Centers
8900, 1400, 5500, 8700
supporting 42 team members

Sandia Strengths
- Uncertainty Quantification
- Earth Systems Modeling
- Risk-Based Analysis for Complex Systems
- Atmospheric Sciences
- Remote Sensing
- Information Sciences

CLDERA Positions SNL for Roles in Climate Security
- Advancing climate science
- Analyzing climate impacts
- Motivating sound climate actions

Exceptional service in the national interest

Analytics for Climate and Earth Sciences (ACES)
COMMUNITY OF PRACTICE

Sandia National Laboratories

CLDERA – CLimate impact: Determining Etiology thRough pAthways

Leadership Team: Diana Bull, Kara Peterson, Laura Swiler, Lyndsay Shand, Irina Tezaur
sandia.gov/cldera

Texas A&M, UNIVERSITY OF MICHIGAN, UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN, COLUMBIA UNIVERSITY

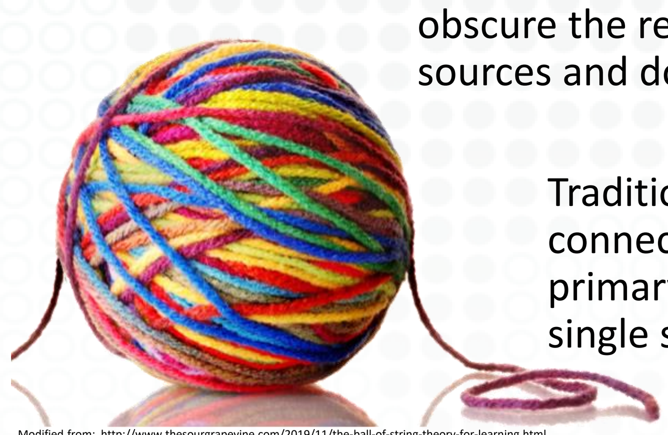
OVERVIEW

CLDERA is enabling multi-step attribution in the climate by developing quantitative relationships between a climate forcing and its downstream impacts. CLDERA aims to improve climate risk assessments and decision-making through its transformation in approaches for climate attribution.

NEED

Climatic impacts (like drought, flooding, or crop yield) are driving national security, legislative and legal foci.

Complex coupling between processes obscure the relationships between sources and downstream impacts.



Traditional attribution connects a source to a primary climate variable in a single step.

Modified from: http://www.thesourgrapevine.com/2015/11/the-ball-of-string-theory-for-learning.html

The technical challenge is to draw quantitative relationships in a multi-step attribution framework.

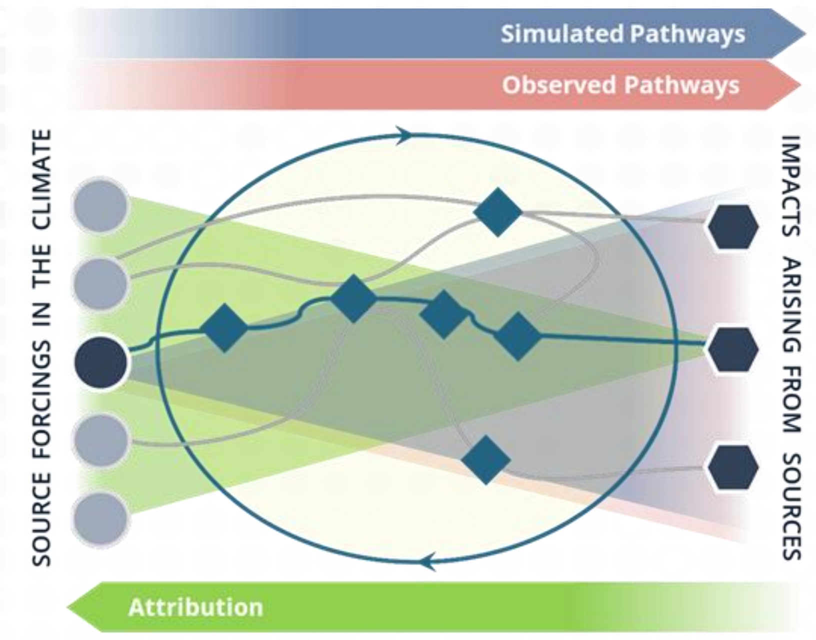
APPROACH

Develop quantitative representations of the pathway, e.g. the spatio-temporally evolving chain of physical processes, between a source and its downstream impacts.

Pathways combine multiple variables to strengthen the connection between source and impact.

