Simulating the climate forcing of **volcanic aerosols** with a **simplified interactive model**

Plain Language Summary: Volcanic eruptions deposit aerosols into the upper-atmosphere, which are capable of altering temperature and wind patterns for years following. This poster describes a method of simulating this effect within a computational model of the Earth system. From top-to-bottom of the poster's central section, we describe the simulated injection of volcanic substances into the stratosphere, followed by the response of the atmosphere.

Abstract: Here we present a standalone module for the representation of climate forcing by volcanic aerosols within an coupled climate model framework, as demonstrated in the Energy Exascale Earth System Model (**E3SM**). Our implementation does not require the presence of any radiation or aerosol parameterizations, but rather computes grid-point-level heating rates (in K/s) directly through idealized Beer-Lambert forms on two broad shortwave (SW) and longwave (LW) radiation bands. Our model's lack of these other parameterization dependencies allows it to be activated in any atmospheric component set; here we demonstrate it in a modified Held-Suarez-Williamson (**HSW**) atmosphere. The experimental design was specifically chosen to produce datasets for use in climate attribution studies through the **CLDERA** (CLimate impact: Determining Etiology thRough pAthways) initiative at Sandia National Laboratories (**SNL**).

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Forcing Strategy

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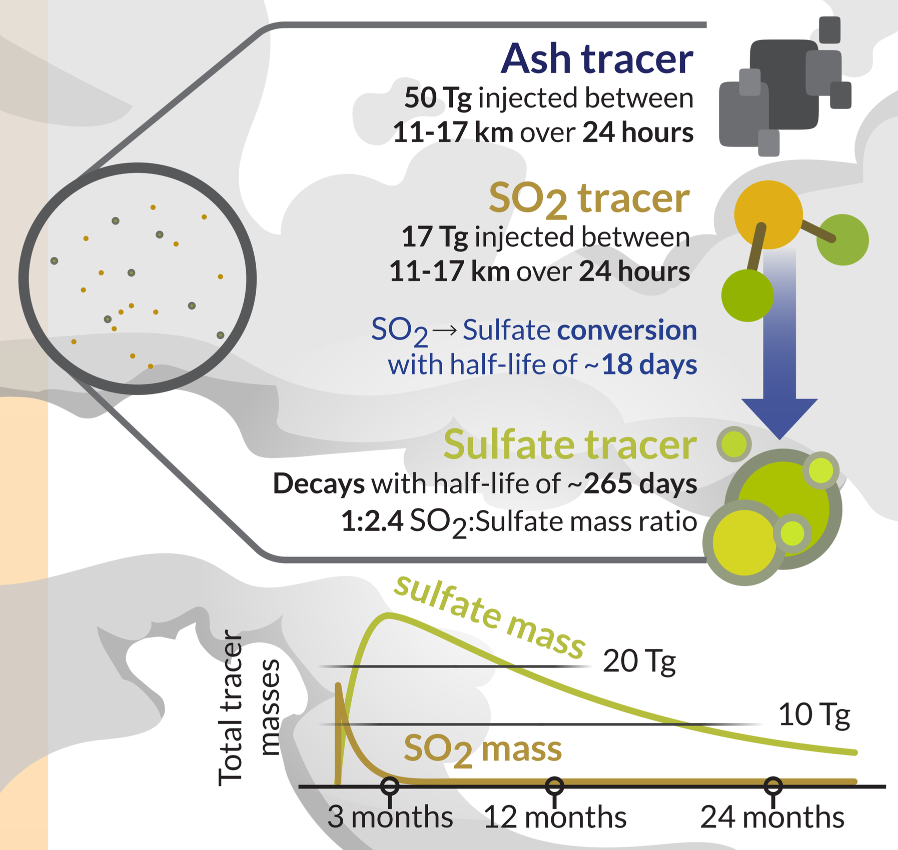
Injected Aerosol Species

