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2023 Sandia FORCEE Summer Research Symposium

Dynamically Identifying Atmospheric Forcing by Volcanic Sulfate Aerosols

8931: Climate Systems

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Future of Research Climate, Earth & Energy
2023 SANDIA FORCEE

U.S. DEPARTMENT OF ENERGY
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Volcanic Stratospheric Aerosol Injection (SAI)…
…as a proxy for Solar Radiation Modification (SRM)

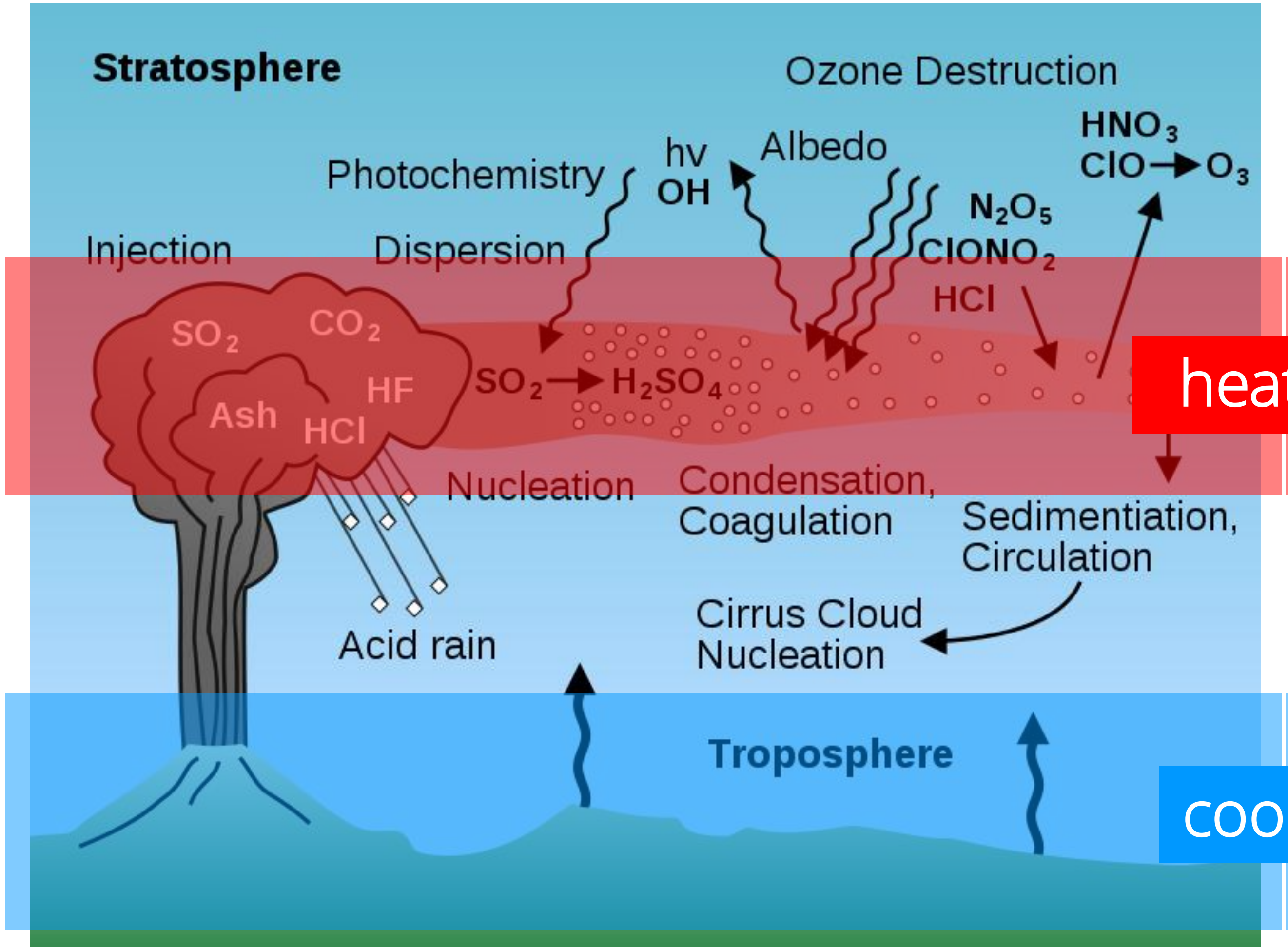

Image from U.S. Geological Survey Open-File Report 97-262

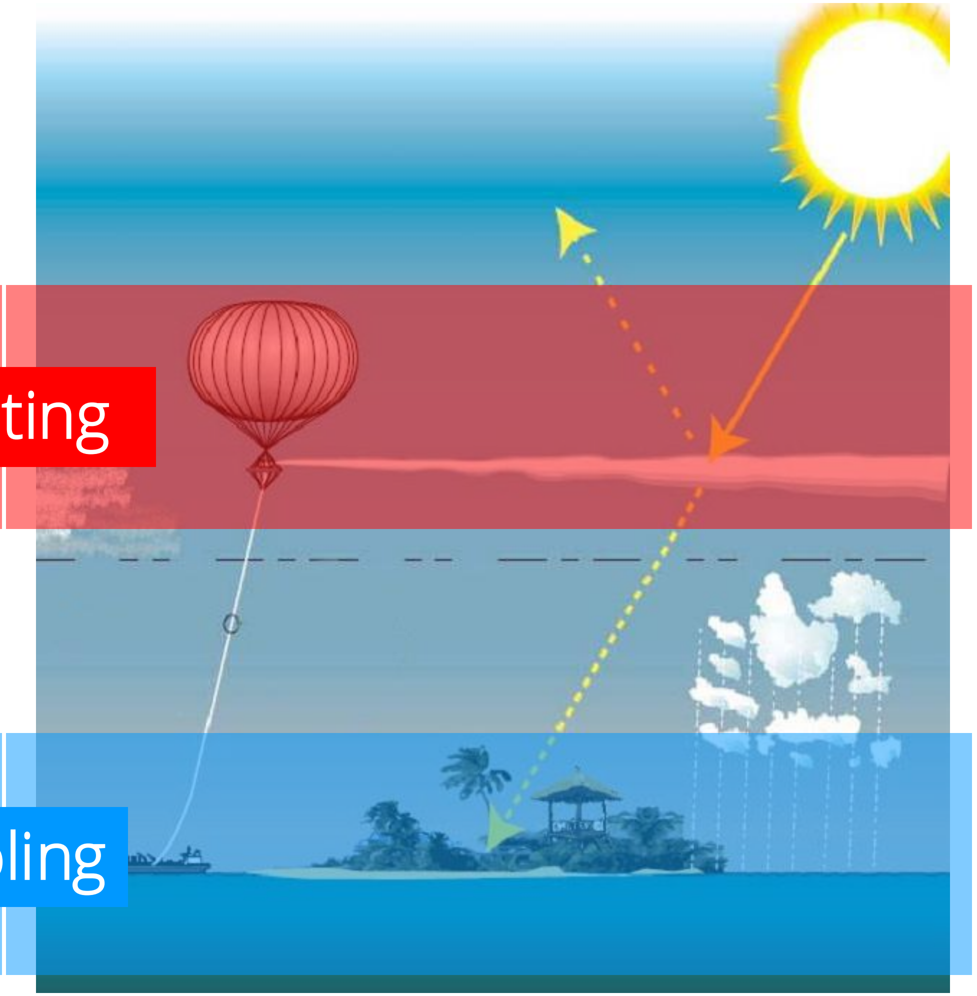

Image from Prof. Hugh Hunt, SPICE Project

Volcanic Stratospheric Aerosol Injection (SAI)…
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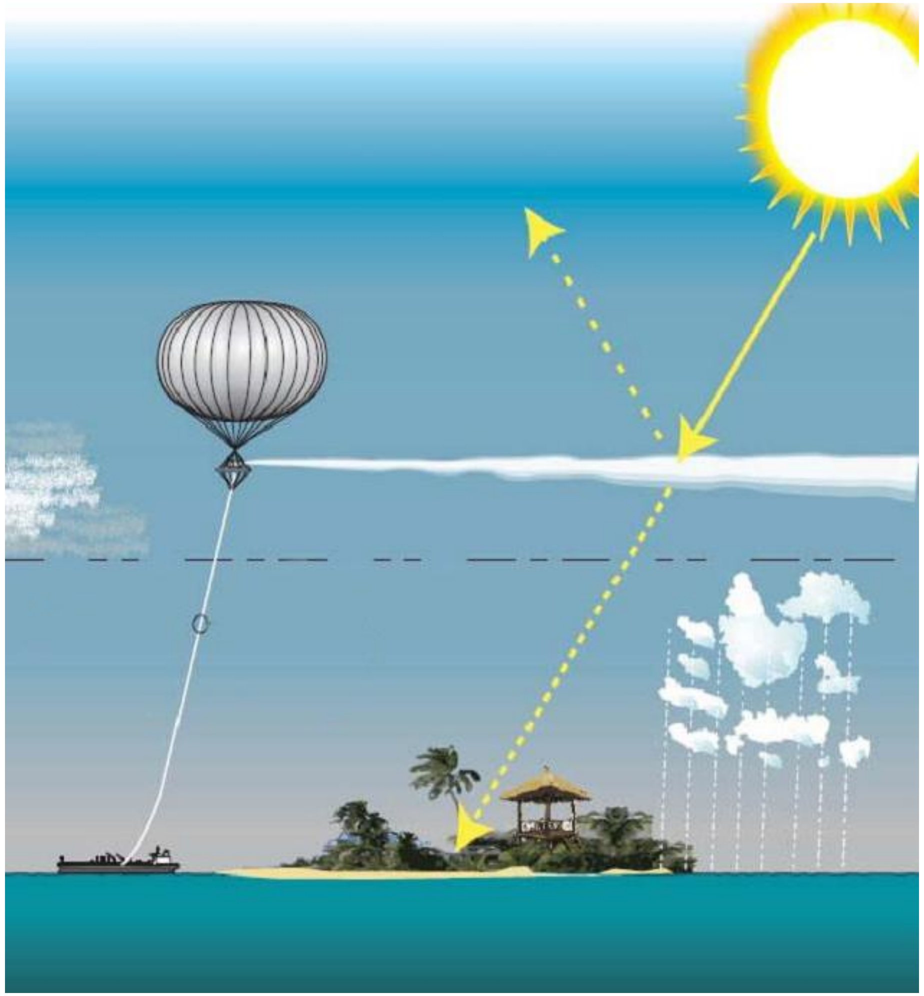
Questions:

Is this possible, in theory?
- According to current models, **yes**
  (e.g. Nguyen et al., yesterday's symposium)

Is this possible, in practice?
- Maybe

If the answer to both questions above are "yes", then **should we do it**?
- Answering this question requires a robust methodology for **quantifying side-effects**!
- Even if SRM activities are able to reach target *mean surface temperatures,* will they induce other secondary and/or local atmospheric impacts?



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Problem Statement:
How can we identify spatio-temporal impacts on large-scale atmospheric dynamics in the volcanic SAI “proxy problem”?

Hypothesis:
By releasing custom species of “tracers” into a simulated atmosphere, and analyzing their response to a volcanic forcing event

Outline

- Definition & Implementation: “passive” tracers *E90* and *ST80*
- Preliminary results: perturbations to the passive tracers fields
- Definition & implementation: “dynamic” tracers *PV* and *PT*
- Preliminary results: diabetic forcing signatures in the dynamic tracer fields
- Conclusions

Passive Tracers Implemented in the E3SM Climate Model

Tracer: a substance, expressed in mass-density, that is *advected* (transported) with the winds of the atmospheric model

- **Passive:** the tracer advects "passively", and does not provide any dynamical feedback to the atmosphere (i.e. the atmosphere evolves identically with or without the presence of the passive tracer species)

Figure (right) shows the initial *spinup* of the so-called **E90** passive tracer species. Defined simply as:

- Constant, uniform emission across the Earth's surface

- Constant, uniform decay over the entire atmosphere (e-folding timescale of 90 days)

