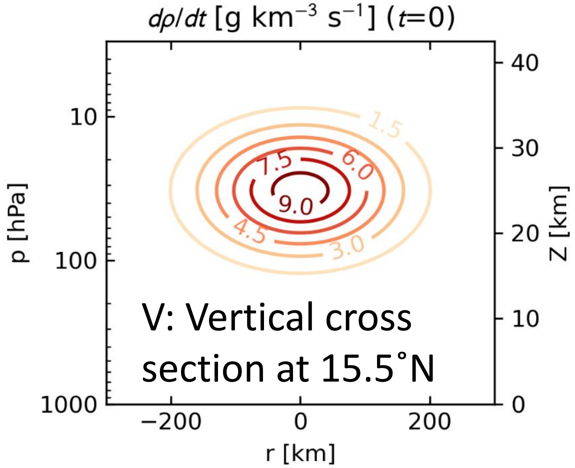
Vertical shape

Sink:

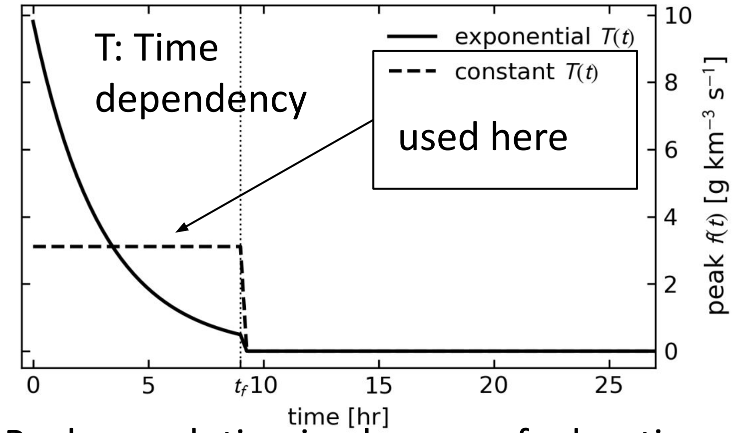
$$R(\rho) = -k\rho$$

r: great circle distance
z: height
k: inverse removal time scale

Profile of the SAI injection for SO_2 (and ash)



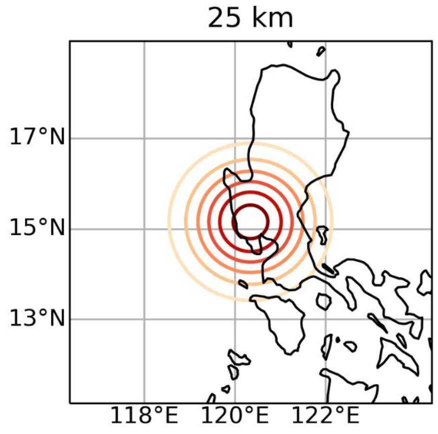
V: Vertical cross section at 15.5˚N



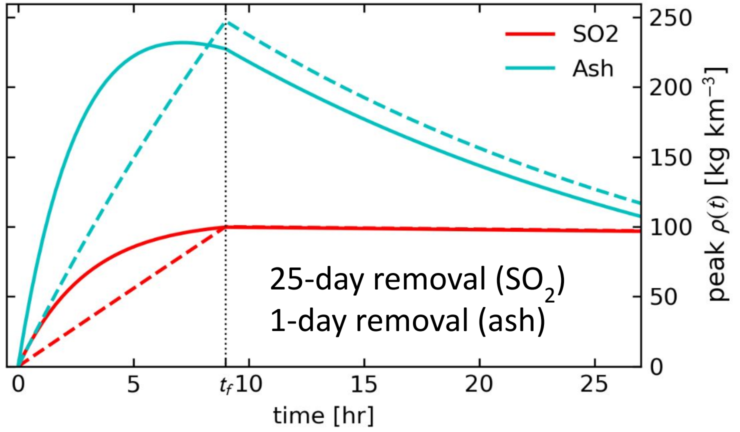
T: Time dependency

used here

Peak ϱ evolution in absence of advection



H: Horizontal cross section



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Source:

Horizontal shape ↓ Time dependency ↓

$$f = AH(r)V(z)T(t)$$

↑ Amplitude ↑ Vertical shape

Sink:

$$R(\rho) = -k\rho$$

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z: height
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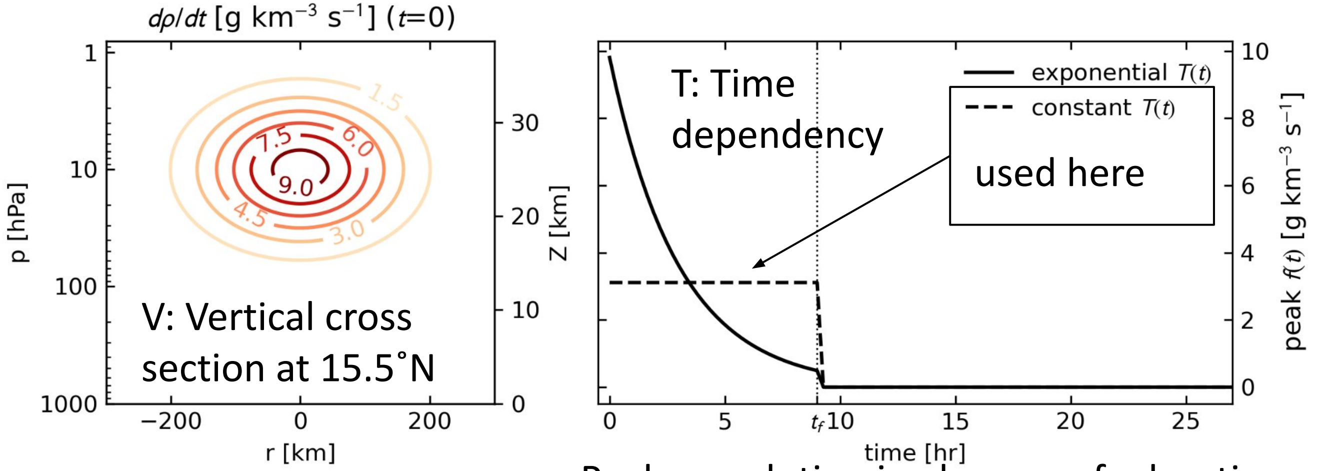
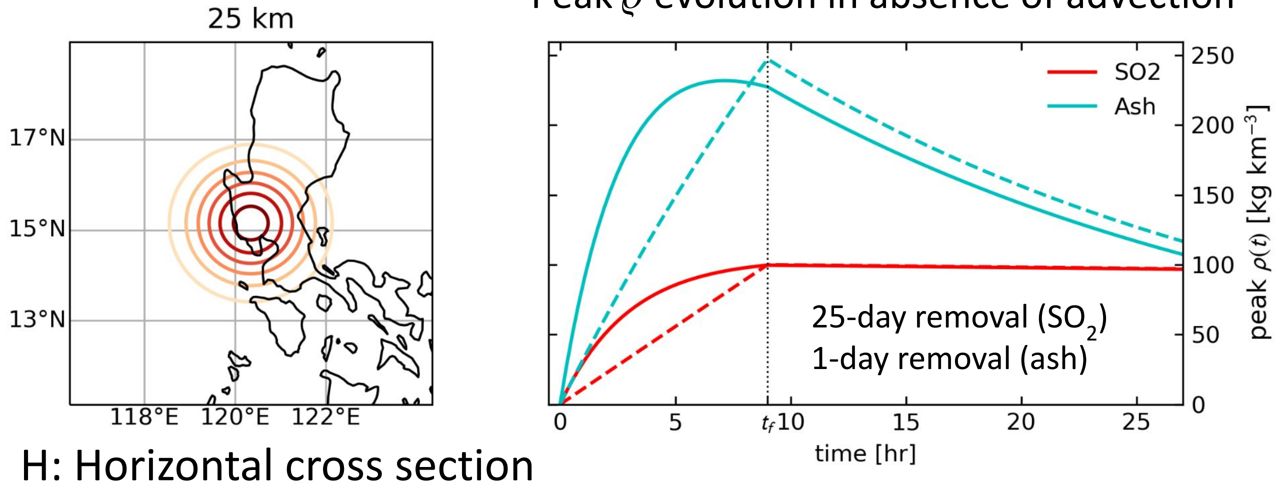
Profile of the SAI injection for SO_2 (and ash)



