SAND21-1207
LDRD PROJECT NUMBER: 224535
LDRD PROJECT TITLE: The Fingerprints of Stratospheric Aerosol Injection in E3SM
PROJECT TEAM MEMBERS: Benjamin M. Wagman, Laura P. Swiler, Kamaljit Chowdhary, Benjamin Hillman

ABSTRACT: The June 15, 1991 Mt. Pinatubo eruption is simulated in E3SM by injecting 10 Tg of SO_2 gas in the stratosphere, turning off prescribed volcanic aerosols, and enabling E3SM to treat stratospheric volcanic aerosols prognostically. This experimental prognostic treatment of volcanic aerosols in the stratosphere results in some realistic behaviors (SO_2 evolves into H_2SO_4 which heats the lower stratosphere), and some expected biases (H_2SO_4 aerosols sediment out of the stratosphere too quickly). Climate fingerprinting techniques are used to establish a Mt. Pinatubo fingerprint based on the vertical profile of temperature from the E3SMv1 DECK ensemble. By projecting reanalysis data and preindustrial simulations onto the fingerprint, the Mt. Pinatubo stratospheric heating anomaly is detected. Projecting the experimental prognostic aerosol simulation onto the fingerprint also results in a detectable heating anomaly, but, as expected, the duration is too short relative to reanalysis data.

INTRODUCTION AND EXECUTIVE SUMMARY OF RESULTS: The capability to detect changes in the climate and attribute them to specific climate forcings is important for scientists and decision makers. In climate modeling, detection and attribution use a technique called "fingerprinting." A fingerprint is a unique climate response to a climate forcing, determined by climate models and statistical techniques. Detection and attribution [1-4] find the signal of the fingerprint in observations, or further, attribute climate change to the forcing associated with that fingerprint. Fingerprinting, detection, and attribution are typically applied to long-term (multi-decadal or longer) time series: a canonical problem is detecting the fingerprint of global warming using time series of models and observations from the preindustrial era to the present.

Fingerprinting, detection, and attribution methodology can also be applied over shorter time scales, where signal detection from the noise of natural variability is even more challenging. For example, a future application of fingerprinting could be to attribute climate impacts to specific emissions scenarios or intervention strategies, e.g. anthropogenic stratospheric aerosol injection (SAI). Observed explosive volcanic eruptions are a natural analogue to the anthropogenic SAI problem. This work examines the viability of fingerprinting a volcanic SAI event in the Energy Exascale Earth System Model (E3SM). The specific activities of this LDRD are capability driven, to develop the capabilities to support SAI attribution studies for this project and beyond. The following three activities were performed:

1. Implementation of a simple "prognostic volcanic aerosol" capability in E3SM;
2. Implementation of a fingerprinting algorithm;

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

3. Demonstration of fingerprints on some quantities of interest from a limited set of climate runs available for the SAI problem.

We achieved success with each item (1, 2, and 3), although we note that (3) is a relatively simple example. Each item is summarized below and described in more detail in later sections.

AEROSOLS IN E3SM

Climate models are key to successful fingerprinting, detection, and attribution as they must simulate the spatial pattern and time scale of responses to the forcings of interest and quantify natural variability. However, simulating SAI and its climate effects is challenging for most climate models, and is an active area of research and development. All of the simulations included in this work were performed on E3SM [6]. E3SM treats most aerosols using a modal aerosol model (MAM4 [7]). MAM4 predicts aerosol size and number distributions in four aerosol modes. Codes within E3SM and MAM4 treat aerosols prognostically from either emission of nucleation through their lifetime and include interactions with chemistry, microphysics, and radiation. A notable exception are aerosols produced by explosive volcanic eruptions in the stratosphere: these aerosols are prescribed in E3SM, not predicted. The prescription occurs in one of two types:

1. Prescribed volcanic H_2SO_4 (sulfuric acid) mass mixing ratio (MMR), extinction optical depth, single scattering albedo, and aerosol asymmetry factors are read into E3SM from a file;
2. Prescribed volcanic H_2SO_4 MMR, E3SM model computes the optical properties.

Using prescribed volcanic aerosols ensures that all models participating in multi-model comparisons, e.g. CMIP, have relatively accurate and similar stratospheric aerosol forcing. The E3SMv1 five-member DECK historical ensemble uses the type 1 (as categorized above) prescribed aerosols. Both types of prescriptions contain observed volcanic eruptions, including Mt. Pinatubo (June 15, 1991).

Prescribing volcanic aerosols in the stratosphere comes with several drawbacks. Notably it precludes changing the location, date, size, or other parameters of a stratospheric aerosol source. Control over these parameters is essential for studying SAI, whether anthropogenic or natural. Prognostic volcanic aerosols are also necessary to actually simulate aerosol transport, feedbacks, deposition, and potential aerosol-cloud interactions in the troposphere.

Prognostic volcanic aerosols are not included in E3SM v1 or v2, but they have been implemented in some chemistry climate and whole-atmosphere models, e.g. WACCM. A full and accurate prognostic treatment of volcanic aerosols in E3SM would require additional chemistry (e.g. prognostic OH and other species) and new MAM aerosol modes for the stratosphere. These types of solutions take years to implement and test. However, E3SM and MAM already have the capability to convert a source of SO_2 gas into sulfate aerosols—the same process that occurs in the stratosphere after a volcanic eruption—but it is not used for explosive volcanic eruptions. The code runs in the troposphere, but is not developed for the stratosphere, where the aerosol sizes and chemistry are different. Running decades or centuries-long simulations with these types of biases would result in energy balance problems and poor model performance. However, for seasonal to interannual simulations, the consequences of these biases may be less important. In this work, we experimented by injecting SO_2 gas into the stratosphere in E3SM without making any code changes to the model chemistry or MAM4 to address model biases. The purpose of the experiment was to test the prognostic volcanic aerosol capabilities of E3SM for a single observed volcanic eruption: Mt. Pinatubo in June 1991, using our fingerprinting framework.