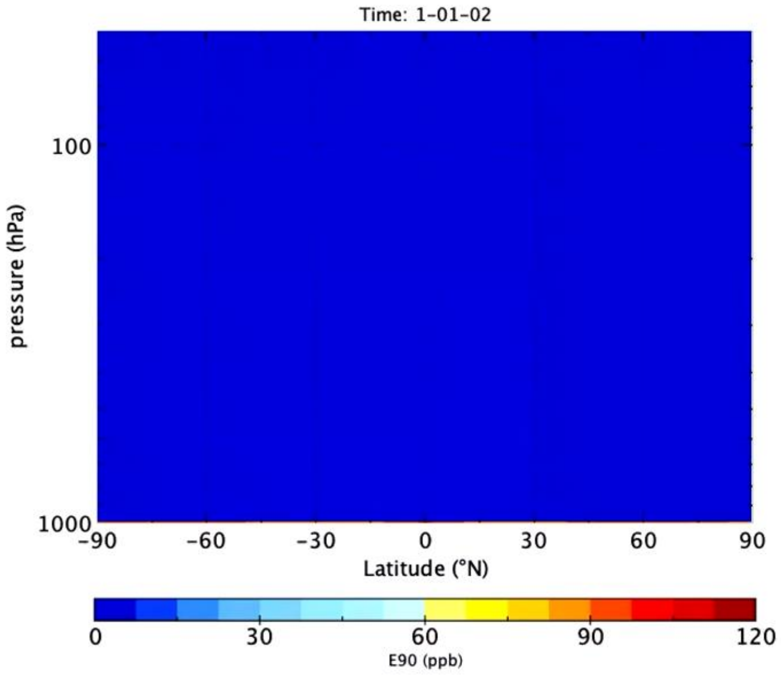

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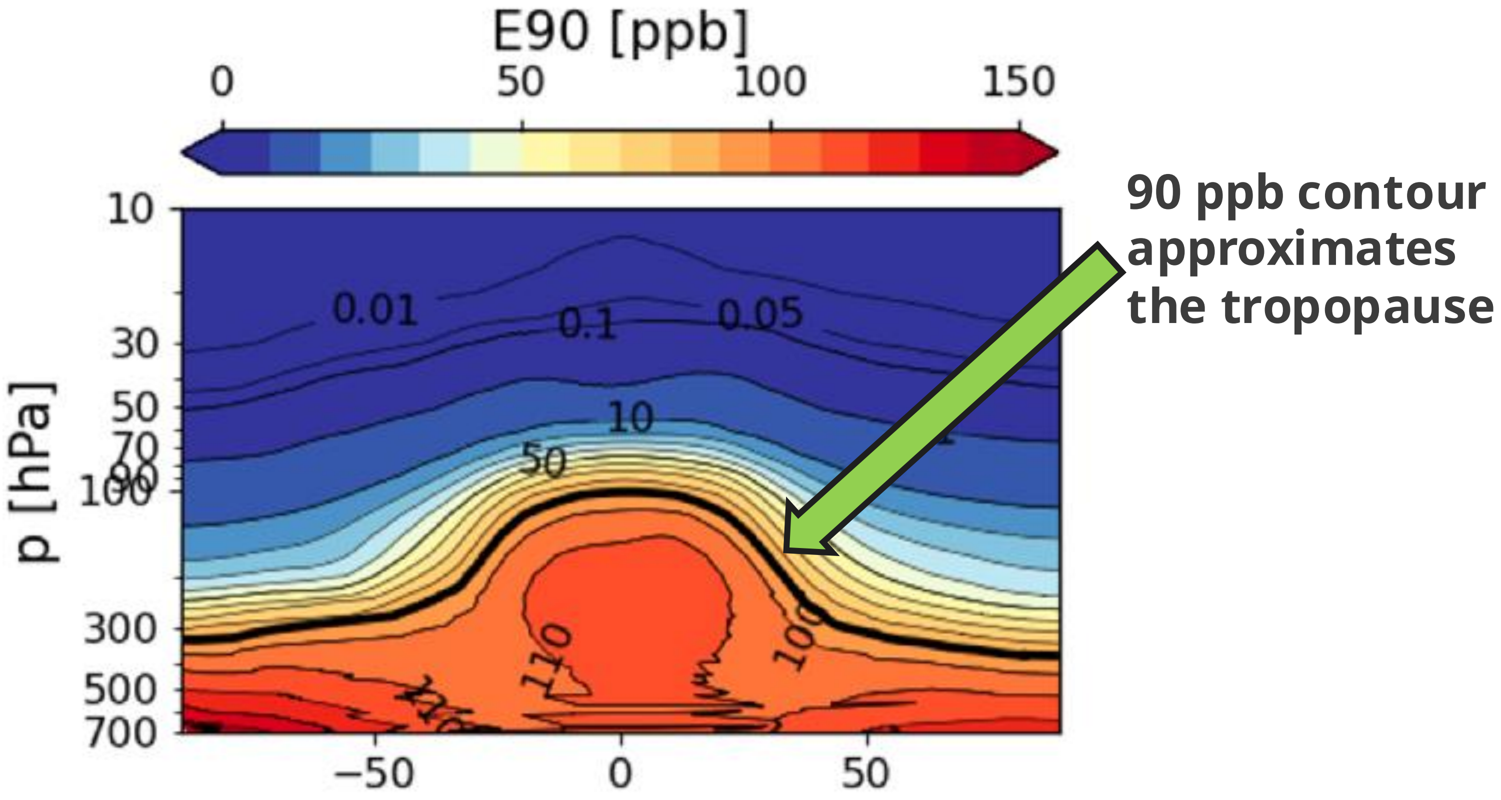
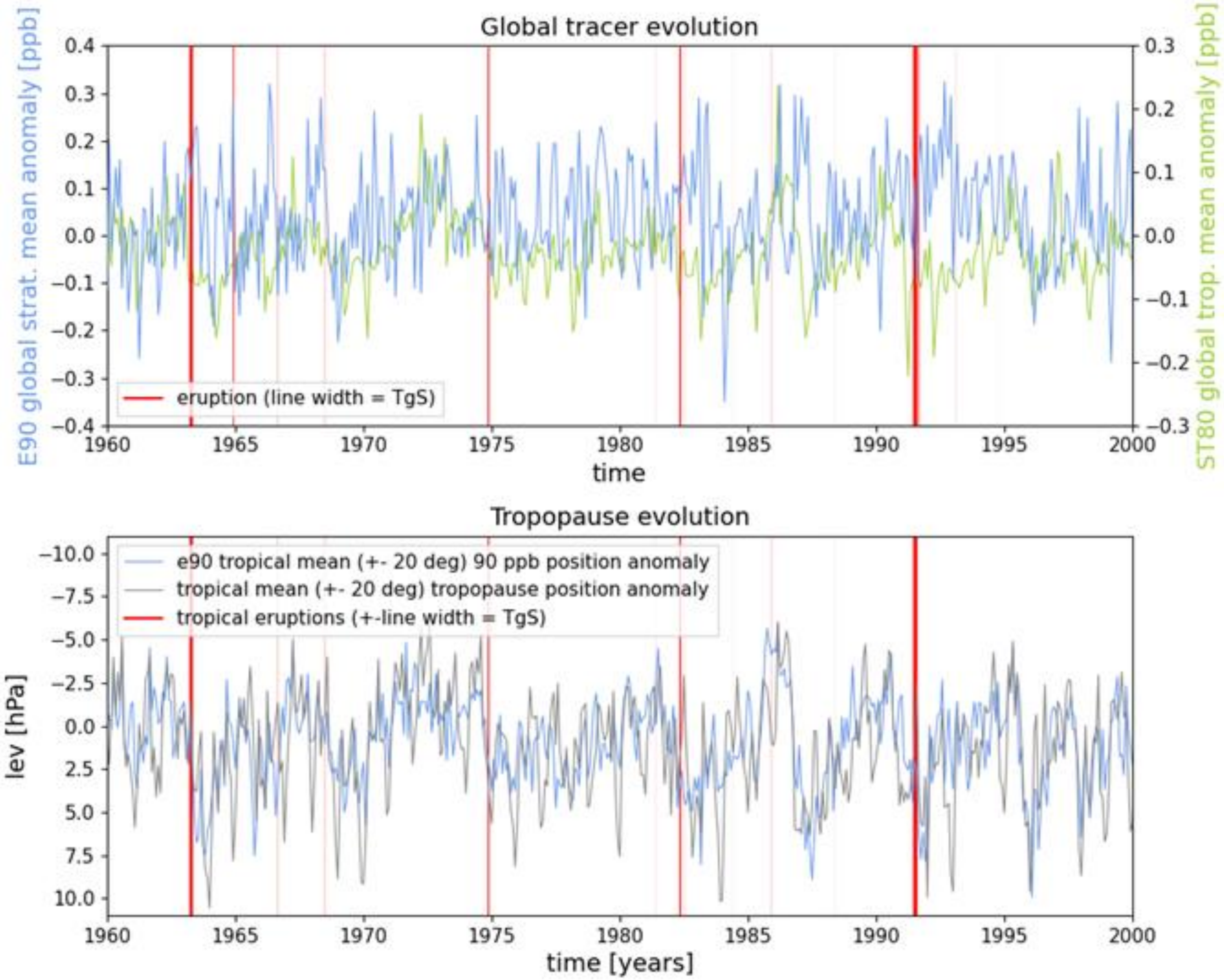
Figure (right) shows the initial **160-year mean *steady-state*** of the **E90** passive tracer species.

