Sandia National Laboratories

CLDERA – CLimate impact: Determining Etiology thRough pAthways

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OBJECTIVE

There is a great divide between current attribution science and what is needed for decision-makers.

Will a shift in mid-latitude climate be attributable to the disappearance of Arctic Sea Ice?

Will a shift in Indian monsoon be attributable to the development of Sky River?

Complex coupling between Earth system processes obscures relationships between sources and downstream impacts.

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

Modified from: http://www.thesourgrapevine.com/2019/11/the-ball-of-string-theory-for-learning.html

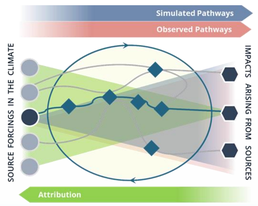
APPROACH

Employ well-observed and researched localized source forcing for method development

- Stratospheric injection of sulfur dioxide in the 1991 eruption of Mt. Pinatubo in the Philippines

Develop quantitative approaches capable of representing multi-variate pathways (e.g., spatio-temporally evolving relationships) between source and impact

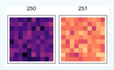
- Understand climate system
- Detect changes
- Represent relationships
- Model the time evolution of relationships



Use approaches to develop attribution techniques

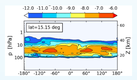
Ensure robust quantitative approaches through tiered verification

DEVELOPING METHODS USING INCREASINGLY COMPLEX DATASETS



Synthetic Relationships (M. Brown)

Wind Driven Gaussian Plume (Hart et al., 2023)



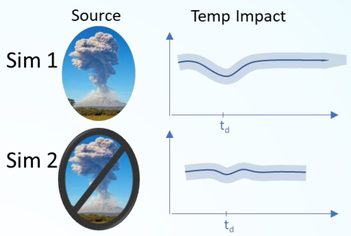
Idealized atm. + embedded pathways (Hollowed et al., 2024)

Mt. Pinatubo in fully coupled climate model (H. Brown et al., 2024)

Sandia is advancing attribution science in the climate through quantitative approaches that capture the pathway from source to societally-relevant impacts.

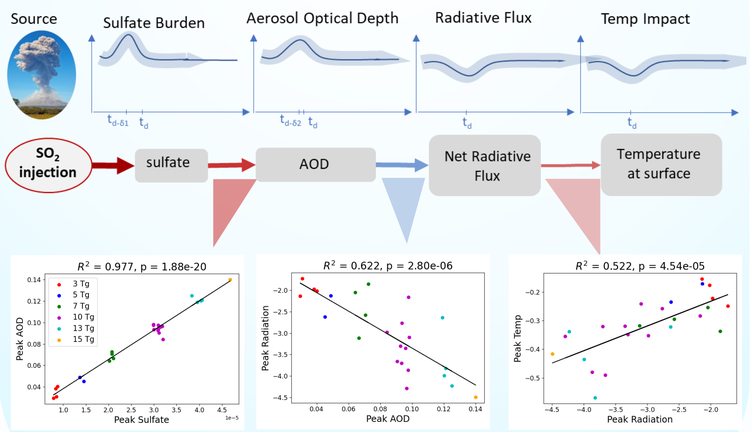
Before CLDERA

- ***Posit*** and fingerprint to establish impact's relationship to source



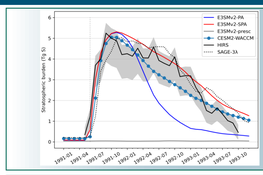
After CLDERA

- ***Model*** impact's relationship to source through multiple steps over space and time