IMPLEMENTATION OF A FINGERPRINTING ALGORITHM

Climate fingerprinting has been used to increase the signal-to-noise ratio for detection and attribution in climate science for over two decades [1-4]. Fingerprinting is a statistical technique that detects the significance of a source contributing to an impact: it relies heavily on proper quantification of the natural climate variability and often requires expensive "one-at-a-time simulations" in which each transient climate forcing is simulated while the others are held fixed. The one-at-a-time simulations are a barrier to entry for fingerprinting because they are costly and only performed by a subset of models.

Alternative methods have been developed for fingerprinting in the absence of the one-at-a-time simulations, by making assumptions about the timescales of coevolving transient forcings [3]. We apply the alternative method in this report by fingerprinting the 1985-1996 ensemble-mean of historical climate simulations with all forcings varying at once. We argue that the fingerprint represents the explosive volcanic forcing because that forcing changes the fastest over the time period.

The result is an approximation of the fingerprint for a single emission: a response to Mt. Pinatubo SAI. Fingerprinting a particular discrete event is a novel application, as far as we are aware. The application comes with some challenges. A typical detection problem is to detect the emergence of a forced pattern over decades to centuries, taking advantage of the climate models' skill for boundary-value problems. Fingerprinting monthly to seasonal responses relies on model capabilities over those timescales, which are less established, and must contend with larger natural variability. Full attribution requires reconstruction of the observations from a linear combination of model forcings, but the climate response to forcing may not be linear as the time period shortens. These issues may prove formidable for smaller signals than the eruption of Mt.

Pinatubo and are motivation for future research. However, the Mt. Pinatubo forcing is so strong that using monthly means for detection in this application is successful.

DEMONSTRATION OF FINGERPRINTS

Fingerprinting, detection and attribution, generally proceed as follows:

1. Determine the expected pattern or fingerprint, usually from an ensemble of targeted simulations.
2. Detect the expected pattern (usually in observations).
3. Attribute the observed pattern to a forcing (usually using a linear regression on one-at-a-time experiments).

Steps (1) and (2) were successfully demonstrated here, and (3) was beyond the scope of the project. For step 1, we used the five-member E3SM DECK ensemble of historical simulations from the period 1985-1996 to generate a fingerprint based on the vertical profile of temperature in the atmosphere. The fingerprint is an area averaged vertical temperature profile which excludes the polar regions and heights above 30 hPa. The profile captures the temperature difference between the stratosphere and the troposphere, and it undergoes a sudden change in projection amplitude in the DECK experiments immediately after Mt. Pinatubo erupts in June 1991, with recovery taking about 30 months.

We then projected the reanalysis data (observational data merged with model data if necessary to produce consistent data sets), and the experimental prognostic aerosol E3SMv2 simulations onto this fingerprint. The results show that the observations and the prognostic aerosol simulations show a strong signal of the searched-for fingerprint on monthly means, detectable at much greater than two standard deviations above the mean climate every month for the next 18 months in reanalysis, and even longer in some simulations.

DETAILED DESCRIPTION OF RESEARCH AND DEVELOPMENT AND METHODOLOGY: E3SM MODEL AND SIMULATIONS

All model output used in this report is from E3SM. The simulations used are outlined in the table below.

Name	# of members	Years used	Configuration	Resolution
V1 DECK1	5	1985-1996	Historical, fully-coupled	ne30np4
V2 Pinatubo	3	1985-1996	F20TR, prescribed SST	ne30pg2

Table. 1. E3SM ensembles used in this study.

Run Name	Aerosol treatment
Control "prescribed"	Prescribed volcanic aerosol mass mixing ratio and optics
Control "volcmmr"	Prescribed volcanic aerosol mass mixing ratio
Experiment "SO_2"	SO_2 injection, prognostic volcanic aerosol

Table. 2. E3SMv2 Pinatubo simulations used in this study, detail.

The E3SM v1 DECK historical simulations is a five-member initial conditions ensemble (Table 2) of fully-coupled historical simulations (https://esgf-node.llnl.gov/search/e3sm/). These simulations contain a prescribed Mt. Pinatubo eruption (prescribed H_2SO_4 MMR and optics). Because aerosols are prescribed, even though the weather and climate state at the date of eruption are different in each member, the prescribed aerosols and their identical optics are transported in the exact same way across members, so the Mt. Pintaubo aerosol forcing is identical for all members.

The E3SMv2 Pinatubo ensemble (Table 2) consists of three ensemble members that differ in their treatment of aerosols. "v2" is shorthand for the state of the E3SM master code branch as of July 15, 2021, but the code predates the release of E3SMv2 and has not been scientifically validated. The E3SM code can be retrieved from https://github.com/E3SM-Project/E3SM and the exact code used for these simulations corresponds to the commit hash: 485caceb7900b904d680bcbff2d137fcc0dff2c5. The ensemble was run on Sandia HPC. All simulations a prescribed time-evolving sea surface temperature and sea ice, in contrast to the DECK experiments which use a coupled ocean.

The aerosol treatment for each E3SMv2 Pinatubo ensemble member is described here and summarized in Table 2. The control "prescribed" simulation uses prescribed volcanic H_2SO_4 MMR and optics, as in the DECK simulations. The control "volcmmr" simulation uses prescribed volcanic H_2SO_4 MMR but calculates its own aerosol optics. The experiment "SO_2" simulation uses a stratospheric SO_2 injection for Mt. Pinatubo on June 15, 1991 and calculates its own aerosol MMR and optics. Subsequent volcanic eruptions (e.g. Cerro Hudson August, 1991) are not included in the simulations. The SO2 emissions for the perturbed run, used for Mt. Pinatubo, were provided courtesy of Mike Mills at NCAR (from ftp://nitrogen.acom.ucar.edu/user/mmills/inputdata/atm/cam/chem/stratvol/StratVolcSO2Emis1990-2016SchmidtV1.4_2deg_c160811.nc) [7]. The emission takes place over a 6-hour period between 18-20 km altitude, 0-15° N, 120.350°E, and contains 10 Tg SO_2.