The tracer distribution will vary about this steady state according to diurnal cycles, seasonal cycles, atmospheric variability, and **diabatic forcing events**



Passive Tracers Response to Volcanic Forcing in the Historical Record

Figure 2 (right): *(top)* time series of mean stratospheric E90 and mean tropospheric ST80 concentration anomalies.
(bottom) time series of E90 90ppb isoline and tropopause altitude anomalies.
Eruption months are shown in red, with line thickness being commensurate with eruption magnitude. E90 concentration and tropopause anomalies post-eruption are suggested (see next slide)



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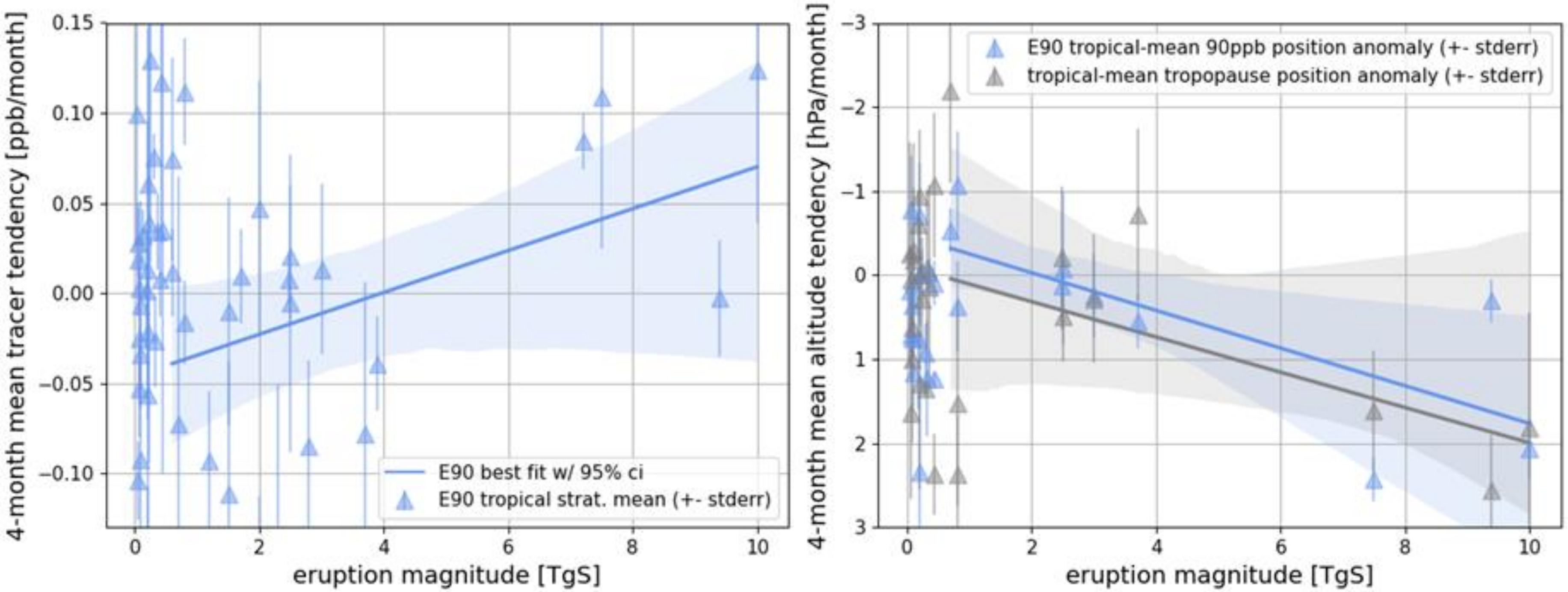


Figure: (left) the mean 4-month time tendency in anomalous E90 tropical stratospheric mean concentration as a function of eruption magnitude, *(right)* the mean 4-month time tendency in anomalous E90 90ppb isoline (blue points, line) and tropopause (grey points, line) altitude as a function of eruption magnitude.

Tendencies were computed as the slope of the linear best-fit line to monthly-averaged data over a 4-month period for each eruption. Error bars are the standard error on the slope of the fits, and the shaded band of the overall fit are 95% confidence intervals obtained via bootstrapping. Analysis would be more robust with higher-frequency E90 data

Takeaway:

Volcanic sulfate forcing of lower-mid stratosphere causes both a *lofting of the tropopause*, as well as *enhanced exchange across the tropopause* from troposphere to stratosphere

Dynamic Tracers Implemented in the E3SM Climate Model

Dynamic tracer: a substance that is *advected* (transported) with the winds of the atmospheric model, which represents a particular atmospheric dynamic quantity, enabling checks of non-conservation. Namely: **Potential Vorticity (PV)** and **Potential Temperature (PT)**

"Diagnostic" Potential Vorticity (PV)

$$q = \frac{1}{\rho}(2\boldsymbol{\Omega} + \nabla \times \boldsymbol{u}) \cdot (\nabla\theta)$$

PV is conserved in barotropic atmospheric conditions, or more generally, on surfaces of constant potential temperature (PT), or *isentropes*

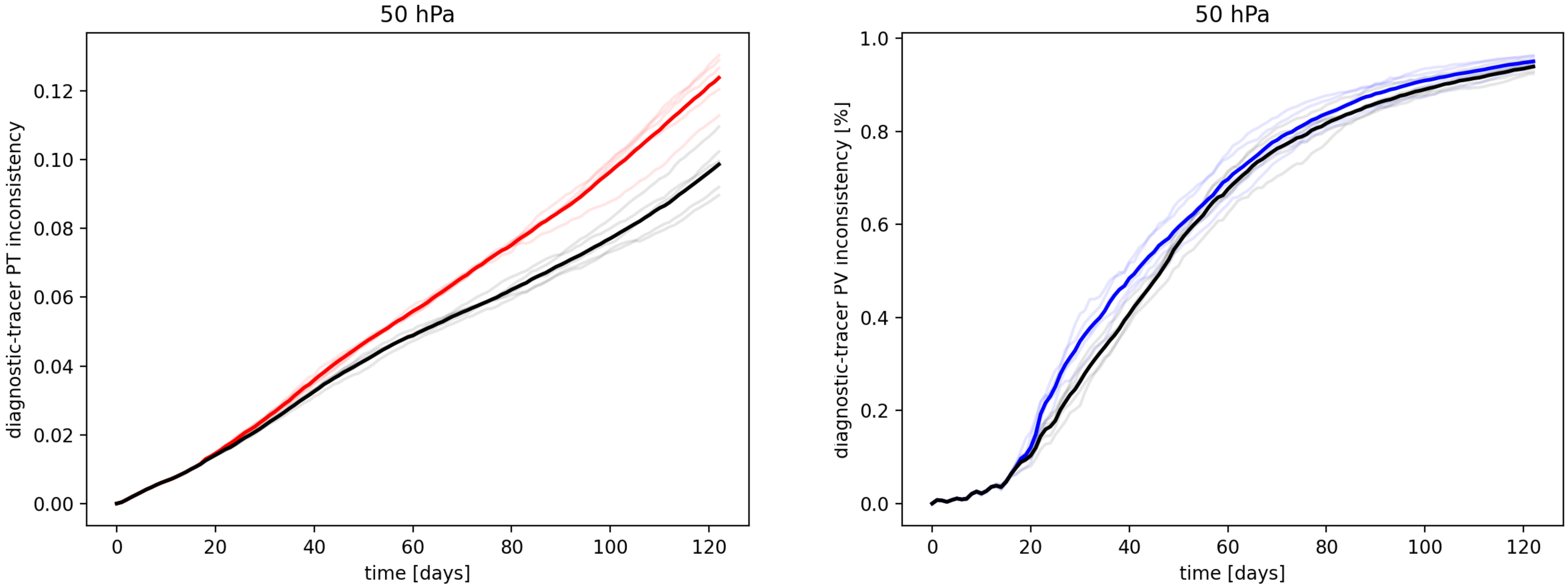
Implied advection equation for a PV "tracer"