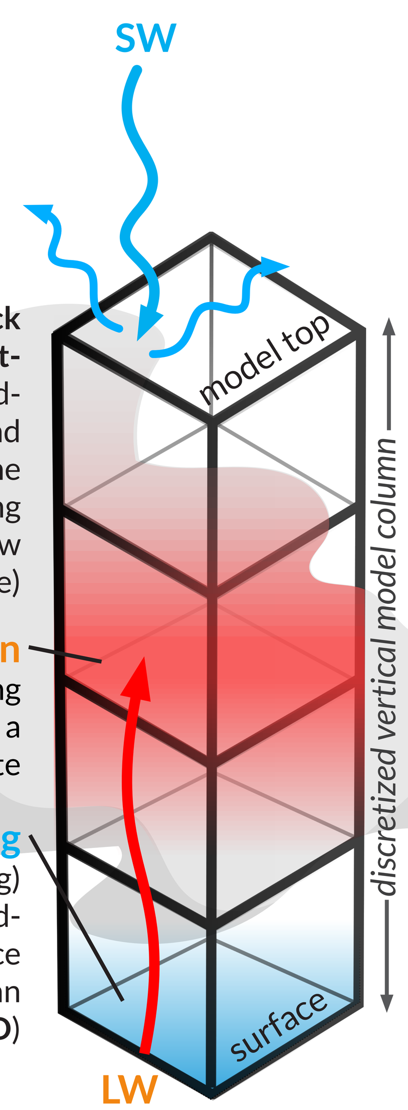
Begin with a column-uniform introduction of SO_2 and **ash** tracers at the eruption location:

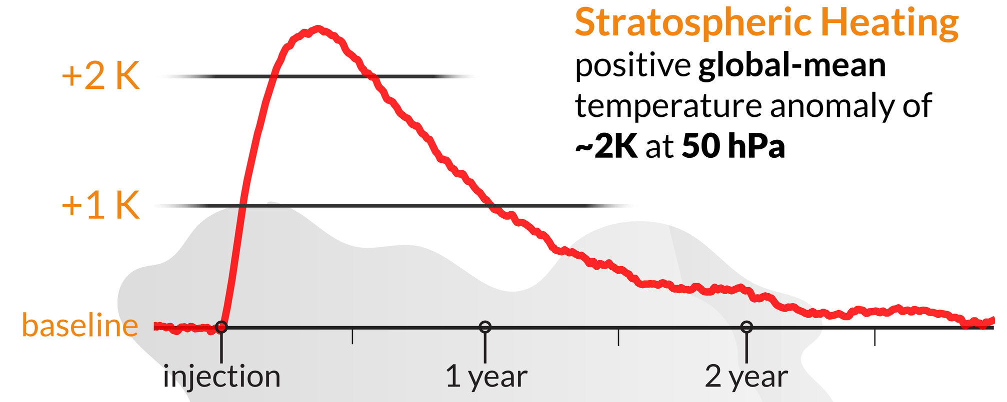


Aerosol radiative feedback is modeled as **uniform attenuation** of two broadbands, longwave (**LW**) and shortwave (**SW**), over the model column (right) using a simple Beer-Lambert Law form (see QR code above)

Longwave Absorption
Attenuation of upwelling LW radiation modeled as a local heating rate

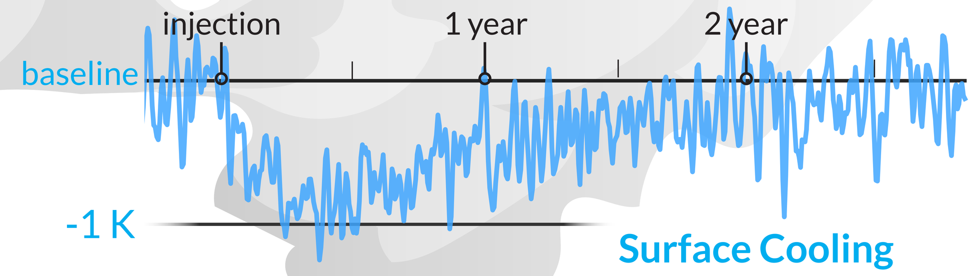
Shortwave Scattering
Attenuation (by sacttering) of solar SW radiation modeled as an effective surface cooling rate by column aerosol optical depth (**AOD**)





Stratospheric Heating
positive **global-mean** temperature anomaly of **~2K** at **50 hPa**

