CLDERA - CLimate impact: Determining Etiology thRough pAthways

CLDERA will develop new methods to confidently attribute climate impacts to localized sources using a novel pathways approach built upon discovering and representing evolving chains of physical processes. CLDERA aims to improve climate risk assessments and decision-making through its transformation of approaches for climate attribution.

THE CHALLENGE

Climate **impacts** have broad economic, health, political, and national security ramifications. Discovery and quantification of the impact's **source** are needed to guide policy decisions that may ameliorate or establish liability for undesirable impacts, as well as guide U.S. national security posture for impacts that may require response. However, in highly coupled complex nonlinear systems, like the Earth's climate, traditional understanding of causal relationships does not apply and many drivers may contribute to a detected change or impact.

Progress to address these issues has been made in **climate change attribution** that strives to identify impacts of long-term anthropogenic greenhouse gas emissions. The methods have addressed three classes of attribution: 1) attribution of changes in climate state variables to anthropogenic activity (e.g., global mean temperature); 2) assigning relative responsibility to different sectors, activities, and entities that contribute emissions; and 3) evaluation of the relative frequency and severity of extreme events due to climate change. These attribution methods have two common limiting characteristics. First, they require **long-term records** to identify a signal strength above natural variability. Second, attribution requires **positing source-impact pairs** (as done in #1 and #2) that can only **notionally**, not quantitatively, **link** a source through a series of cascading impacts (as done in #3 and sometimes #1).

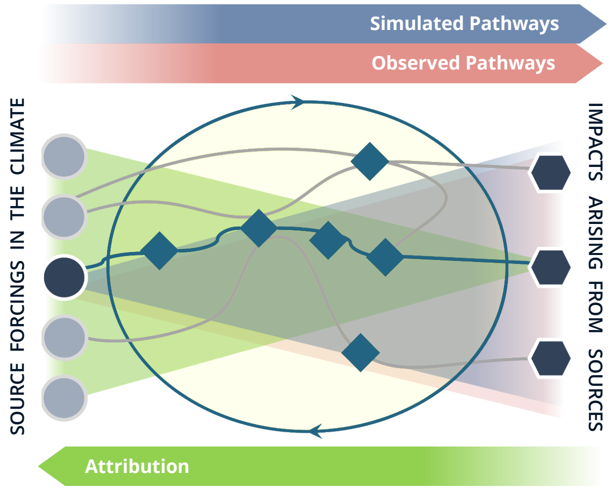
These characteristics make current attribution methods **unsuitable** for a new and increasingly important class of attribution within the climate system – impacts from **geographically and temporally localized sources**. These types of short-term forcings can be seen in volcanic eruptions, climatic tipping points (e.g., the collapse of rainforests or the disappearance of sea ice), or in increasingly plausible climate interventions like solar radiation modification.

The goal of CLDERA is to develop new tools to enable *downstream impact attribution* from geographically and temporally localized source forcings in the climate.

THE APPROACH

CLDERA will develop tools and methods that can distinguish ***how*** a localized source drives the climate system to respond with particular impacts; establish the relative **contribution** of the source to the impact; and employ inverse optimization methods to tangibly associate the **source characteristics** to the observed/predicted outcomes. The *how* is embodied in **pathways** – the spatio-temporally evolving **chain of physical processes** that connects a source to a series of increasingly distant impacts. Pathways **combine** evidence from **multiple processes** to strengthen connection between source and impact, enabling new methods to:

- overcome natural variability to find the source signal,
- rank relative contribution of a source to a specific impact, and
- determine source characteristics by constraining the inverse optimization problem.



Representation of pathways (connective lines) from source to impacts with process-nodes shown as diamonds. Simulated and observed pathways will be traced to impacts (left to right); resulting data will then be used to attribute impacts back to the source (right to left).

Novel analytic tools will be developed and in turn demonstrated on simulations and observations of the 1991 eruption of **Mt. Pinatubo** in the Philippines. Considered the 20th century's second-largest volcanic eruption, this event caused global climatic impacts, including decreases in near-surface temperatures, precipitation, and global sea-level, as well as increases in cirrus cloud cover and diffusivity of incoming radiation.

CLDERA will tailor the US DOE's flagship Earth System Model (ESM), the **Energy Exascale Earth System Model (E3SM)**, to simulate the chemical and microphysical evolution of the volcanically erupted sulfur-dioxide gas into sulfate aerosols in the stratosphere.

This **simulation output** and **observations** from the eruption will be used to develop computational analysis tools specifically designed to **elucidate and represent pathways** between this forcing and a series of increasingly distant, but well documented, impacts. These independently derived pathways will then support attribution, not only serving as constraints in traditional inverse approaches, but also offering dimension-reduced approximations of the system dynamics that can deepen **understanding** of **causal relationships**.

Method robustness is central to CLDERA's design. Characterization of the location and magnitude of an eruption which may produce attributable impacts, the susceptibility of a pathway to initial conditions, and the variability of the impacts will be examined through **sensitivity studies** of **eruption characteristics** and **E3SM parameterizations**, as well as ensemble analyses.

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 specific impacts 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 implementation 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.

Learn more at: sandia.gov/cldera

CLDERA is a large internally funded research program supported by Sandia's Laboratory Directed Research and Development (LDRD) program

CLDERA will fuse scientific, computational, and analytical expertise from nine distinct Sandia research centers and four academic partners — University of Illinois Urbana-Champaign, Texas A&M University, Columbia University, and University of Michigan. As a result, this project will create a multifaceted climate community with a **cadre of climate analysts** who can provide decision-support to an array of sponsors.

SANDIA CAPABILITIES

Sandia's broad science and engineering foundation, arising from our high-assurance nuclear weapons stockpile stewardship role, will be fully leveraged to create the integrated suite of CLDERA capabilities, including:

- Modeling and Simulation
  - Multi-physics simulations (e.g., Sierra)
  - Uncertainty quantification (e.g., Dakota)
  - Computational Science (e.g., ASC and E3SM)
- Detection and Attribution
  - Multicomponent sensor systems (e.g., USNDS)
  - Inverse optimization (e.g., ROL)
  - Information Sciences (e.g., PANTHER)
- Risk Analysis and High Reliability Engineering
  - Analysis of extremes (e.g., Z-pulsed power facility)
  - Regulatory Frameworks (e.g., WIPP)

EXPECTED OUTCOMES

CLDERA will **advance climate attribution science** by identifying impacts from localized sources and demonstrating current limits of impact-attribution. Further, this work will develop machine learning, reduced order modeling, and statistical tools to elucidate and represent pathways, that are a foundational means for understanding **dependent causal-like relationships** in *many* complex nonlinear systems.

New methods and tools developed through CLDERA will offer a framework that can be translated to other localized sources such as large wildfires, changes to ocean currents (e.g., Atlantic Meridional Overturning Circulation), or climate interventions (e.g., stratospheric aerosol injection).

With these new capabilities, Sandia will be able to:

1. **Inform** policies, agreements, regulations, treaties,
2. **Lead** advances in decision support using ESMs, and
3. **Develop** requirements for monitoring and measuring climate variables.

CLIMATE SECURITY AT SANDIA

Sandia is integrating capabilities from across the Labs to support our missions and address the national and global security threats associated with the rapidly evolving climate crisis. Our vision is to advance climate security through science, technology, and action.

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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