$$\begin{aligned} \frac{\mathrm{D}q}{\mathrm{D}t} &= 0 \\ \Leftrightarrow \frac{\partial q}{\partial t} + \boldsymbol{u} \cdot \nabla q &= 0 \end{aligned}$$

Thus, if we both compute the "true" PV, and advect a "PV tracer", the non-conservation between the two measures the net local diabatic forcing

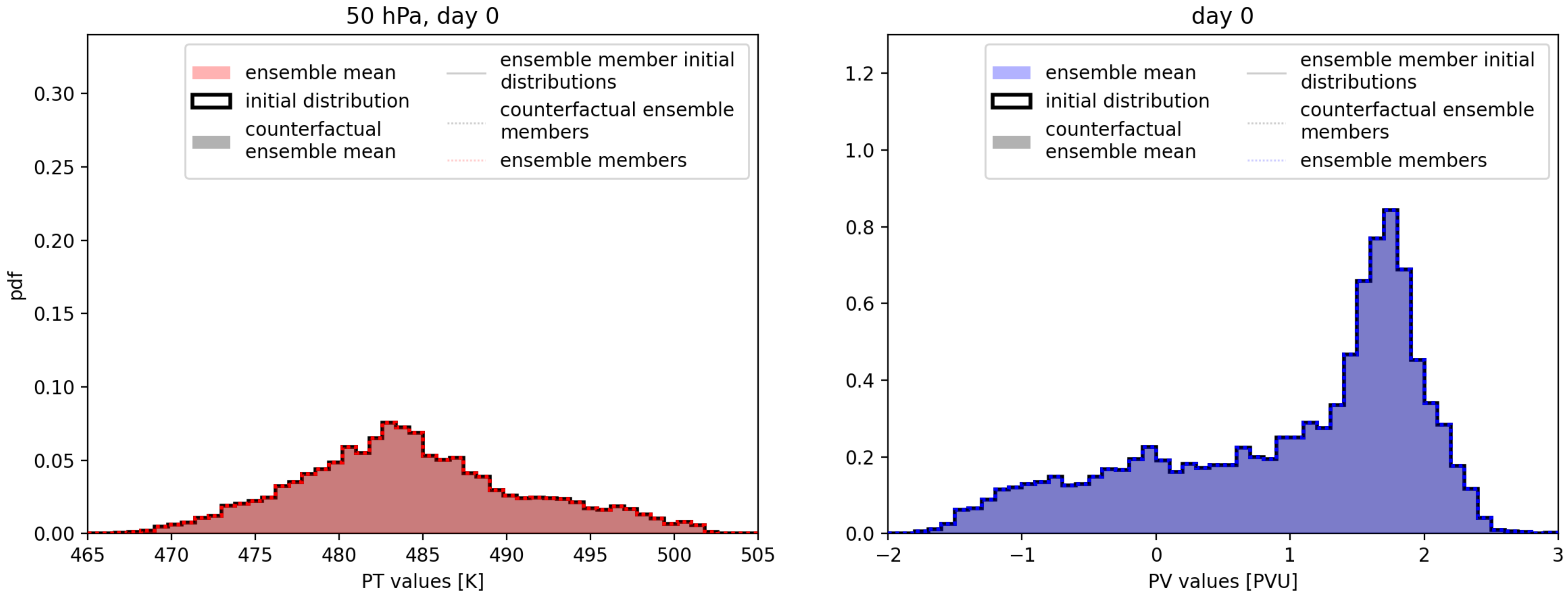
Mean Dynamic Tracers Response to Volcanic Forcing

Figure: Separation of the time series of the **PT, PV** *diagnostic inconsistency* in the tropical middle-stratosphere (50 hPa) for an ensemble-mean of E3SM simulation runs **with (colored lines)** and **without (grey lines)** a **large volcanic forcing event**



Mean Dynamic Tracers Response to Volcanic Forcing

Figures (below): Drift in **PT, PV** value distributions in the tropical middle-stratosphere (50 hPa) both **with (red histogram)** and **without (grey histogram)** a **large volcanic forcing event**



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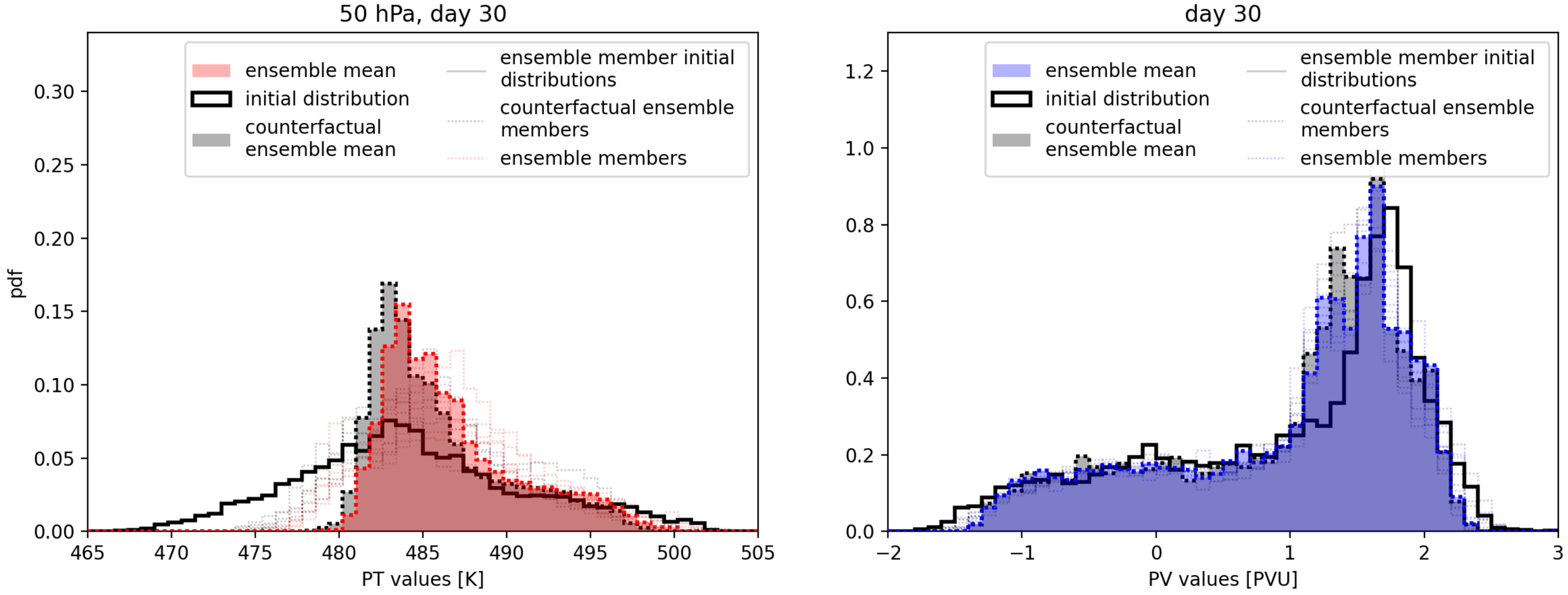