Peak ϱ evolution in absence of advection

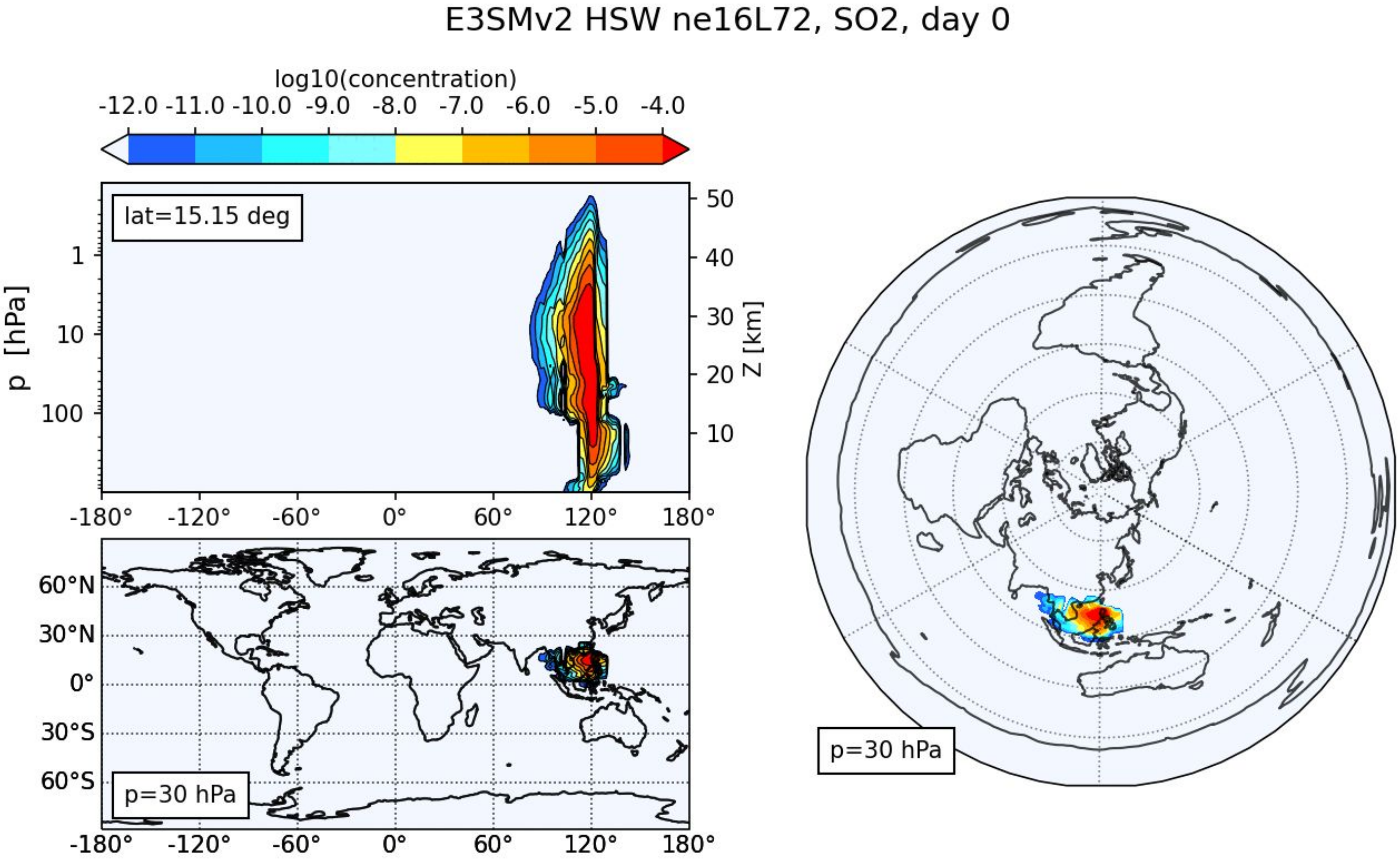


H: Horizontal cross section

SO_2 Evolution in E3SMv2 HSW (over 30 days)

17 Mt SO_2 injected over 48-hour period at (15 N, 120 W)

Circulates the globe in ~20 days; quasi-realistic!



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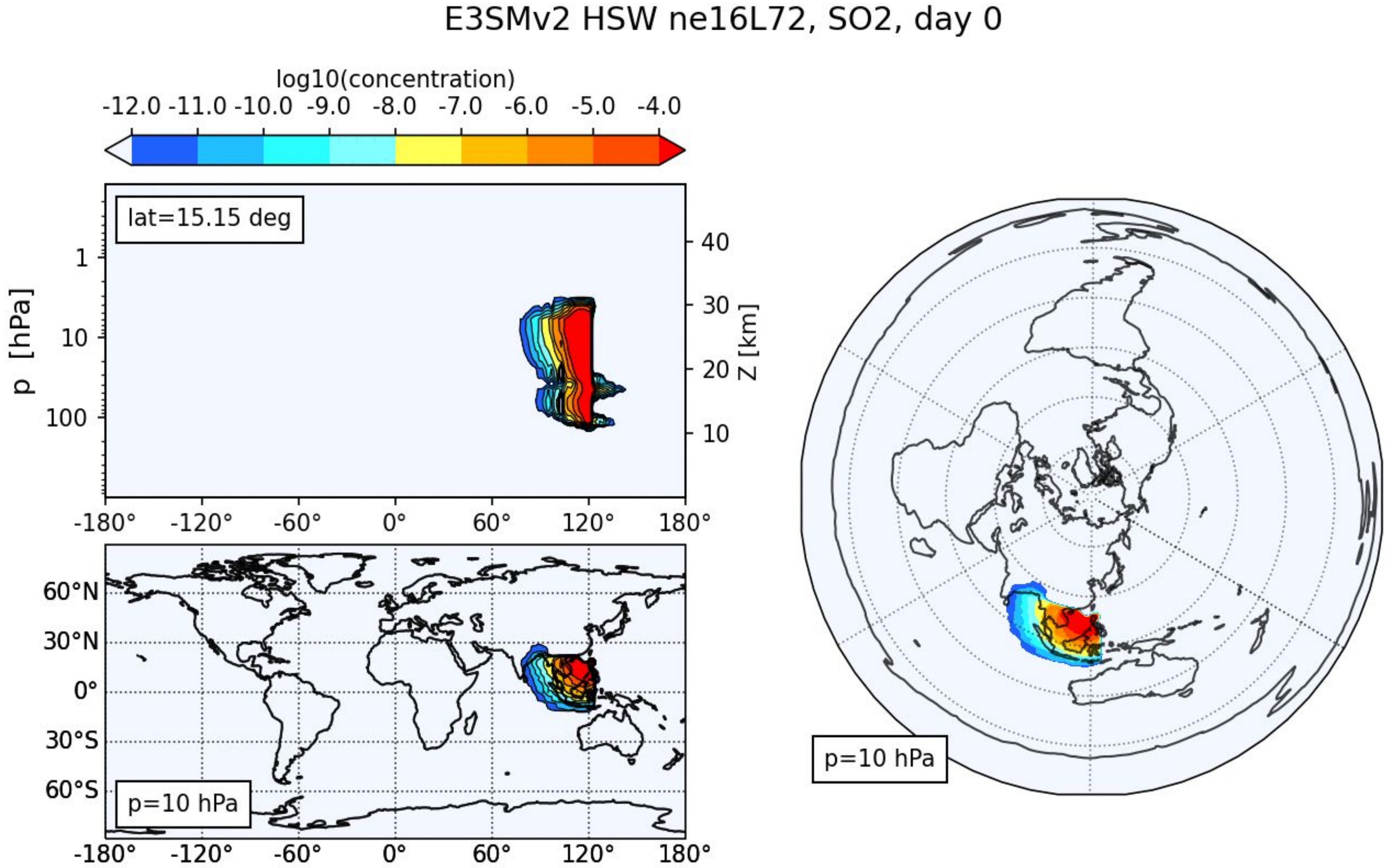