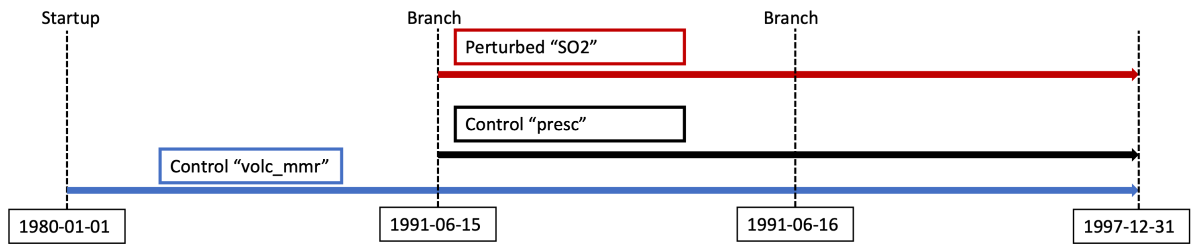

Fig. 1. E3SM v2 Pinatubo simulations

The control "volcmmr" simulation starts in 1980 and the perturbed and the other two simulations are branched off on June 15, 1991 (the day of the Mt. Pinatubo eruption) (see Fig. 1). Preliminary simulations were run in an ultra-low resolution (ne4pg2), and from these it was established that the two control experiments were within 0.5 Wm^{-2} of each other from 1980-1991, and therefore there was no need to run both control simulations at ne30pg2 resolution until Mt. Pinatubo erupted.

FINGERPRINTING METHODS

The statistical approach used in fingerprinting is Principal Component Analysis (PCA). PCA is a widely used dimension reduction technique [8-10] that is commonly used in exploratory data analysis. In PCA, a singular value decomposition is performed on the covariance matrix of the data. The right singular eigenvectors obtained from PCA represent a coordinate transformation of the original data, where each new coordinate highlights the variance present in the data, in decreasing order. Thus, PCA is a variance-based decomposition technique.

The steps of PCA involve constructing a data matrix X, where X involves N samples of an underlying process or state. In this case the data matrix is composed of the ensemble-mean E3SMv1 DECK simulations from 1985-1996: N=144 months of a temperature profile at 29 isobaric levels (from 1000 to 50 hPa). Each monthly sample contains a data vector of length M=29, so the matrix dimension of X is N x M (144 x 29). The objective of the dimension reduction is to compress the dimensionality of M. After X is constructed, we remove the linear trend in time, and the annual cycle by subtracting the monthly mean (computed over the time series) from each month. This preprocessing step is unique to this experiment and is not a necessary step for performing PCA in general. The data is then centered by taking the mean of each column of X and subtracting it from that column: this creates a centered anomaly matrix X_c with the same dimensions, N x M. Then, a singular value decomposition is performed on the covariance matrix of the centered data (which is $X_c^T X_c /N$). The eigenvectors of this covariance matrix, or equivalently the right singular eigenvectors of the SVD of X_c, are the principal components and the eigenvalues (in sorted order) represent the variance attributed to each eigenvector, i.e. the total variance after projecting the data onto each eigenvector. Ideally, a small number of eigenvectors, K < 10, will be sufficient to explain the variance in the underlying process. In climate statistics, the principal components are also called Empirical Orthogonal Functions and refer to the fingerprints. The fingerprint in our example is the leading (1st) EOF.

The details of computing the EOFs and their respective projections are shown in Algorithm 1. After centering the data matrix, we perform a straightforward SVD, from which the fingerprint, projections, and convergence of the dimension reduction technique can be obtained. The right singular eigenvectors of the SVD, which are the columns of V (see below), represent the PCA components or fingerprints. The number of fingerprints chosen, p, can be computed by computing the cumulative explained variance of the PCA representation. This is helpful in determining the relative influence, in terms of percent variance, of each fingerprint. After the fingerprints are obtained, we can then perform a coordinate transformation or projection of the original data, X_c, onto the EOFs, to obtain a reduced space or latent time-series representation of the data. These projections are stored in the left singular eigenvectors of the SVD on X_c.

Algorithm 1: Principal Component Analysis for Climate Fingerprinting

Input: Data matrix of climate experiments, $\mathbf{X}_c \in \mathbb{R}^{n \times m}$, e.g., n is the number of temporal sample points and m the zonally averaged aerosols at different latitudes.

Output: Empirical orthogonal functions (EOFs), $\mathbf{\Phi} \in \mathbb{R}^{m \times p}$, and projections of data onto these p EOFs, $\mathbf{\Psi} \in \mathbb{R}^{n \times p}$.

1: Compute (thin) singular value decomposition (SVD): $\mathbf{X}_c = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^T$, where $\mathbf{U} \in \mathbb{R}^{n \times k}, \mathbf{\Sigma} \in \mathbb{R}^{k \times k}, \mathbf{V} \in \mathbb{R}^{m \times k}$ and $k = \min(m, n)$.

2: Set $\mathbf{\Phi} = [\mathbf{v}_1, \ldots, \mathbf{v}_p] \in \mathbb{R}^{m \times p} \subset \mathbf{V}$, where $p = \min_{i \in \Gamma(v)}$, $\Gamma(v) := \{i \mid \sum_{j=1}^{i} \sigma_j^2 / \sum_{k=1}^{m} \sigma_k^2 \geq v\}$ and $\mathbf{\Psi} = [\mathbf{u}_1, \ldots, \mathbf{u}_p] \in \mathbb{R}^{n \times p} \subset \mathbf{U}$.