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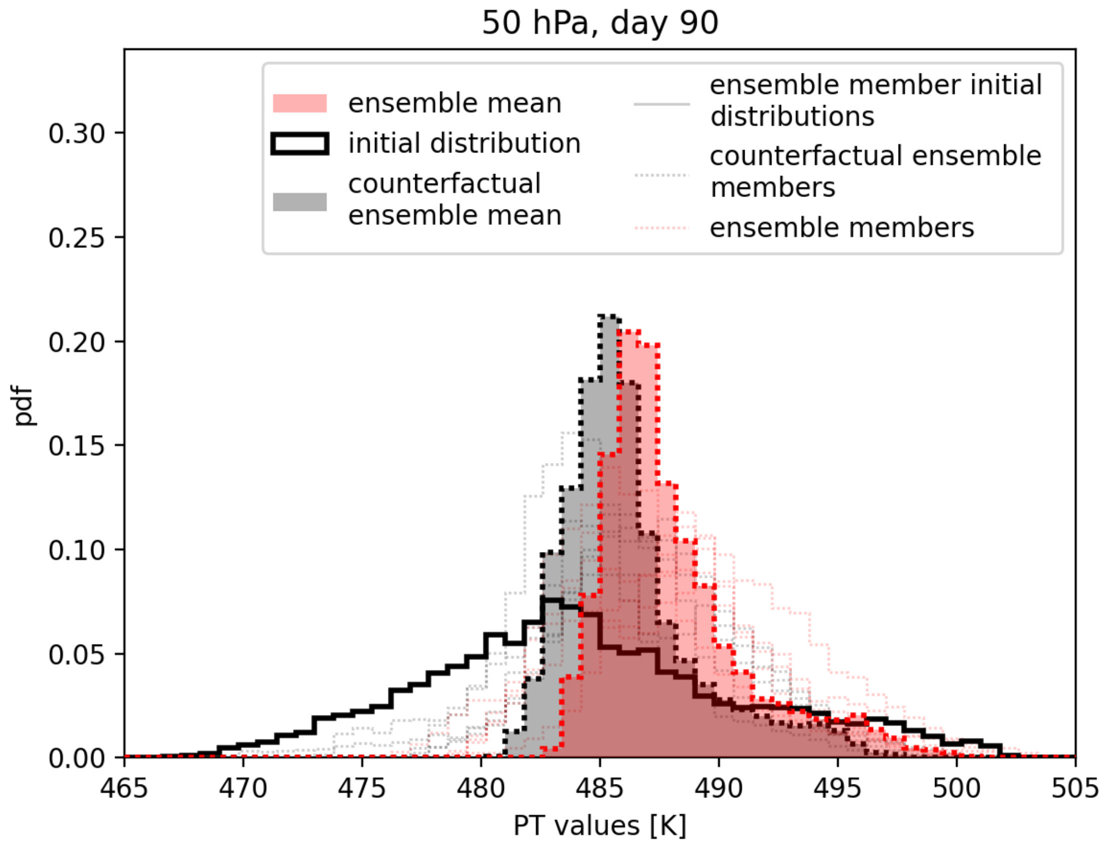
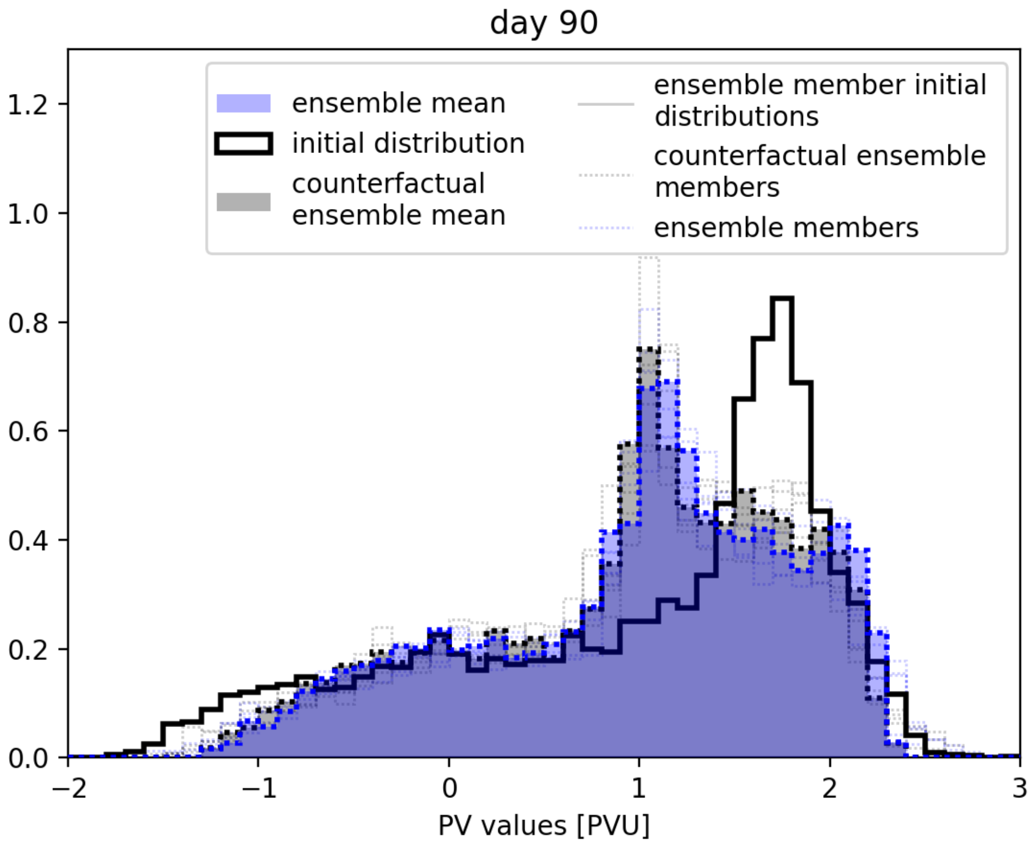
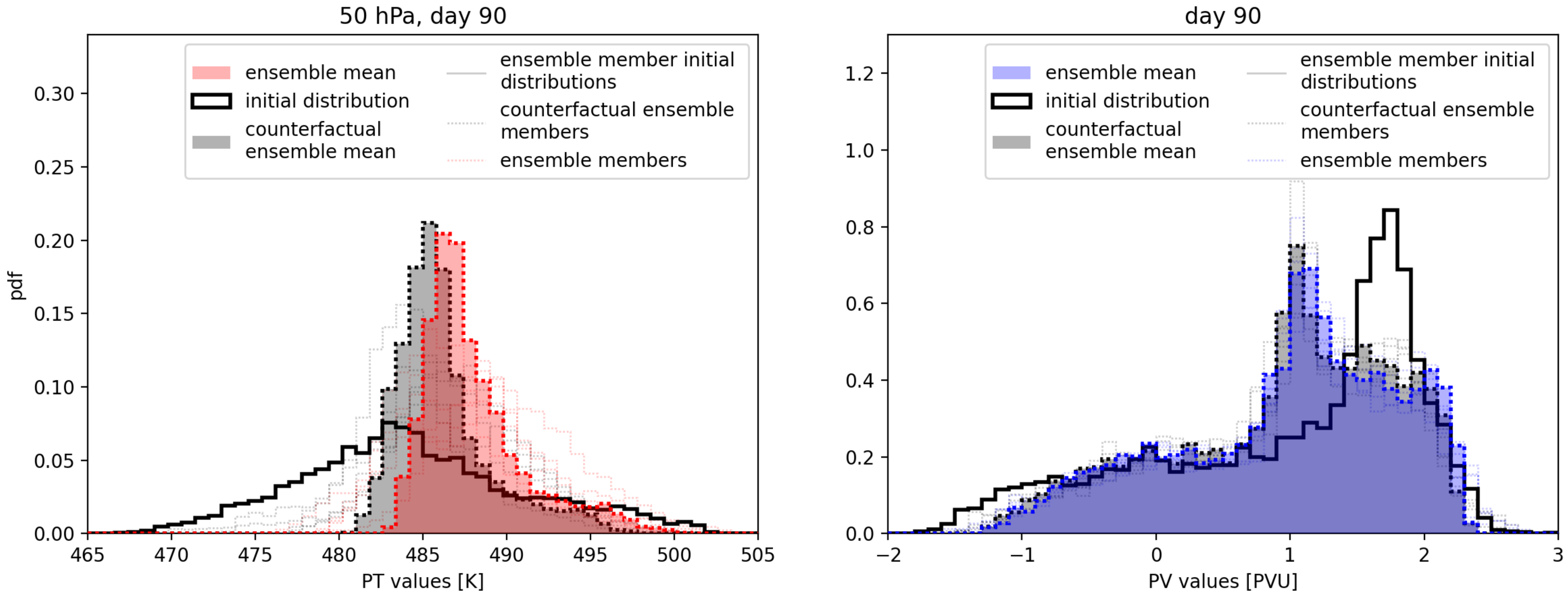