SO_2 and Ash Evolution in E3SMv2 HSW (over 30 days)

17 Mt SO2, 50 Mt ash injected over 48-hour period at (15 N, 120 W)

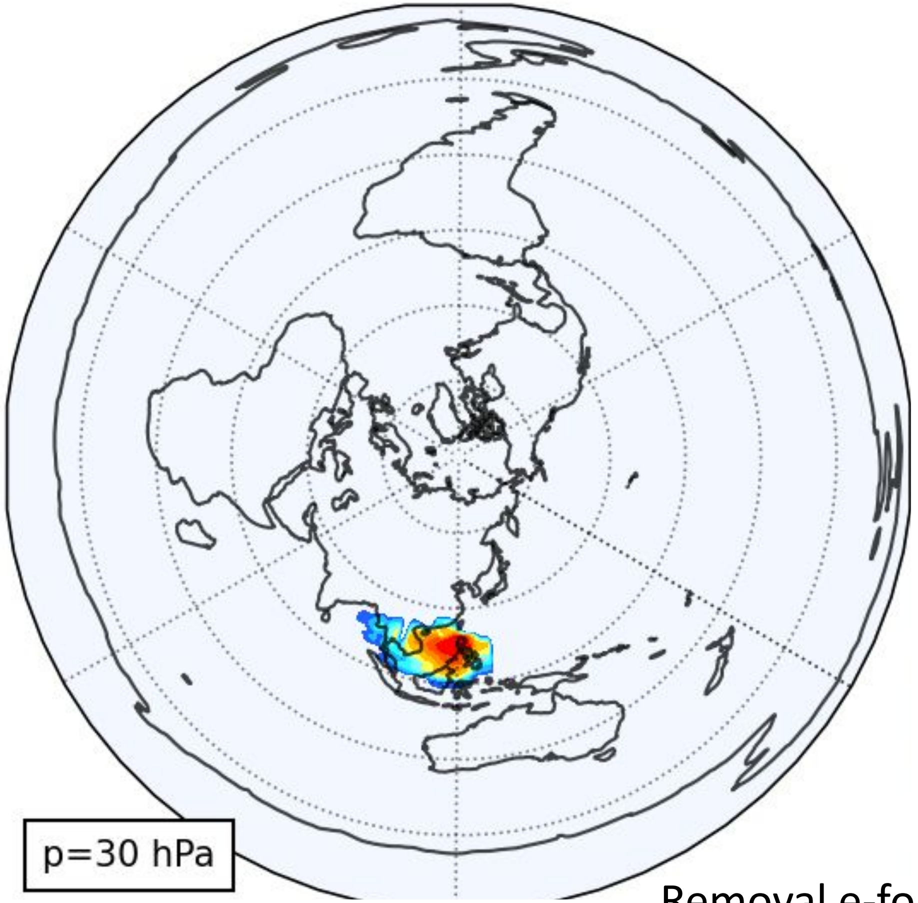
SO_2 Circulates the globe in ~20 days

Ash dissipates below 1e-12 by day ~20

E3SMv2 ne16L72 HSW

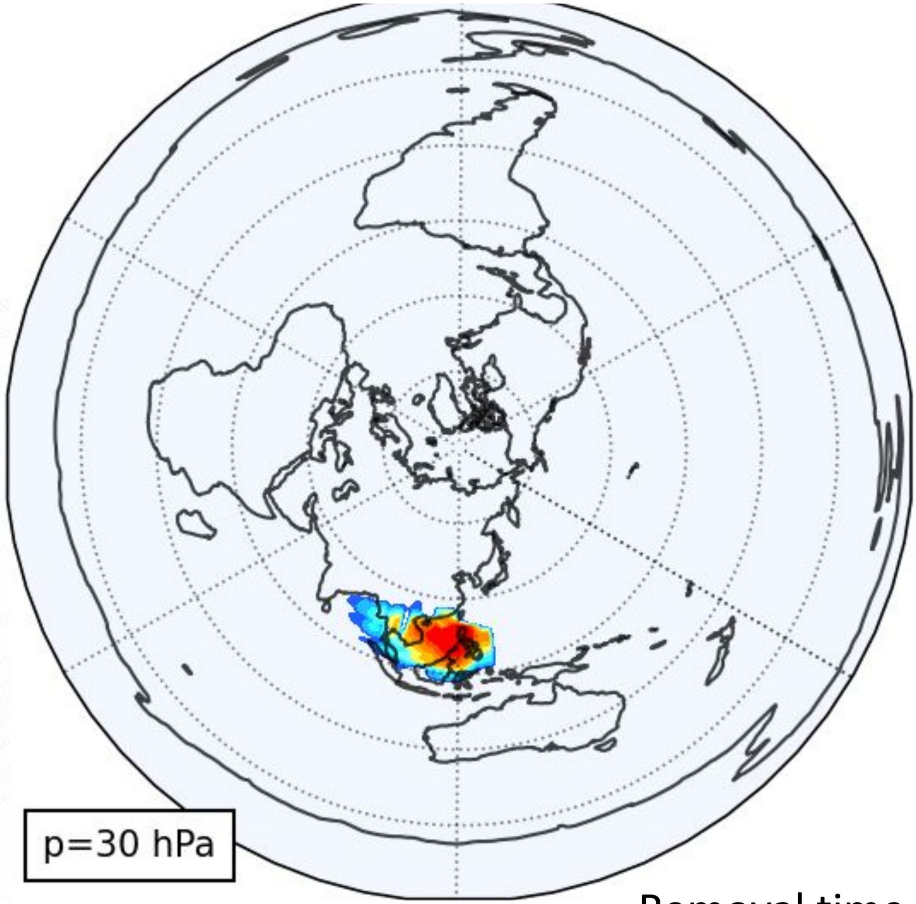
day 0

SO2



Removal e-folding time scale 25 days

Ash



Removal time-scale 1 day

SO_2 and Ash Evolution in E3SMv2 HSW (over 30 days)