When using fingerprints for detection of a significant anthropogenic forcing, one tests whether the reconstruction of the observations from a linear combination of fingerprints requires weighting a fingerprint beyond what is expected from natural variability. Attribution goes further, demonstrating using multiple linear regression that the climate change can successfully be reconstructed from a linear combination of the fingerprints, but cannot be reconstructed without one or more of them [4]. In this work, we focused on generating the fingerprints. Although we show that the observed climate response contains the searched-for fingerprint at a magnitude far beyond natural variability, we do not go as far as using a multivariate regression of all possible fingerprints for detection or attribution because we did not run the one-at-a-time forcing simulations necessary to calculate the fingerprints for the other forcings.

RESULTS AND DISCUSSION: E3SM SIMULATIONS

The E3SMv2 simulations conducted for this study are shown in Table 2. The perturbed simulation, in which we injected SO2 into the stratosphere on June 15, 1991, was a novel simulation type and so we first verify that the SO_2 injection is being read into the model. Figure 2 shows that the annual-mean total atmospheric mass per unit surface area of SO_2 in the perturbed simulation spikes in 1991, as expected. Integrated globally, this spike corresponds to an annual mean of 2.06 Tg SO_2, but it also includes the first 5.5 months of the year, before the nearly instantaneous 10 Tg SO_2 injection on June 15, 1991. The SO_2 mass anomaly is zero again by 1992. The sink for SO_2 is gas-phase oxidation into H_2SO_4 vapor [11].

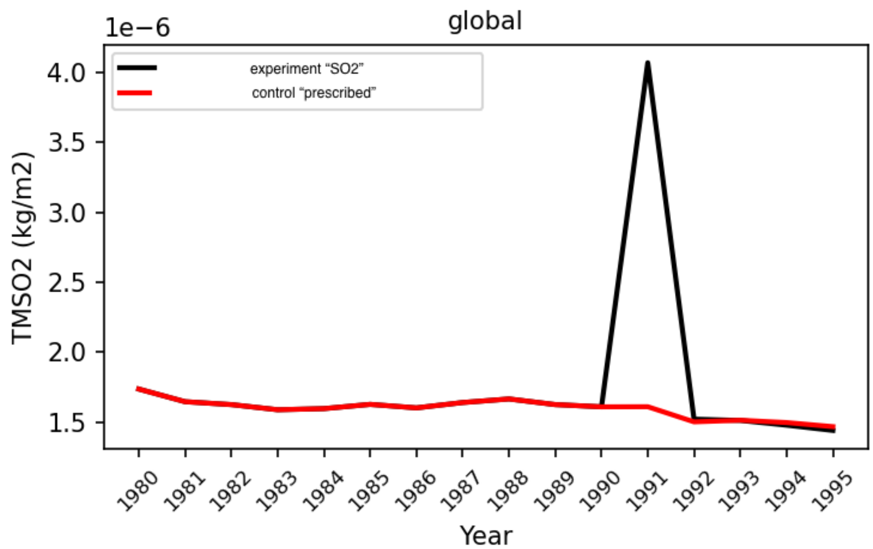

Fig. 2. Annual-mean SO_2 mass per m^2 in the E3SMv2 control "prescribed" simulation (red) and experiment "SO_2" simulation with prognostic volcanic aerosols (black).

The H_2SO_4 mass anomaly also spikes in 1991 and then persists into 1992 (Fig. 3). The code both nucleates new aerosol particles in the presence of H_2SO_4 vapor and allows for condensation of H_2SO_4 vapor onto existing aerosols.

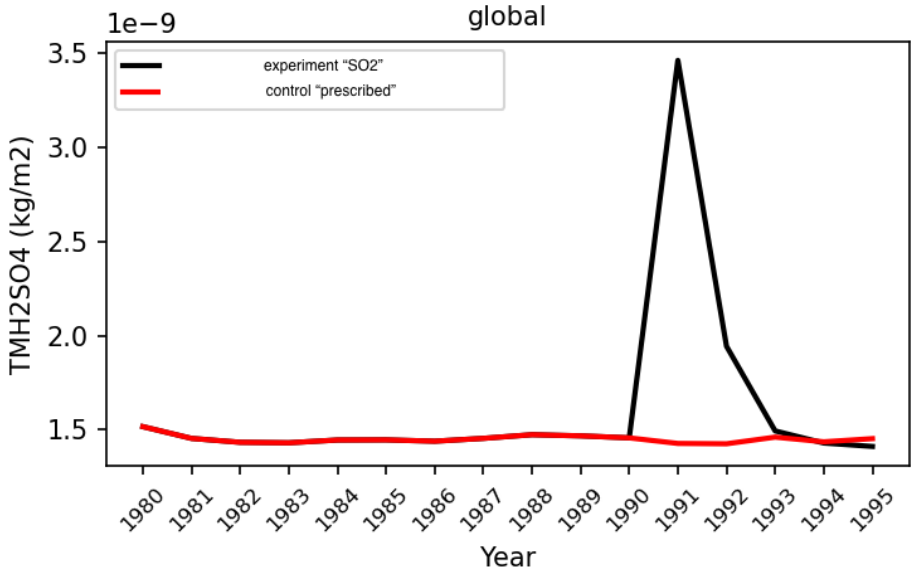

Fig. 3. H_2SO_4 mass per m^2 in the E3SMv2 control "prescribed" simulation (red) and experiment "SO_2" simulation with prognostic volcanic aerosols (black).

The control "prescribed" simulation (red line) does not increase in SO_2 or H_2SO_4 after the eruption, as expected.