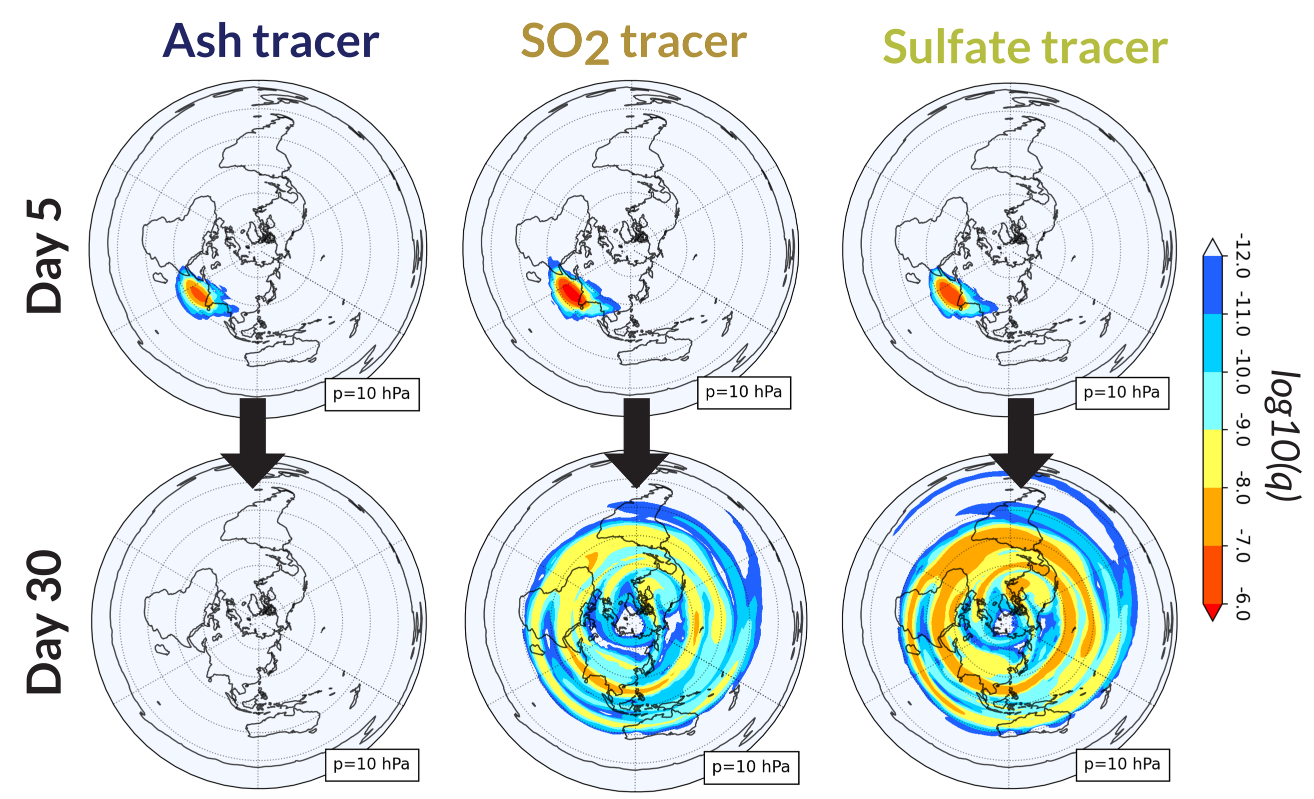
Pictured: *Anomaly in the* ***globally-averaged*** *temperature field after* ***radiative forcing*** *by a stratospheric injection of 17 Megatons (Tg) of* SO_2*. A robust* ***warming signal (~2K)*** *is seen in the stratosphere (50 hPa; above), and a* ***noisy cooling signal (~1K)*** *near the surface (1000 hPa; below). Data derived from* ***5-member ensemble mean****. Baseline derived from* ***10-year mean background climate****.*