17 Mt SO2, 50 Mt ash injected over 48-hour period at (15 N, 120 W)

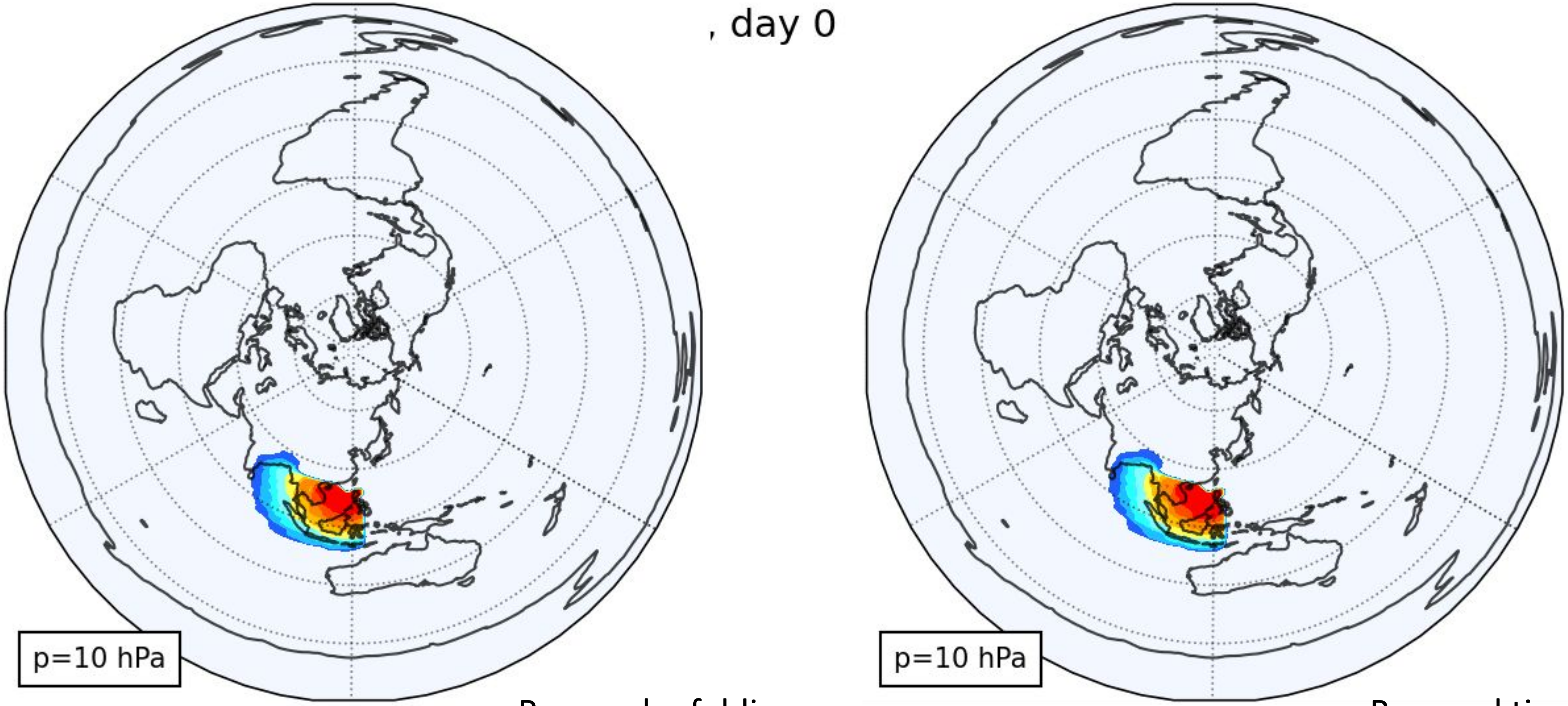
SO_2 Circulates the globe in ~20 days

Ash dissipates below 1e-12 by day ~20

E3SMv2 ne16L72 HSW

SO2

Ash

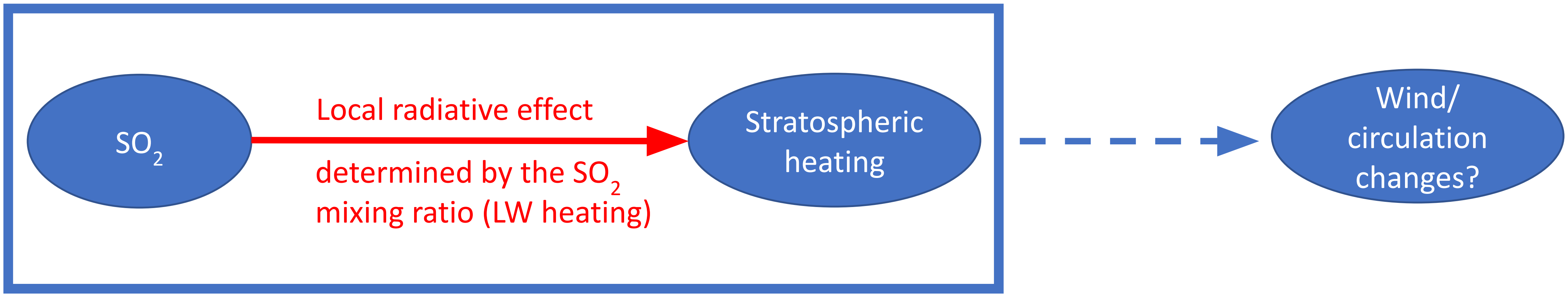


Removal e-folding time scale 25 days

Removal time scale 1 day

Embed Pathway 1

- All embedded pathways are guided by tracer distributions (injection event)
- 2-node pathway with a single radiative response: heating in the stratosphere



SO_2

Local radiative effect

determined by the SO_2 mixing ratio (LW heating)

Stratospheric heating

Wind/ circulation changes?

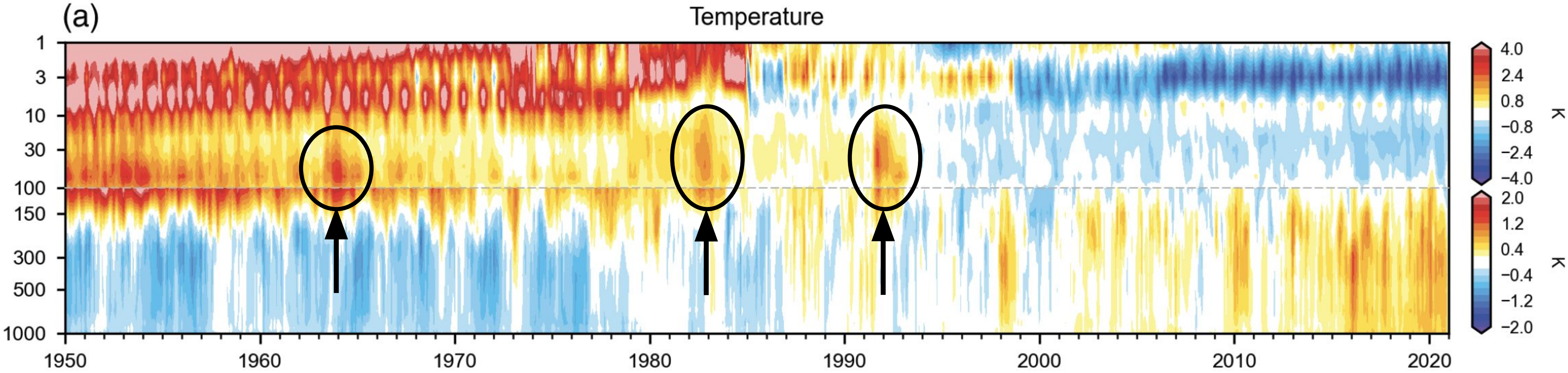
Main pathway

Secondary circulation effects:
Are they detectable?