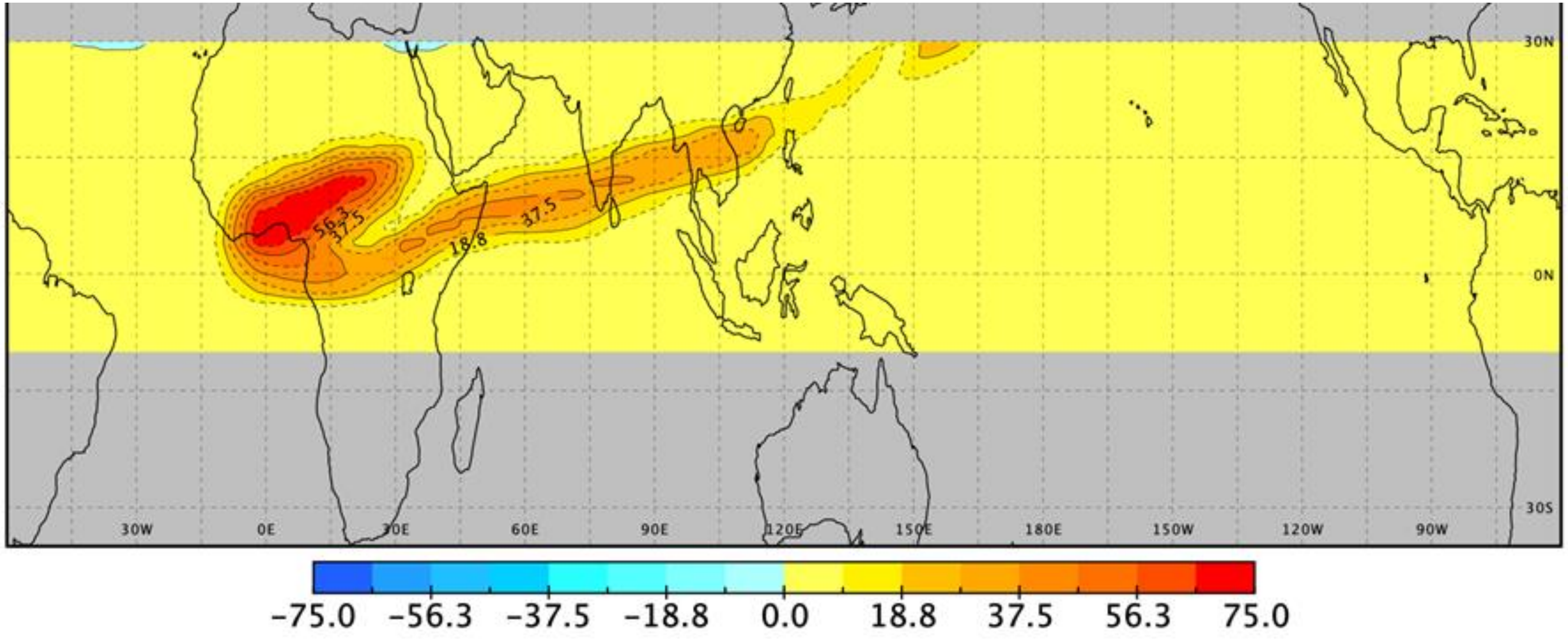
Mean Dynamic Tracers Response to Volcanic Forcing

A volcanic signal does exist in the **shift in the means** of the (grey) and (red) distributions in PT; a challenge in extracting that signal is that the drift away from the initial condition for both the counterfactual and eruptions runs is **larger than the difference between the two**



Local Dynamic Tracers Response to Volcanic Forcing

Figure (below): The **drift** between the advected and diagnosed PT and PV In the tropics at 50 hPa. The obvious structure in PT is a **volcanic sulfate plume**. Large values on these plots signify a large dynamical effect from the diabatic volcanic forcing. PV inconsistencies generally coincide with steep gradients in the PT inconsistency



(Advected PT) – (Real PT) [K]