Map views of the months before and after the SO_2 injection show that the SO2 spreads zonally, as expected, but its lifetime is too short to survive the slower meridional spread outside of the tropics (Fig. 4). One concern is that SO_2 may be oxidized into H_2SO_4 too quickly in these simulations, as OH is prescribed and therefore is not destroyed when it participates in chemical reactions. However, the lifetime and chemical reaction rates are not examined here.

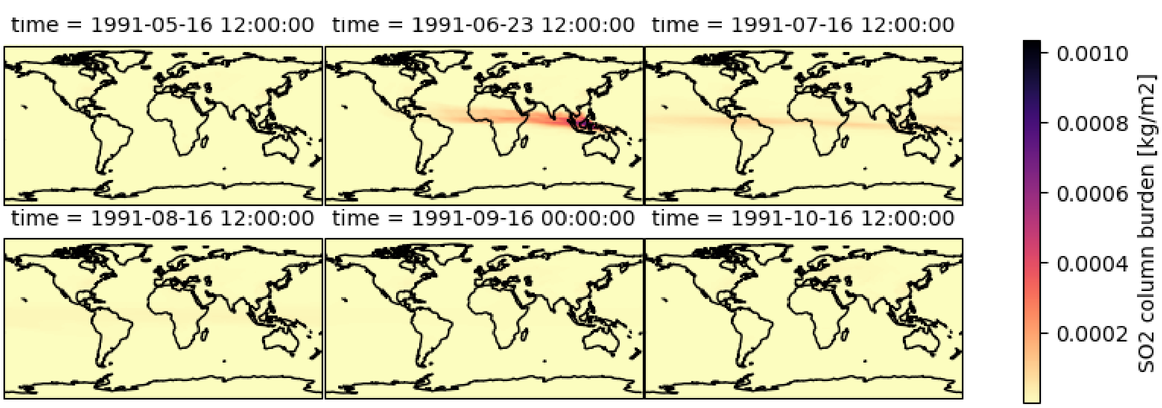

Fig. 4. SO_2 mass per m^2 in the E3SMv2 experimental "SO_2" prognostic volcanic aerosol simulation.

H_2SO_4 increases in total mass burden as SO_2 is oxidized and becomes widespread globally, except in the arctic, by October 1991 (Fig. 5).

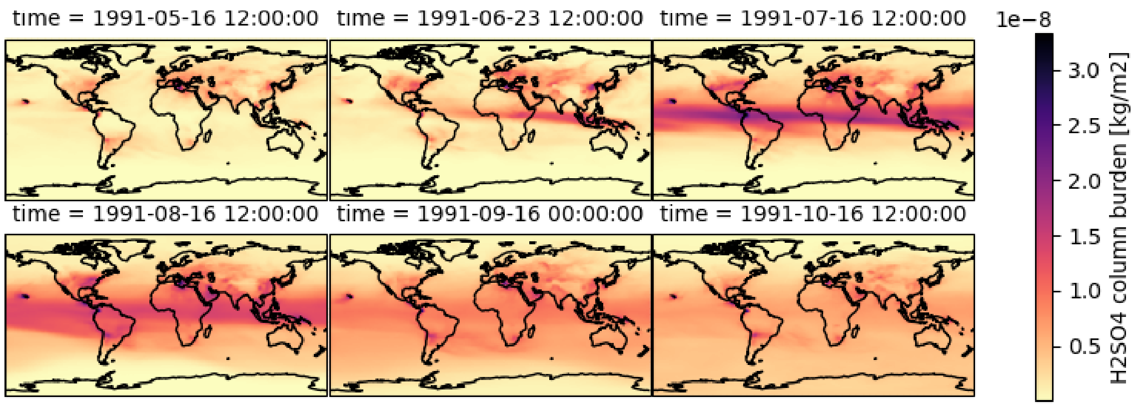

Fig. 5. H_2SO_4 mass per m^2 in the E3SMv2 experimental "SO_2" prognostic volcanic aerosol simulation.

The most well-known effect of volcanic eruptions on climate is a heating of the stratosphere and a cooling of the surface. The stratospheric heating occurs as a consequence of absorption of outgoing longwave radiation and some absorption of incoming solar radiation by the sulfate aerosols (even though they primarily scatter). The cooling in the troposphere is due to the decrease in shortwave radiation reaching the surface, which is more than offset by the increase in longwave radiation from the stratosphere. In Fig. 6 we plot the vertical profile of the area-averaged temperature anomalies for each of the E3SMv2 Pinatubo simulations.

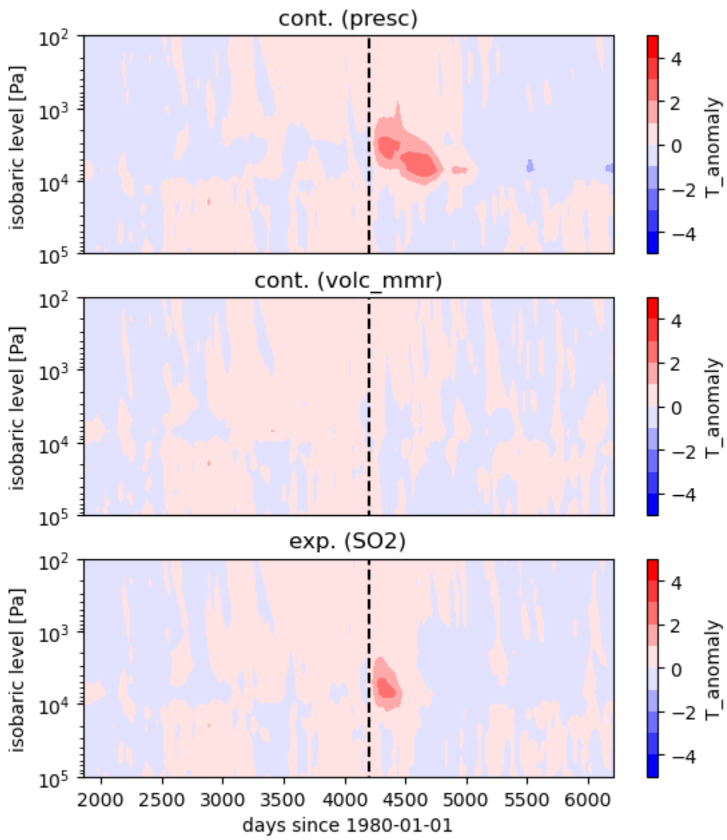

Fig. 6. Area-averaged temperature anomaly for each of the 3-member E3SMv2 Pinatubo ensemble. The data are detrended and the annual cycle removed. The Mt. Pinatubo eruption is marked by the dashed black line.