Temperature pathways are also described here:
https://sems-atlassian-son.sandia.gov/confluence/display/cldera/Temperature+signature+focus

Embed Pathway 1

- 2-node pathway with a single radiative response in the stratosphere
- Magnitude of our **heating anomaly is informed by ‘observations’** (ERA5 renanalysis)
- Large tropical volcanic eruptions: Agung (March 1963), El Chichon (April 1983) and Mt. Pinatubo (June 1991) triggered heating anomalies around **3-4 K at 30 hPa**



ERA5 estimates of the heating anomaly (Bell et al., QJ, 2021): monthly and globally averaged upper-air anomalies with respect to the 1981–2010 monthly climatology for (a) temperature. Note the different color scales used above and below 100 hPa. See also Sukhodolov et al. (GMD, 2018), Fig. 6

Pathway 1: Initial demonstration project

- Stratospheric heating is directly connected to SO_2 mixing ratio (maybe $\log_{10}(SO_2)$) with peak heating tendency of a few K/day

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

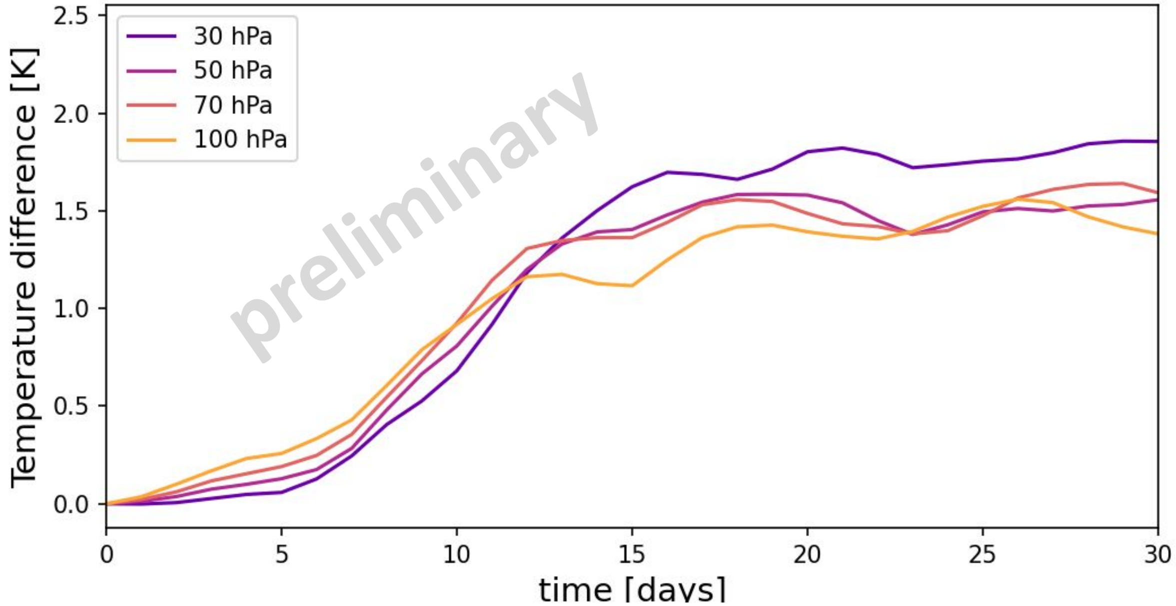
$$\boxed{s \equiv \frac{Q_{\text{strat}}}{m}} = \frac{c_{\text{SO}_2}}{c^*} c_p \delta T_{\text{strat}} \implies \boxed{\frac{\partial T}{\partial t}} = \ldots + \frac{c_{\text{SO2}}}{c^*} \delta T_{\text{strat}}$$

SO2 mixing ratio

heating magnitude. = 0.3 K/day

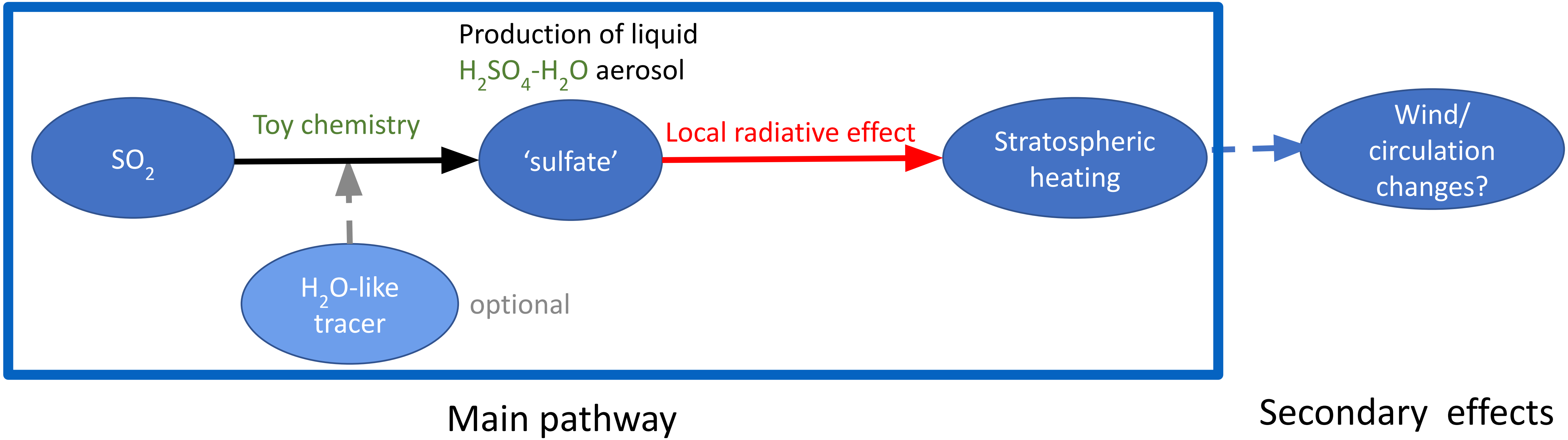
normalization

Evaluating the temperature difference across the stratosphere between two E3SM injection runs
with and **without**
this heating pathway enabled



Embed pathway 2

- 3-node mixed pathway (via toy chemistry) with a single radiative response: heating in the stratosphere
- Replace the (linear) removal process for SO_2 with toy chemistry, potentially informed by the presence of a second passive tracer like water vapor
- SO_2 chemistry sink becomes liquid H_2SO_4-H_2O sulfate aerosol source



Embed pathway 2

- Tropical liquid H_2SO_4-H_2O (sulfate aerosol) observations by the SAGE satellite instrument after 1991 eruption
- Observations of liquid H_2SO_4-H_2O inform the toy chemistry process (production rate of fake 'sulfate aerosols', see schematic diagram)
- Liquid 'sulfate aerosol' is produced and serves as a new sink for SO_2
- Lifetime of liquid H_2SO_4-H_2O aerosol in the stratosphere is about 1 year (slower removal time scale than SO_2)