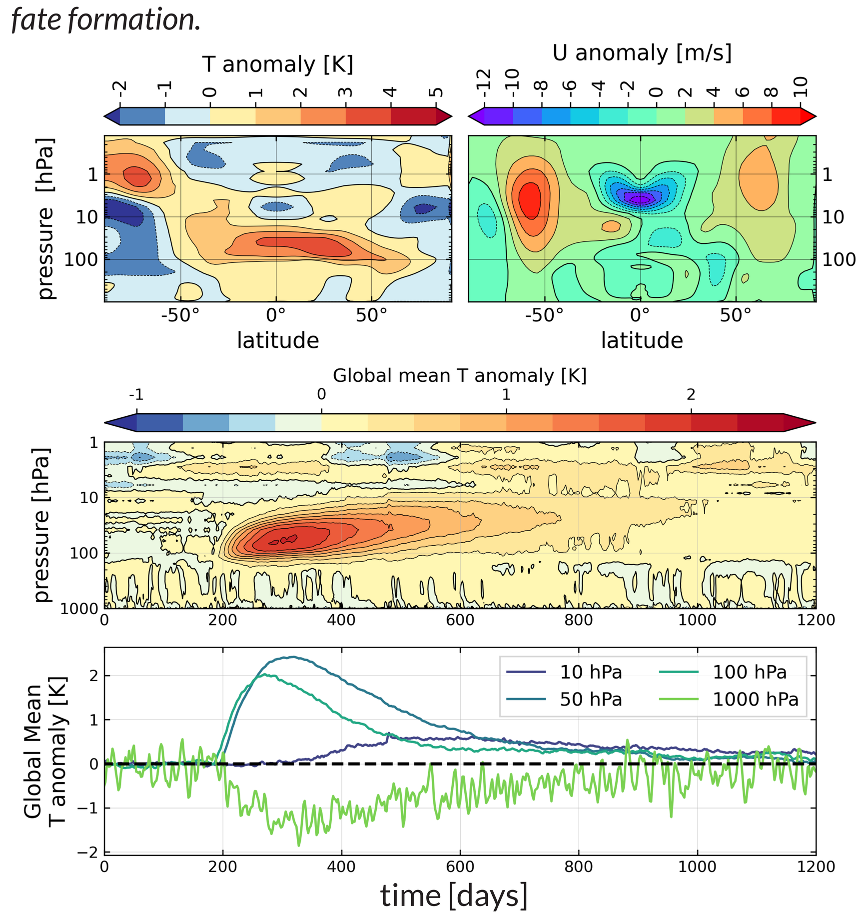
Surface Cooling
negative **global-mean** temperature anomaly of **~-1K** at **1000 hPa**

Transport & Impacts

q = "mixing ratio" = (kg tracer) / (kg air) in grid cell



Above: *Transport of the aerosol plume after stratospheric injection, being advected by easterlies at 10 hPa.* **Ash** *reaches as far as Northern Africa before dissipating.* **SO2** *and* **sulfate** *circulate the globe by ~20 days. By 30 days, SO2 densities are declining, giving way to sulfate formation.*

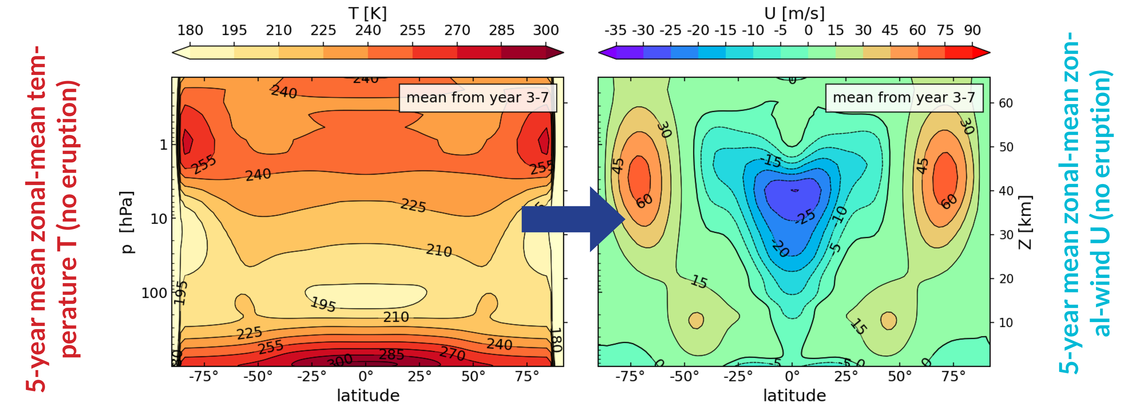


Left: *Signatures of the aerosol forcing in atmospheric variables, as the mean of a* **5-member injection ensemble** *with uniformly sampled initial conditions.*
(top) *Zonal-mean* ***temperature*** *and* ***zonal-wind*** *vertical sections at 5-months post-injection. We observe a persistent* **strengthening** *of the tropical stratospheric easterlies, as well as* **strengthening/shifting** *of the southern polar jet.*
(middle, bottom) global-mean temperature anomaly in time-pressure coordinates. The anomaly peaks at **~2K**, near (**1 year, 30 hPa**). The upward tilt of the contours is **self-lofting** of the plume.