Pathways enable new methods to
- address variability
- rank source importance
- constrain attribution approaches

Demonstrate computational approaches on simulations and observations of the 1991 eruption of Mt. Pinatubo in the Philippines



OUTCOMES

Tools to discover and represent pathways, and analyses to establish pathway robustness to changing conditions.
Cross-validation using simulated and observed pathways will inform areas for model improvement and new measurements.

Contributory ranking of sources to an impact using pathways.
Capability enables robust risk analysis and offers the potential to guide future climate actions.

Attribution of source characteristics using inverse optimization methods.
Will provide credible methodology to deter unilateral development of climate interventions.

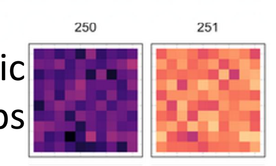
Beginning-to-end attribution in the climate system
Tracing evolving chains of physical processes to enable attribution of climate impacts from a localized source.

Tiered Verification

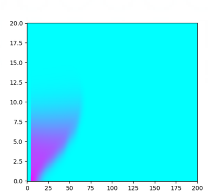
Develop data sets of increasing complexity with key characteristics of the multi-step attribution problem to explore sensitivities, establish viability, and prove usefulness of advanced methods/tools.

Data & Model complexity (dimensionality of data, number & interaction between processes, …)

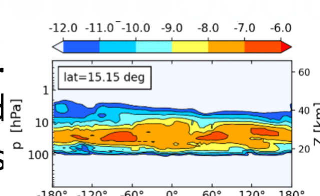
Synthetic Relationships



Gaussian Plume with prescribed winds



Idealized atm. + embedded pathways



Mt. Pinatubo in fully coupled climate model

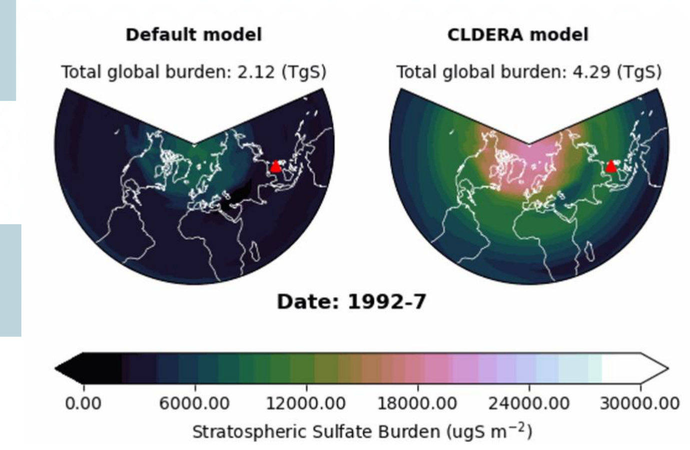
Energy Exascale Earth System Model (E3SM)

Prognostic Aerosol Modeling: Simulate stratospheric volcanic aerosol in E3SM from SO_2 emissions.

Evaluate E3SM's Stratosphere: Characterize biases and understand what physical processes can be captured.

Establish climate variability surrounding Mt. Pinatubo: Characterize signal-to-noise for detection & attribution.

Sensitivity Analyses: Determine pathway robustness to altered: eruption characteristics and model parameterizations.