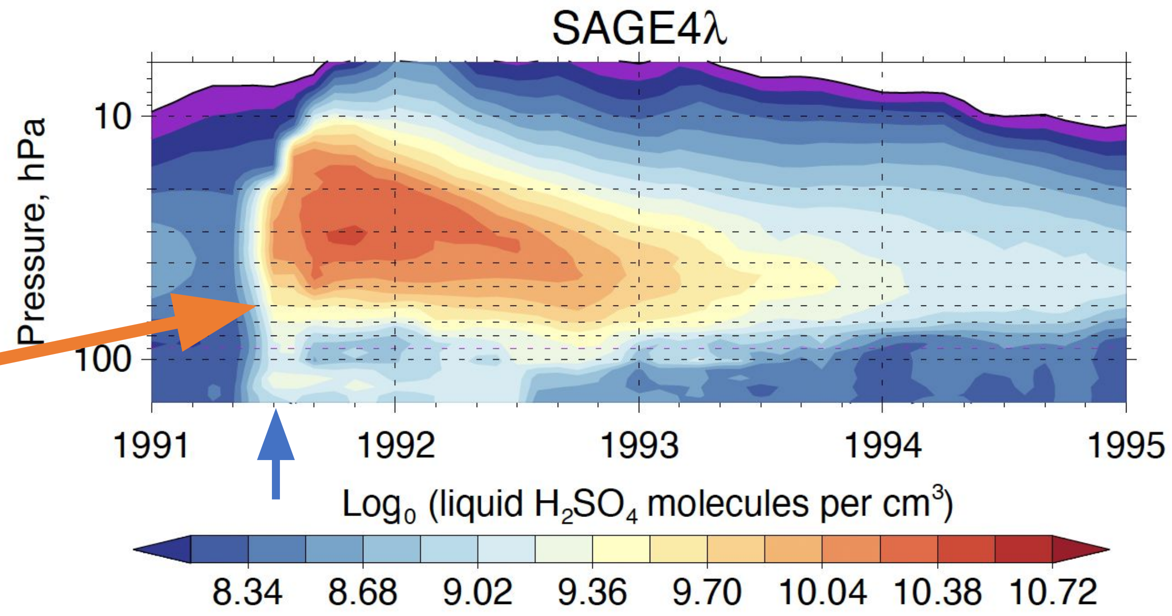
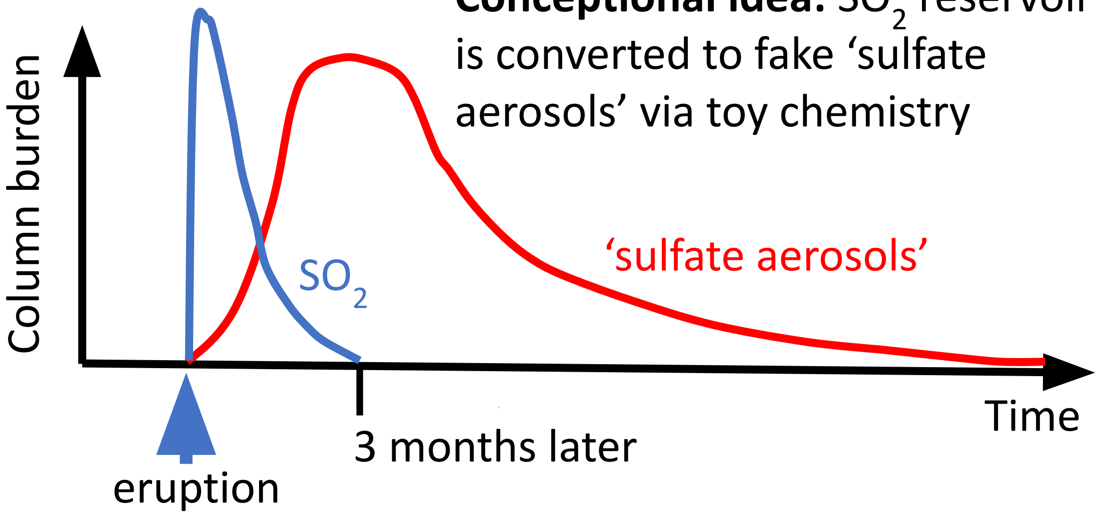


Figure 7. Vertical distribution of liquid H_2SO_4 concentration averaged over the tropics (20° S–20° N). Source: Sukhodolov et al. (GMD, 2018)

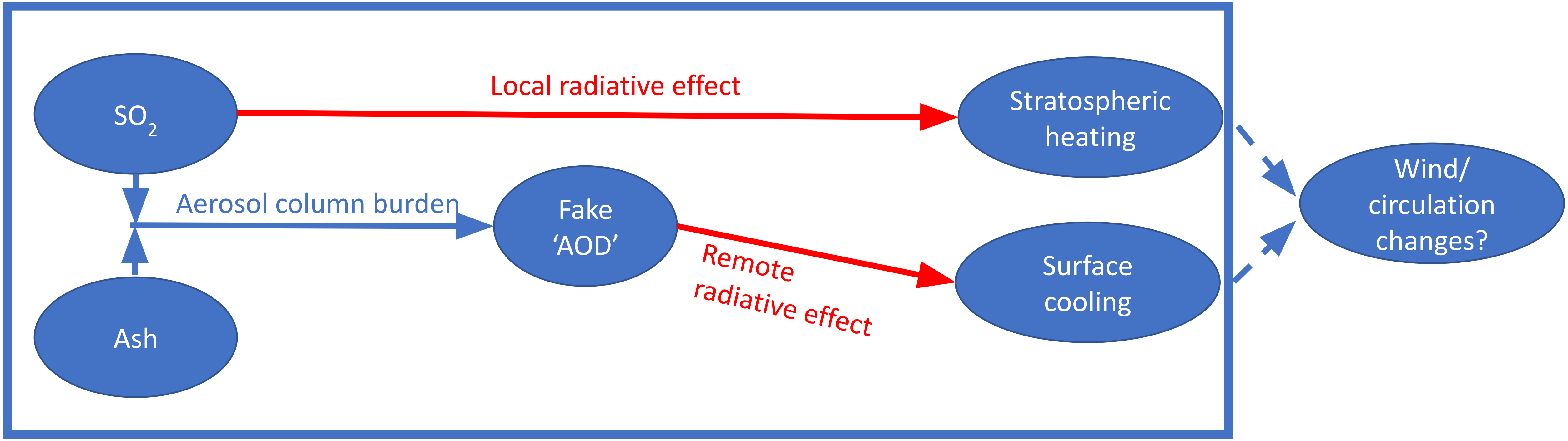


Conceptional idea: SO_2 reservoir is converted to fake 'sulfate aerosols' via toy chemistry

for SO_2 and ash column burden observations after the eruption, see also Sekiya et al. (JGR, 2016)

Embed pathway 3

- 3-node mixed pathway with a dual radiative response: stratospheric heating & surface cooling
- Use the (vertically integrated) column-burden of SO_2 and ash to mimic AOD
- Might need longer removal time scales for SO_2 and ash for 90-day runs