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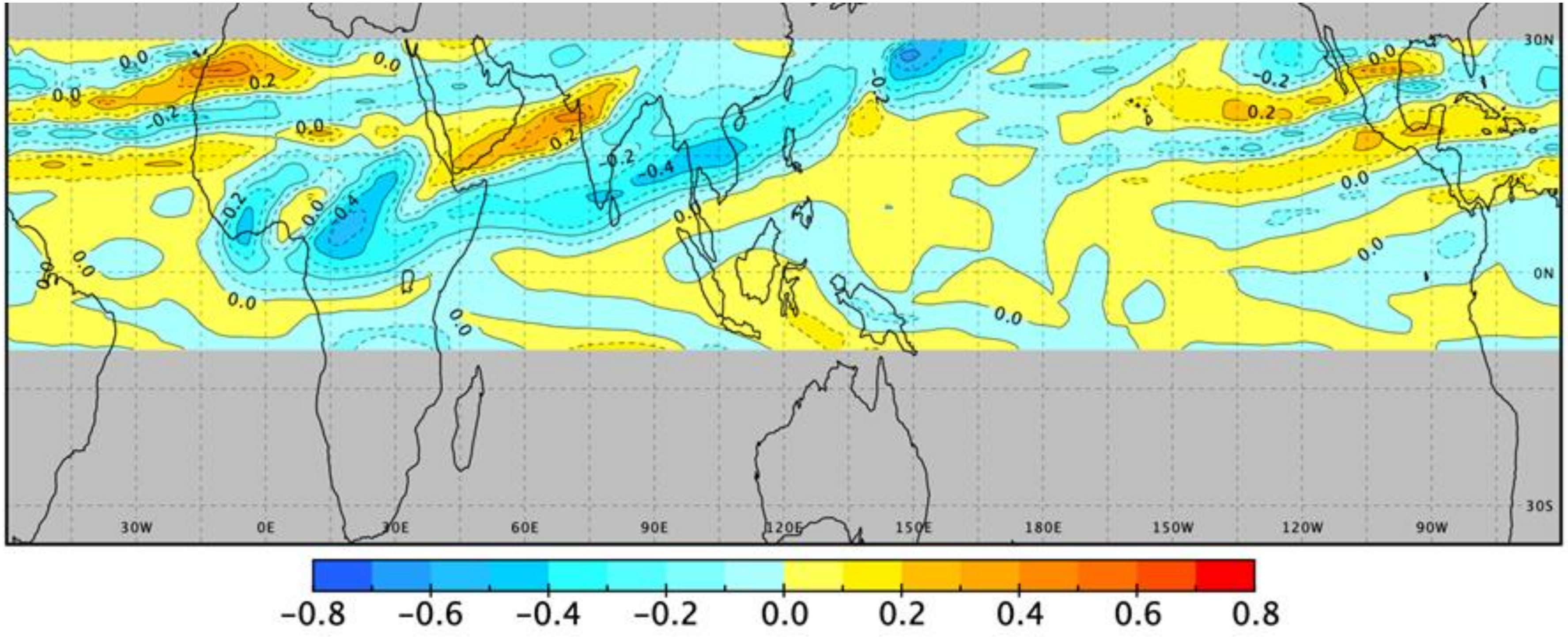

(Advected PV) – (Real PV) [PVU]

Conclusions: Revisiting Motivating Questions

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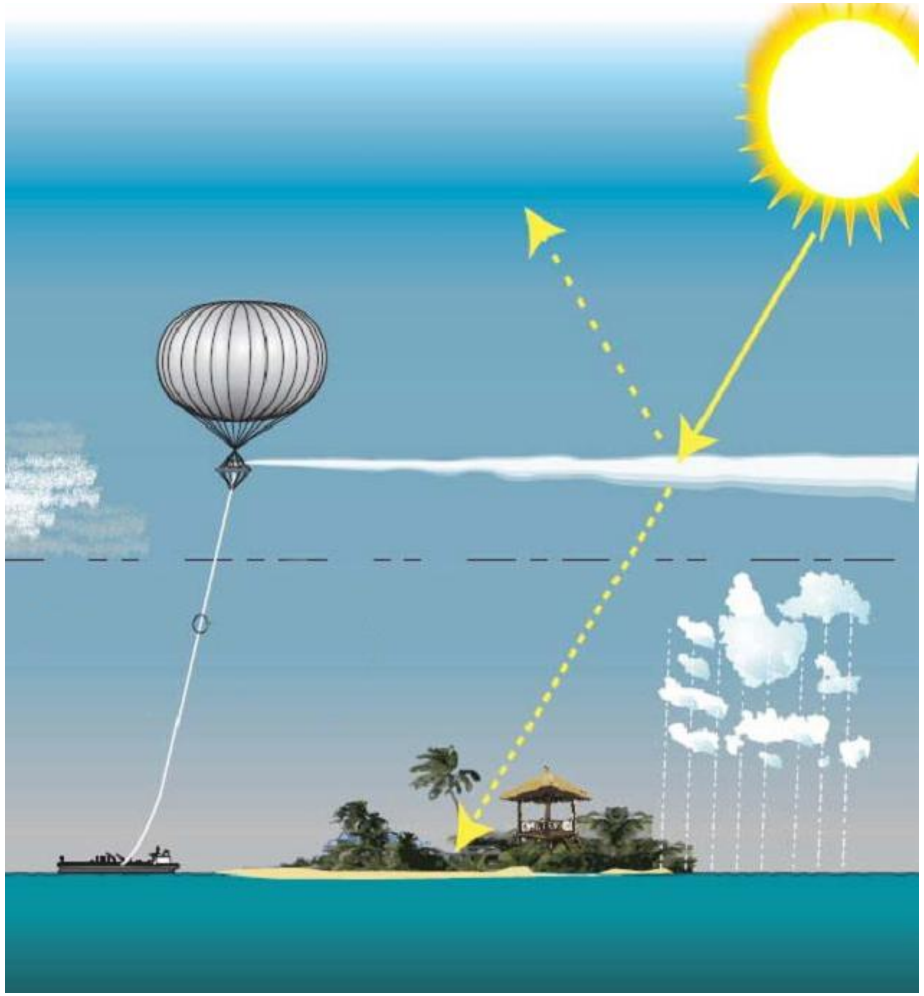

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Did we answer these questions?
- **No**

Are we closer?
- **Yes;** we are starting to develop tools to identify specific impacts of volcanic sulfate forcing on atmospheric dynamics;
  - The **E90 passive tracer** allows investigation on perturbations to troposphere-stratosphere **mass exchange**, and tropopause physics
  - The **PV/PT tracers** allow localization of diabatically-driven changes to both **temperature and winds**

Acknowledgements

This work would not have been possible without constant support from the members of the CLDERA (*Climate impacts: Determining Etiology through pAthways*) team, especially my Sandia mentor Tom Ehrmann, our project lead Diana Bull, our group manager Tom Lowry, my advisor Christiane Jablonowski, as well as Sandia scientists Benjamin Wagman, Ben Hillman, and Hunter Brown

Thank you for your attention!

Questions? Email me at hollowed@umich.edu