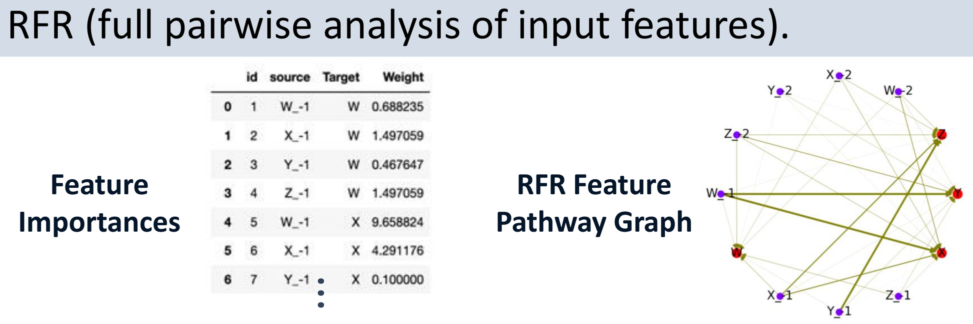


Simulated Pathways

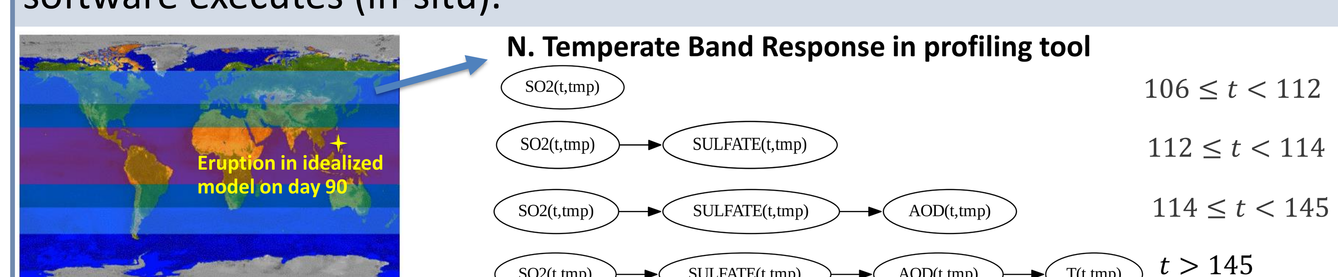
Random Forest Regression (RFR): Generate feature pathway networks using multi-variate RFR (full pairwise analysis of input features).

$$W_t = \epsilon_{W_t}$$
$$X_t = 0.5W_{t-1} + 0.2X_{t-1} + \epsilon_{X_t}$$
$$Y_t = -0.5W_{t-1} + \epsilon_{Y_t}$$
$$Z_t = 0.3X_{t-1} + 0.5Y_{t-1} + \epsilon_{Z_t}$$

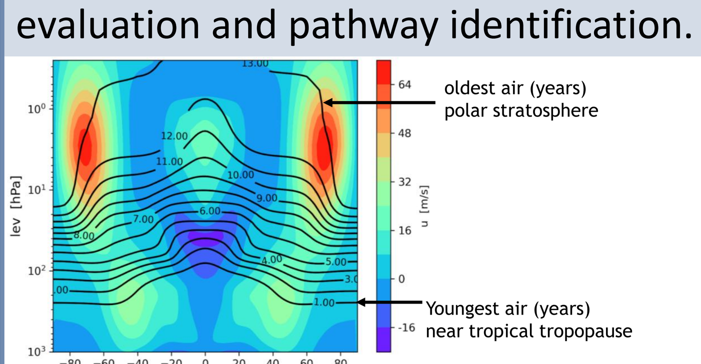
Synthetic Dataset



Profiling: Dynamically trace pathways through the E3SM software as the software executes (in-situ).

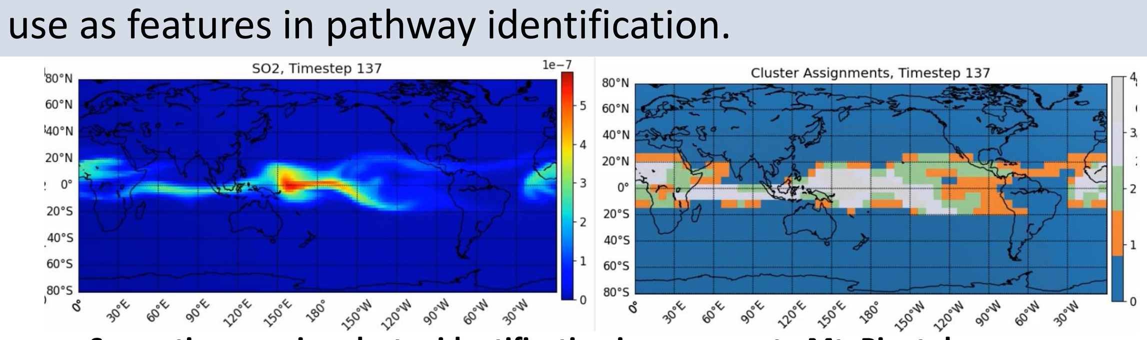


Tracing: Add active and passive tracers to E3SM to enable model evaluation and pathway identification.



10-year mean Age of Air in Spectral Element dycore (2°) with idealized climate. Steep gradients in age (in years) imply barrier to mixing (e.g. strong polar jets shown in color)

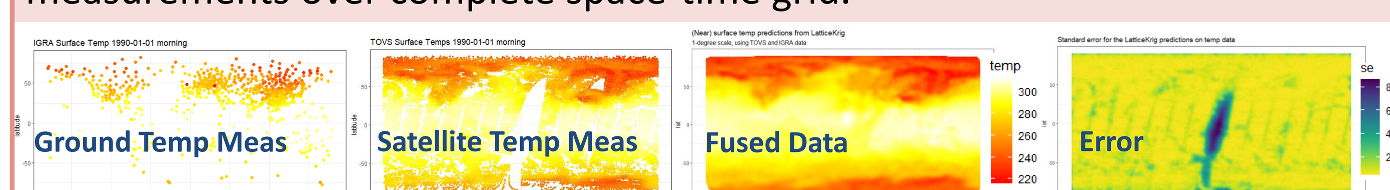
Signature-Based Clustering: Find & track non-stationary variable clusters for use as features in pathway identification.