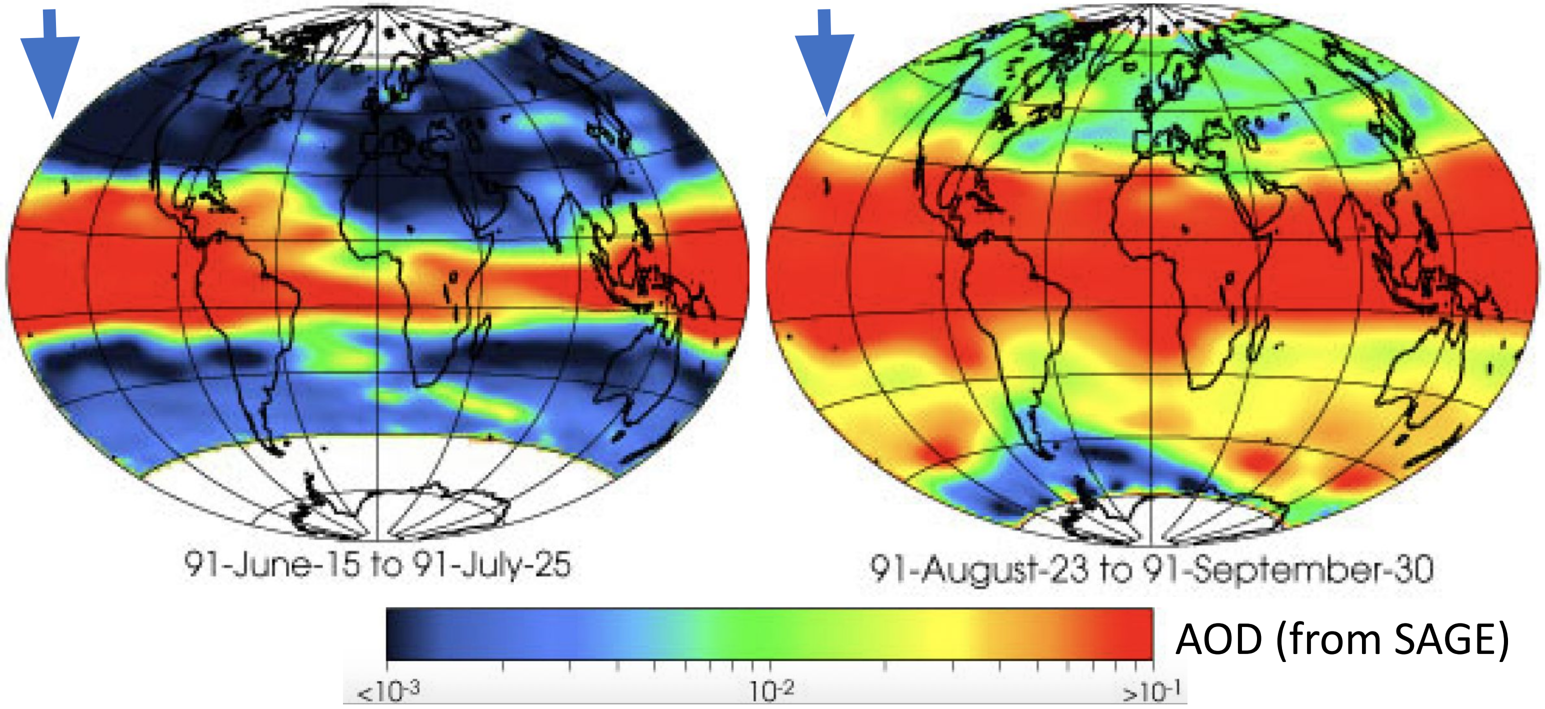


Main pathway

Secondary effects

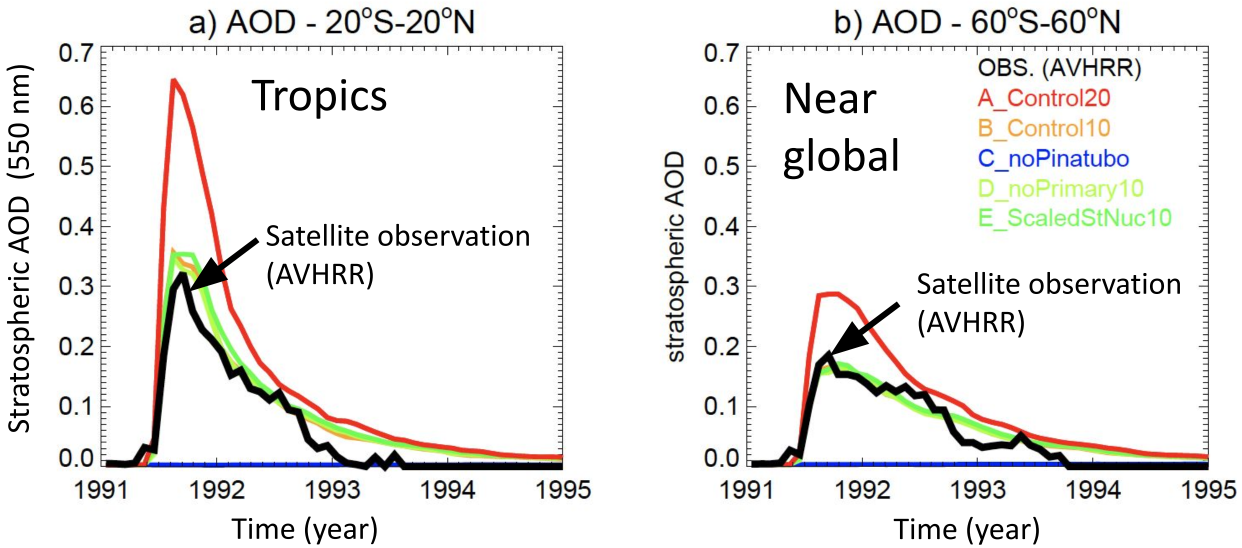
Embed pathway 3

- 3-node mixed pathway with a dual radiative response: stratospheric heating & surface cooling
- Use the (vertically integrated) column-burden of SO_2 and ash to mimic AOD (informed by satellite observations)
- Aerosol amount (AOD/column burden) informs cooling magnitude