Atmospheric Model

COUPLED CLIMATE MODEL:	**E3SM (Energy Exascale Earth System Model)**
ATMOSPHERE MODEL:	EAM (E3SM Atmosphere Model)
DYNAMICAL CORE:	**SE (Spectral Element)**
HORIZONTAL RESOLUTION:	~2 degree quasi-uniform grid
VERTICAL DISCRETIZATION:	**72 levels to ~60 km (~0.1 hPa)**
CONFIGURATION:	HSW (Held-Suarez-Williamson)

- The **"HSW"** model configuration prescribes a constant **reference temperature** profile (Held+Suarez 1994, Williamson 1998).
- At all times, we gently **nudge** the atmosphere's temperature field toward this reference profile.
- This single forcing **replaces all radiation and convection** forcing schemes
- The atmosphere is **dry** and **aseasonal**, with **no diurnal cycle**



This allows the **entire temperature tendency** to be written as a sum of just three terms. This is a significant **simplification** over more complex configurations, and is necessary for developing and validating CLDERA **climate attribution** tools (see right panel)

fluid dynamics and dissipation from the dynamical core | climate forcing defined in the HSW protocol | our idealized volcanic aerosol radiative forcing

$$\frac{dT}{dt} = \left(\frac{\partial T}{\partial t}\right)_{\text{dycore}} + \left(\frac{\partial T}{\partial t}\right)_{\text{HSW}} + \left(\frac{\partial T}{\partial t}\right)_{\text{volc}}$$

REFERENCES

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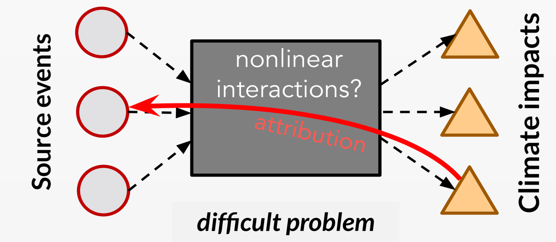
Motivation

THE CLDERA PROJECT
CLimate attribution: Detecting Etiology thRough pAthways

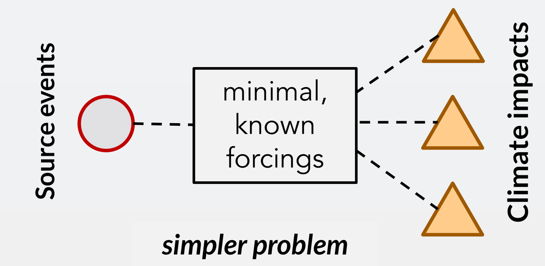
The **CLDERA** project is an initiative at Sandia National Laboratories (SNL), striving to develop tools to solve the **attribution problem**, connecting observed **climate impacts** to spatio-temporally localized **source events**.

Ultimate goal: discover and characterize the causal **"pathways"** that exist within the climate system (schematic below) via e.g. causal inference, in-situ profiling, spatio-temporal clustering.



Above: *Source events and downstream climate impacts are thought to be connected by causal "pathways". These traverse through the full set of nonlinear interactions of the atmosphere dynamics and physical parameterizations, where identifying them becomes highly nontrivial*

Contribution of this work: CLDERA has chosen a high signal-to-noise externally-forced source event as an exemplar for the development of its attribution methods: the **1991 eruption of Mt. Pinatubo**. Our work provides datasets which embed Pinatubo-like climate impacts with a **minimized set of known temperature forcings** (as in the simplified pathway schematic below) for CLDERA tool development & validation.



Above: *In our model, we have intentionally replaced the normal library of physical parameterizations with exactly two contributing forcing terms (HSW, and the aerosol radiative forcing), and isolated the injection in an environment with no other external source events for all-time. These data will make the attrobution problem more accessible.*

THE HIERARCHY OF VOLCANIC FORCING

We choose an implementation that **compromises** between the **simple** and **complex** established forcing approaches (schematic below).

Above: *sketch of the spectrum of aerosol forcing implementations.* ***Left:*** *simple/affordable approach, where forcing is prescribed from offline datasets, or functions.* ***Right:*** *accurate/expensive approach: forcing is computed interactively with aerosol distributions that are transported with the atmosphere's motion and radiatively simulated to high detail.* ***Our approach:*** *intermediate complexity. Aerosols are interactively "traced", while local forcing calculations are highly simplified.*

In this way, we attempt to embed tractible "pathways" within our data, without compromising on the full spatio-temporal describtion of the tracer distributions