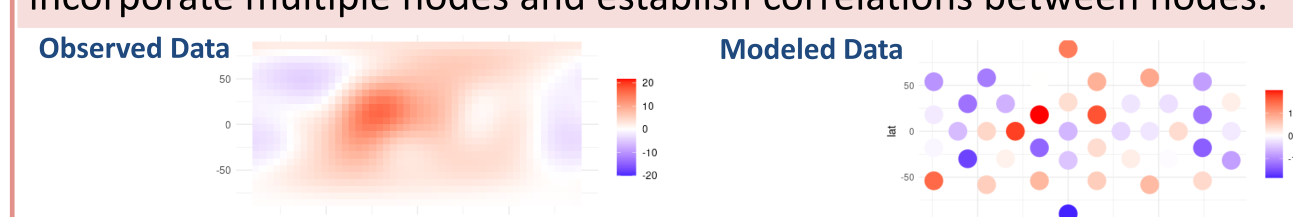
Space-time varying cluster identification in response to Mt. Pinatubo source.

Observed Pathways

Data Fusion: Fuse observational datasets to obtain near-real time measurements over complete space-time grid.

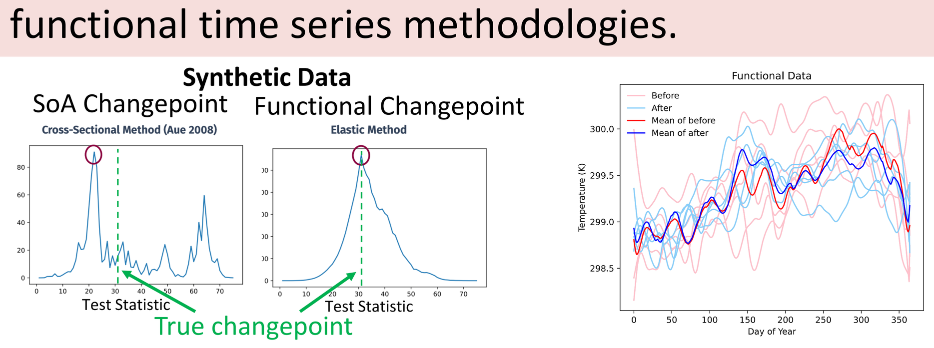


Dynamic space-time models: Adopt space-time dynamic models to incorporate multiple nodes and establish correlations between nodes.



Synthetically modeled spatial evolution at time t using radial basis functions;
Can estimate spatially-varying dependence between multiple variables through basis coefficients

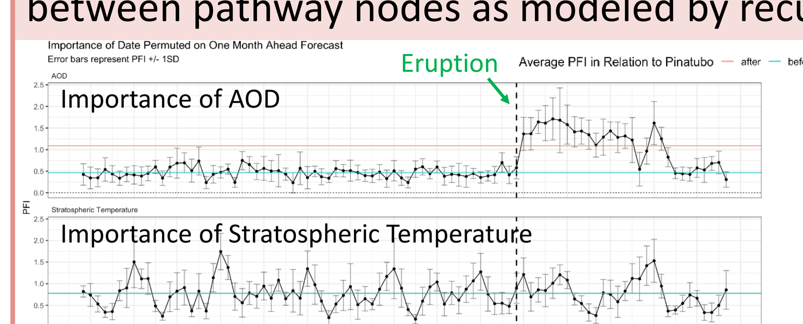
Changepoint methods: Detecting significant climate shifts at both regional and global spatial scales using spatially-varying changepoint methods and functional time series methodologies.



Ten years of ERA5 reanalysis presented as a functional time series. Before and after Mt. Pinatubo eruption.

Tucker, Yarger, Functional Changepoint Detection, Environmetrics

Explainable Echo State Networks (ESNs): Develop explainable (permutation feature importance) and interpretable methods to quantify relationships between pathway nodes as modeled by recurrent neural networks.