40-day-mean AOD after the eruption, aerosols confined within the tropics

Mean during month 3 after eruption, aerosols start to reach poles

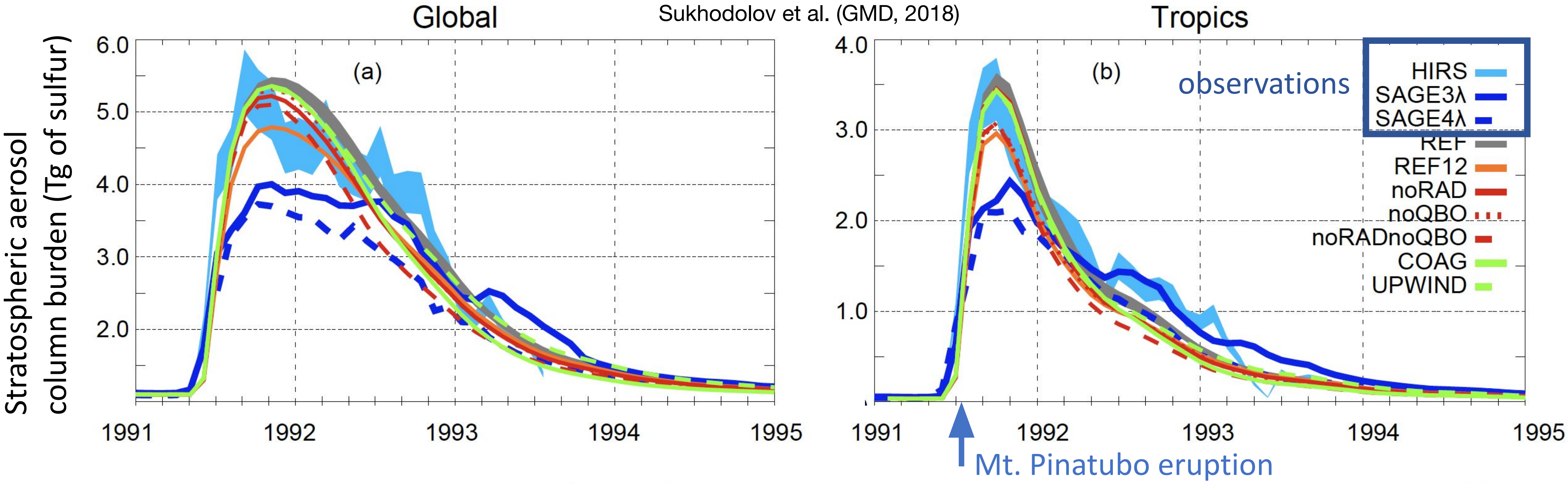


a) AOD - 20°S-20°N

b) AOD - 60°S-60°N

Sources: https://earthobservatory.nasa.gov/features/SAGEIII/SAGEIII_2.php (top figure)
Dhomse et al. (ACP, 2014), bottom figure

Aerosol column burden mimics AOD, drives surface cooling

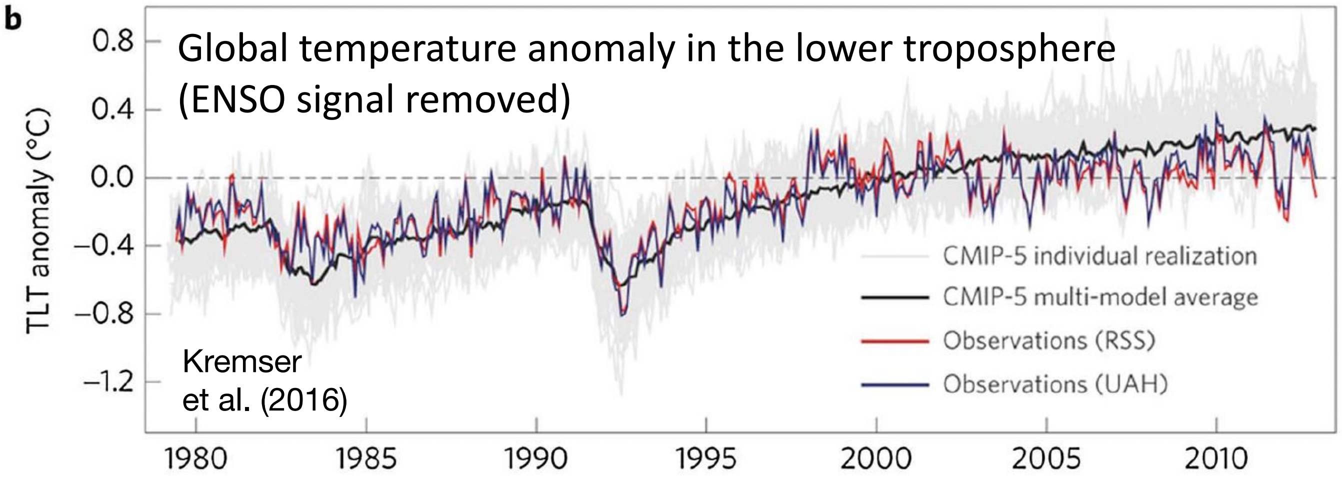


Sukhodolov et al. (GMD, 2018)

observations

Mt. Pinatubo eruption

- From observations: Increased aerosol column burden (increased AOD) after eruption triggers cooling in the lower troposphere (TLT): -0.4 - -0.8 K
- Informs our cooling magnitudes



Global temperature anomaly in the lower troposphere (ENSO signal removed)

Kremser et al. (2016)

Discussion Points: Idealized climate data

1. Scientific design of the pathways and idealized atmospheric circulation
    - Are the three suggested pathways just right, too simple, or too complicated?
    - Provide feedback, other pathway designs are possible
    - More complexity is possible, e.g. with idealized topography or idealized moisture processes. Is there a need?
2. Design of potential ensembles
    - Are the tools robust: variations of the initial conditions or injection profile using identical pathways
    - Can tools detect the strength of the pathway correlations? E.g. doubling the heating strength?
    - Is random noise in the pathways needed or desired?
3. Data questions
    - File formats: All files will be in **netcdf** format. Does this work for the tools? Desired data location (e.g. Sandia HPC)? One file per variable or all variables in one file? How many time snapshots per file? Etc.
    - Grid: Native cubed-sphere L72 grid? Is 4D (lon, lat, lev, time) remap desired as a postprocessing step?
    - Resolution: suggested starting point is ne16 (200 km) with 72 levels (L72), ne30 (100 km) is possible
    - Output variables: which ones are needed? 2D needed, e.g. data on pressure levels, vertically-integrated?
    - Output frequency: e.g. 1hr, 3hr, 6hr, daily, monthly, instantaneous or time-means?
    - Simulation length: suggested starting point is 90 days (aerosols start to reach poles)
    - Number and design of ensembles: initial conditions, variation of coefficients, variation of injection profile, …

Some suggested answers:

- Simulation data will be provided on an HPC system
- We will likely run the ne16L72 (200 km) medium low resolution
  - but if there is a need we can run at the resolution of prognostic runs: ne30L72 (100 km)
- We will output data like E3SM runs on the native cubed-sphere grid on model levels (if 3D)
  - will have to use mappings from native grids, see spatial remapping and vertical remapping

Specific Questions: What are the data requirements for the CLDERA tools?

1. How will you use this data set? (i.e. what are the metrics you will use when using this—what will you be verifying?)
    i) What temporal output frequencies are important for you?
2. How strongly should the implementations be inspired by Pinatubo – i.e. should we try for a “sulfate” or should we put in predator-prey formalisms?
    i) What criteria can help us make this decision?
3. How important are ensemble runs?
4. How much should this be used to understand sensitivities (to initial conditions (QBO phase for instance), to eruption characteristics (location, magnitude, injection height), …)?
5. How should we prioritize simulations? When is a simulation plan needed?

References

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Food for thought:
Other (More Complex) Impacts of Volcanic Eruptions

- Idealized experiments are a stepping stone and support the tiered evaluation of the
- CLDERA tools.
- Build a bridge towards more complex cause-and-effect assessments of volcanic (or future non-volcanic) events:
  - Changes to atmospheric dynamics including NH winter warming
  - Ozone depletion
  - Changes in precipitation
  - Weaker monsoons
  - Reduced ocean heat content
  - Shifts in the position of the Intertropical Convergence Zone (ITCZ)
  - Increased sea ice
  - Shifts in phases of modes of climate variability including the North Atlantic and the El Nino Southern Oscillation (ENSO)
  - Changes to Atlantic Meridional Overturning Circulation and Atlantic Multidecadal Variability
  - Disruption to the Quasi-Biennial Oscillation
  - Changes to the carbon cycle

Marshall et al. (2022)