The 2-3°C heating anomaly associated with the Mt. Pinatubo eruption is captured in the control "prescribed" simulation and the experiment "SO_2" simulation (albeit only for 1991). The control "volcmmr" does not contain a Mt. Pinatubo stratospheric temperature anomaly, which is unexpected and merits further review of the simulation.

FINGERPRINTING

The fingerprint is derived from the first EOF of the time series of the area-averaged temperature anomaly profile in the E3SMv1 DECK ensemble mean (see methodology section). That time series is shown in Fig. 7 (top panel), and for the ERA5 observations (bottom panel). The stratospheric heating and tropospheric cooling anomaly after the Mt. Pinatubo eruption are clear.

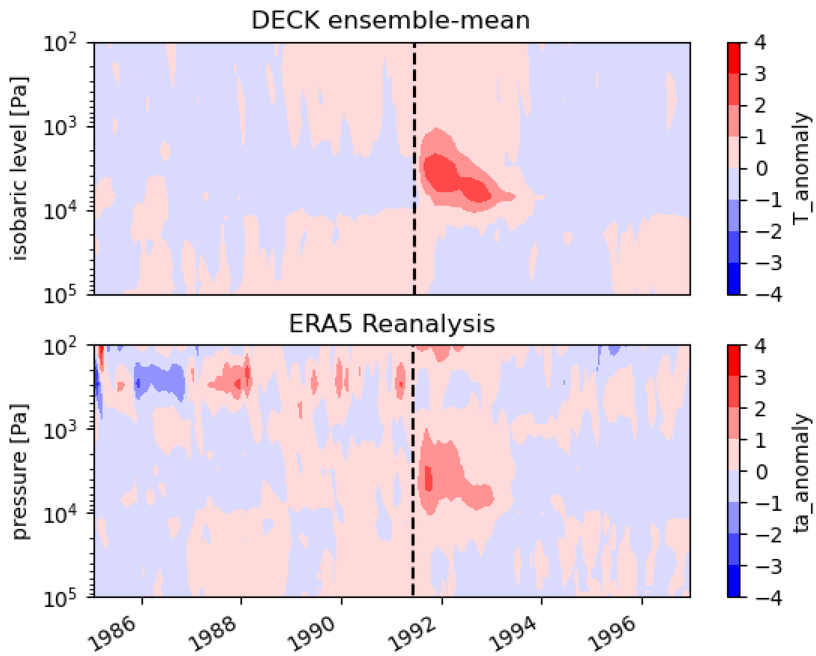

Fig. 7. Area-averaged temperature ("T" or, equivalently "ta") anomalies for the 5-member DECK historical ensemble and the ERA5 reanalysis. The data are detrended and the annual cycle removed. The Mt. Pinatubo eruption is marked by the dashed black line.

We use an area-averaged fingerprint because the forcing moves zonally and meridionally as aerosols are transported (see Fig. 5). Fingerprinting a spatial pattern with a latitude or longitude dimension would perhaps capture a snapshot of the forcing at a given point in time, but it would not capture the spatial pattern of the forcing over its full duration. Variations in aerosol height occur more slowly and are included. Based on the temperature anomalies, the strongest Mt. Pinatubo signal is beneath the quasi-biennial oscillation (QBO)-induced variability, in the lower stratosphere (we choose a threshold of 30 hPa).

Fig. 8 is a fingerprint based on the DECK-mean area-averaged height anomaly shown in Fig. 7. The spatial pattern (aka the fingerprint or the EOF—top panel) shows cooling in the stratosphere and warming in the troposphere. Its amplitude is strongly negative (negative pattern * negative amplitude = stratospheric heating) immediately after the Pinatubo eruption with recovery taking about four years.