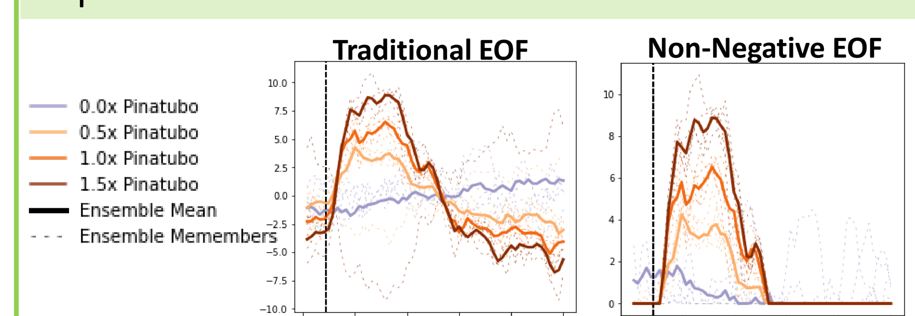


Application of (adjusted) permutation feature importance on echo state network trained on MERRA2 reanalysis data.

Variable importance shows increased importance of AOD immediately following Pinatubo.

Attribution

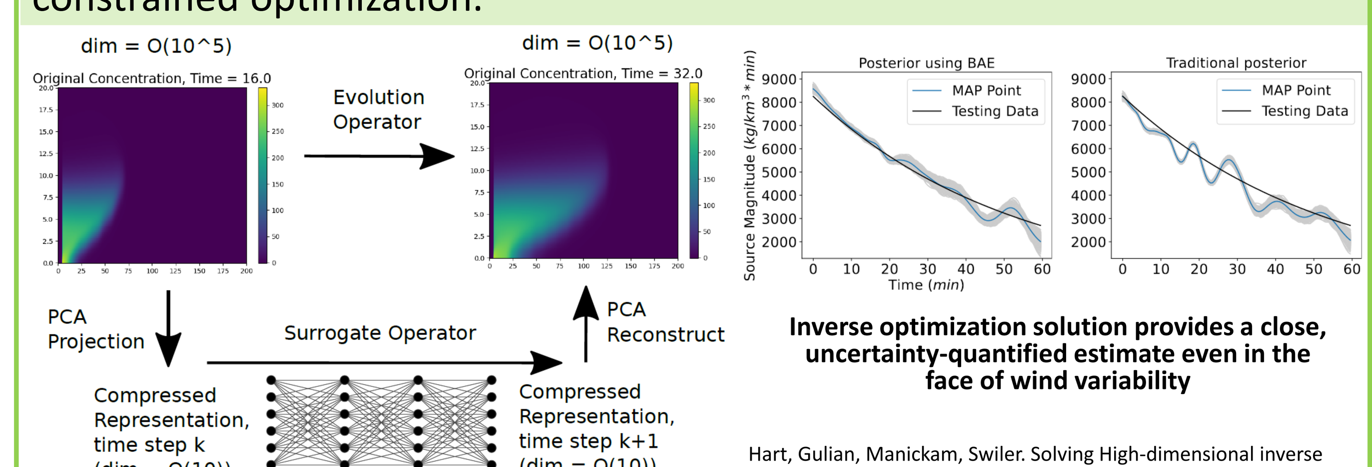
Enhanced Fingerprinting: Investigate advanced principal component analyses (tensor based, non-negative, etc.) and employ multiple nodes in the pathway to sharpen the signal-to-noise ratios and enable downstream impact attribution.



The lat/lon components are averaged per pressure level so that only a 2-D signal (pressure, time) is used in the PCA analysis

Weylandt, Swiler. Beyond PCA: Additional Dimension Reduction Techniques to Consider for Climate Data. To be submitted.

Inverse Optimization: Identify source characteristics by developing deep operator neural networks (DONNs) to model parts of E3SM for PDE-constrained optimization.



Inverse optimization solution provides a close, uncertainty-quantified estimate even in the face of wind variability

Hart, Gulian, Manickam, Swiler. Solving High-dimensional inverse problems with auxiliary uncertainty via operator learning with limited data. Journal of Machine Learning for Modeling and Computing

Causal Modeling: Develop causal discovery method for spatially nonstationary and transient relationships; use directed graphs to represent causal networks.

$$W_t := \eta_{W_t}$$
$$X_t := 2 \times W_{t-2} + \eta_{X_t}$$
$$Y_t := 0.5 \times W_{t-1} + \eta_{Y_t}$$
$$Z_t := 0.6 \times X_{t-1} + \eta_{Z_t}$$