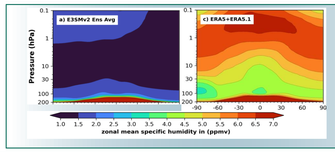


DEVELOPED STRATOSPHERIC EXPERTISE AND AEROSOL MODELING CAPABILITIES IN E3SM

- Developed stratospheric prognostic aerosol
  - Only 5 GeoMIP6 models capable
  - Enhanced tracers – tagging & new diagnostics
- Massive simulation campaign
  - 400+ TB of data encompassing source magnitude varying ensembles
  - Innovative initial condition constrained, paired counter-factual ensembles
- Uncovered biases in E3SM stratosphere
  - Overall overturning circulation slow, QBO fast



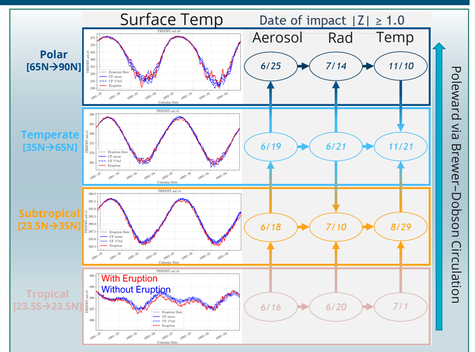
*Validated stratospheric aerosol performance in **E3SMv2-SPA** against observations (Brown et al. 2024)*



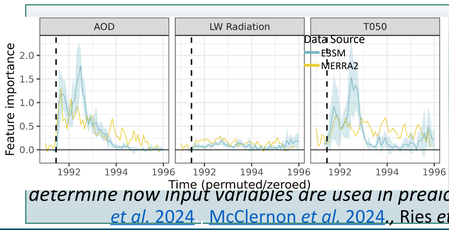
E3SM has strong dry bias in stratosphere (Jablonowski)

CREATED ORIGINAL METHODS TO DETECT AND MODEL PATHWAYS FROM SOURCE TO IMPACT

- Developed and implemented 8 novel methods to understand pathways
  - Advanced machine learning and statistical approaches that all consider multiple variables
  - Exploratory and confirmatory approaches
  - E3SM *in situ* approach
- Extended detection methods for spatio-temporally evolving changes



*Commander profiling techniques with **CLDERA-Tools** for **in situ** tracking of space-time statistics with graph-based pathway depiction (Steyer, et al. 2024, Watkins, et al.)*

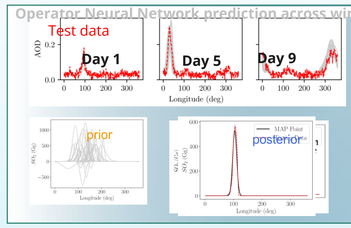


***Explainable Echo State Networks** to identify how input variables are used in predictions (Goode et al. 2024 McClernon et al. 2024., Ries et al. 2024.)*

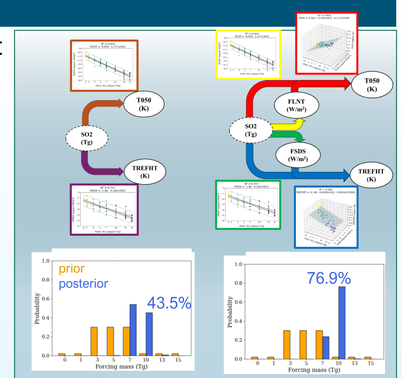
***Networks** to determine how input variables are used in predictions (Goode et al. 2024., McClernon et al. 2024., Ries et al.*

EVOLVED CLIMATE ATTRIBUTION THROUGH NOVEL METHODS, CASES, AND APPROACHES

- Methods to determine forcing magnitude given an impact
- Novel employment of pattern-scaling to identify relationships that are robust to variability in the system
  - Epidemiological dose-response
- Constraining natural variability to sharpen impacts
  - Similar to analogues / storyline approaches
  - ENSO3.4 and QBO initialized to historical values



*Correct source forcing obtained from **inverse optimization** in the face of both wind variability and background aerosol signals using operator learning representations simulation output (Hart)*



Successful demonstration of inverse optimization using deep learning representations of fully-coupled E3SM simulation output (Wentland)

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