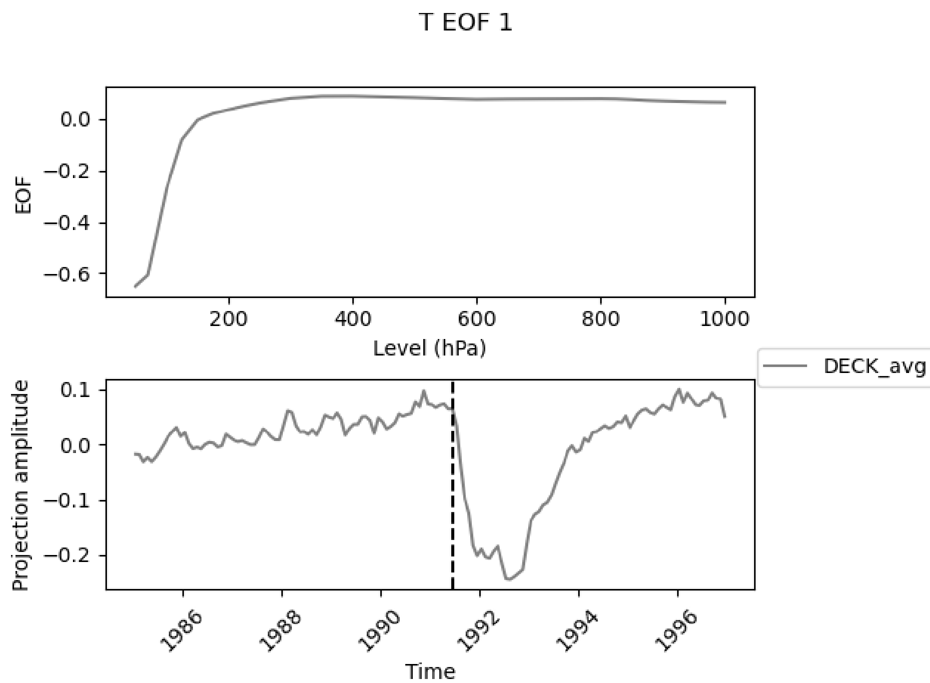

Fig. 8. EOF 1 of the DECK ensemble-averaged, area-averaged temperature anomalies. The data are detrended and the annual cycle removed before EOF analysis. The top plot shows the spatial pattern (the fingerprint) and the bottom plot the time series of its projection amplitude. The Mt. Pinatubo eruption is marked by the dashed black line. This EOF explains 79% of the temperature variance over the time period. The polar regions and levels higher than 30 hPa are excluded.

The fingerprint explains 79% of the temperature variance over the 1985-1996 time period. Next, we project the observations and the E3SMv2 Pinatubo simulations onto the fingerprint (Fig. 9). Additionally, we project 80 years of E3SMv1 preindustrial simulation onto the fingerprint to calculate the standard deviation and an uncertainty band of the projection amplitude from natural variability. Note that the uncertainty band contains the mean project amplitude plus and minus 2σ, covering approximately 95% of its distribution. The preindustrial simulation does not contain explosive volcanic eruptions or trends in any forcings.

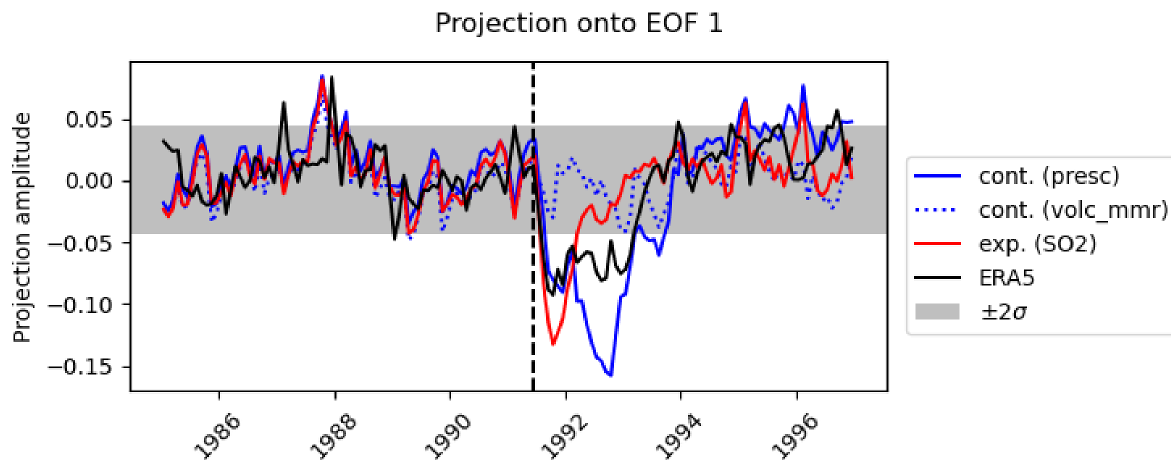

Fig. 9. Projection of the ERA5 observations and the E3SMv2 Pinatubo ensemble onto EOF 1 (see fig. 7). The Mt. Pinatubo eruption is marked by the dashed black line. The gray shaded area is approximately the 95% bound of detectability, computed from the projection of 960 months of E3SMv1 DECK PI control simulation onto the fingerprint.

The results show that the fingerprint is detected at 3-4 standard deviations from the mean in the ERA5 reanalysis (Fig. 9, black line) for the last 6 months of 1991 and remains detectable outside the 95% uncertainty band (gray shaded area) every month through 1992. Therefore, fingerprint is detected in reanalysis. This is expected, given that the Mt. Pinatubo eruption is a relatively large forcing.

Although it is atypical to project model output onto the fingerprint, we do so here to learn about the experimental prognostic simulations. The control "volcmmr" simulation shows no expression of the fingerprint because there is no stratospheric heating (for reasons unknown), whereas the control "prescribed" and the experiment "SO_2" simulation show greater than 4 standard deviations from the mean. The experiment "SO_2" simulation (red line) shows too short a duration of the fingerprint relative to the ERA5 reanalysis. This is consistent with expectations due to model biases, as conversion from SO_2 to H_2SO_4 likely occurs too quickly, and the MAM4 aerosol modes are too large for volcanic aerosol in the stratosphere and therefore sedimentation occurs too rapidly.

ANTICIPATED OUTCOMES AND IMPACTS: NEXT STEPS

This simulation and observational data from this project is ideal for researching detection and attribution of short time scale climate anomalies, as opposed to the usual detection and attribution of long-term trends. Potential next steps include: simulation of anthropogenic SAI; development of a fingerprint with a time-dimension (analogous to a filter); development of a fingerprint that can distinguish between a volcanic eruption and an anthropogenic SAI event; development of a fingerprint that can distinguish between a point source SAI and a distributed SAI; simulating smaller SAI events and searching for an optimal fingerprint; conducting one-at-a-time forcing simulations and then using them for attribution; development of methods to do attribution without one-at-a-time forcings; in depth analysis of the E3SMv2 simulations of the Mt. Pinatubo eruption including an evaluation against observations; and implementing quick fixes to known E3SM model biases for volcanic aerosols that will result in better SAI simulations.

ESTABLISHMENT OF CAPABILITIES EXPECTED TO IMPACT FUTURE WORK

Several capabilities developed in the four months of this LDRD will be used in related projects. Specific to E3SM, this includes: running and supporting E3SM on Sandia HPC resources (Sandia Toss3 is not an E3SM-supported machine and therefore the code does not run "out of the box"), researching the capabilities of E3SM to run prognostic stratospheric aerosol injection simulations, finding an appropriate emissions dataset of SO_2 gas for the Mt. Pinatubo eruption, implementing the SO2 emission and in E3SM, quickly diagnosing the E3SM climate response to an SO2 emission. The CLDERA Grand Challenge and other efforts in Earth Sciences that rely on detection and attribution can benefit from the algorithms developed here for fast fingerprinting and plotting, which are committed to the Sandia Gitlab (contact the author for the address).

CONCLUSION:

The project has two main thrusts with overlapping conclusions: (1) simulating the Mt. Pinatubo eruption in E3SM by injecting SO_2 gas in the stratosphere and enabling prognostic volcanic aerosols, and (2) climate fingerprinting techniques to establish a Mt. Pinatubo fingerprint and projecting the experimental simulation and reanalysis onto the fingerprint.

Injecting 10 Tg of SO_2 into the stratosphere in E3SM caused a plume to spread zonally in the stratosphere and react with OH to form H_2SO_4 in the subsequent months (Figs 2-5). H_2SO_4 aerosols heated the lower stratosphere in E3SM by 2-3°C in 1991 (Fig. 6), which is shorter in duration than the DECK ensemble-mean and the ERA5 reanalysis (Fig. 7). Changes to E3SM chemistry and/or MAM4 aerosol code will be necessary to extend the lifetime of SAI aerosols in agreement with observations of the Mt. Pinatubo eruption.

The Mt. Pinatubo fingerprint is EOF 1 of the DECKv1 ensemble-mean monthly, area-averaged vertical temperature profile excluding the tropics and heights above 30 hPa. This fingerprint is relatively simple but effective: it explains 79% of the variance over the 1985-1996 time series considered (Fig. 8). The natural variability of the climate system, without being forced by explosive volcanic eruptions, contains no precedent for the atmospheric temperature changes captured in the fingerprint. This makes the fingerprint detectable at greater than 2 standard deviations above the mean for every of the next 18 months in the reanalysis data (Fig. 9). The projection of the experimental E3SMv2 simulation with prognostic volcanic aerosol onto the fingerprint shows that the simulation exhibits the spatial pattern of the fingerprint, but for less time than in the reanalysis data, because the lifetime of the prognostic volcanic aerosols are too short in the experimental configuration of E3SM.

ACKNOWLEDGEMENTS: We thank Mike Mills at NCAR for pointing us to his SO_2 emissions dataset. We appreciate the efforts of Andrew Bradley, Oksana Guba, and Jim Foucar at Sandia National Labs for helping maintain E3SM on Sandia HPC.

REFERENCES:

1. Hasselmann, K. (1997). Multi-pattern fingerprint method for detection and attribution of climate change. *Climate Dynamics* **13**(9): p. 601-611.
2. Hegerl, G.C. and G.R. North (1997). Comparison of Statistically Optimal Approaches to Detecting Anthropogenic Climate Change. *Journal of Climate* **10**(5): p. 1125-1133.
3. Marvel, K., M. Biasutti, and C. Bonfils (2020). Fingerprints of external forcings on Sahel rainfall: aerosols, greenhouse gases, and model-observation discrepancies. *Environmental Research Letters,* Article No. 084023.
4. Hegerl, G.C., et al., *Understanding and Attributing Climate Change*, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. , et al., Editors. 2007, Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.
5. Rasch, P. J., Xie, S., Ma, P.-L., Lin, W., Wang, H., Tang, Q., Burrows, S. M., Caldwell, P., Zhang, K., Easter, R. C., et al. (2019), An Overview of the Atmospheric Component of the Energy Exascale Earth System Model, *J. Adv. Model. Earth Syst.*, 11, 2377– 2411. doi:https://doi.org/10.1029/2019MS001629.
6. Liu, X., Ma, P.-L., Wang, H., Tilmes, S., Singh, B., Easter, R. C., Ghan, S. J., and Rasch, P. J. (2016). Description and evaluation of a new four-mode version of the Modal Aerosol Module (MAM4) within version 5.3 of the Community Atmosphere Model, *Geosci. Model Dev.*, 9, 505–522, https://doi.org/10.5194/gmd-9-505-2016.
7. Mills, M. J., Schmidt, A., Easter, R., Solomon, S., Kinnison, D. E., Ghan, S. J., III Neely, R. R., Marsh, D. R., Conley, A., Bardeen, C. G., et al. (2016), Global volcanic aerosol properties derived from emissions, 1990–2014, using CESM1(WACCM), *J. Geophys. Res. Atmos.*, 121, 2332– 2348, doi:10.1002/2015JD024290.
8. Ian T Jolliffe. *Principal component analysis*, second edition. Springer Series in Statistics, 2002.

9. James O Ramsay and Bernard W Silverman. *Applied functional data analysis: methods and case studies*. Springer, 2007.

10. Ian T Jolliffe and Jorge Cadima. Principal component analysis: a review and recent developments. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 374(2065):20150202, 2016.

11. Wang, H., Easter, R. C., Zhang, R., Ma, P.-L., Singh, B., Zhang, K., et al. (2020). Aerosols in the E3SM Version 1: New developments and their impacts on radiative forcing. *Journal of Advances in Modeling Earth Systems*, 12, e2019MS001851. https://doi.org/10.1029/2019MS001851

LABORATORY DIRECTED
RESEARCH & DEVELOPMENT
WHERE INNOVATION BEGINS