U.S. Department of ENERGY | Office of Science

CALIBRATED AND SYSTEMATIC CHARACTERIZATION, ATTRIBUTION, AND DETECTION OF EXTREMES (CASCADE)

With shifting earth system patterns, extreme weather events pose great hazards to both society and the environment. Extreme weather focuses public attention on the dramatic consequences of these events. Low-likelihood, high-impact (LLHI) extreme events in particular—events that are so rare that we may never have encountered anything similar in modern history—can push the bounds of what human systems are designed to tolerate.

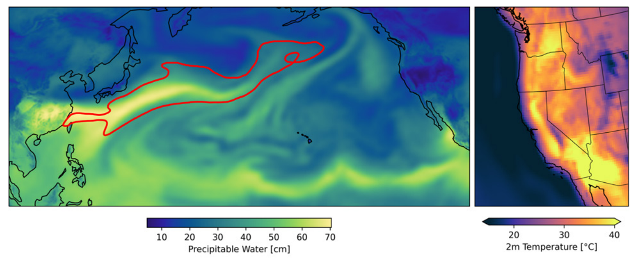
In 2017, for example, Hurricane Harvey broke all previous records for hurricane-related rainfall and caused devastating impacts to the U.S. Gulf Coast and the Caribbean. More recently, Hurricane Helene in 2024 caused unprecedented flooding in the Appalachian region, resulting in loss of life and extensive damage to critical infrastructure. In another example, a summer heatwave in the Pacific Northwest region in 2021 broke numerous records and had a high rate of associated mortality. The heatwave was so large that it exceeded empirical estimates of the upper bound of heatwave temperatures for the region, which points toward a need for developing better ways to estimate the risk of extreme events.

Current research points to an increase in the severity of extreme weather events in general and a possible increase in the occurrence of these LLHI extremes. This will constitute one of the most stressful challenges to the nation's environment, economy, and society. For scientists, it is critical to predict with greater reliability how these LLHI extreme events might change in the future and, to advance that objective, determine with as much certainty as possible whether and why the nature of extreme events has already changed.

CASCADE: TAKING A SCIENTIFIC FOCUS

The intersection of climatic extremes with critical water and energy resources is a key focus area for the U.S. Department of Energy (DOE), as reflected in the DOE Earth and Environmental Systems Sciences Division Strategic Plan.

Sponsored by the Regional and Global Model Analysis area of DOE's Earth & Environmental Systems Modeling program, the Calibrated and Systematic



***Left:** Output of precipitable water (shading) from a 5-day forecast (initialized 06-14-2021 00Z, valid 06-21-2021 00Z) from NVIDIA's FourCastNet model, with CASCADE's Toolkit for Extreme Climate Analysis driving the simulation and doing inline Bayesian AR detection (red). **Right:** A forecast of surface temperatures on 06-28-2021 00Z from FourCastNet (initialized 06-24-2021). Image credit: Travis A. O'Brien*

Characterization, Attribution, and Detection of Extremes (CASCADE) project addresses the critical knowledge gaps on earth system extremes needed to advance DOE's mission. CASCADE is developing capabilities to accelerate DOE's research portfolio in low-likelihood, high-impact extremes and to advance scientific capabilities in earth system analysis:

- Develop a new driver-focused framework for characterizing the risk of LLHI extremes.
- Design new statistical and modeling approaches.
- Characterize the sources of predictability of LLHI extremes.
- Develop machine learning tools and other computational capabilities.

These capabilities will be used to answer several key science questions:

- How can new approaches—including ML-based emulation of ESMs, new model ensembles, and new experiments—suggest promising ESM development pathways for greater fidelity of simulated LLHIs?
- How can the observational record be leveraged to improve statistical and physical understanding of LLHIs?
- What are the sources of LLHI predictability that can provide early warning of LLHIs at months to decades in advance?

CASCADE PROGRAM OBJECTIVES

Understanding drivers of observed changes in extremes: CASCADE investigates the causes of specific extreme events and their driving mechanisms, quantifies changes in both the magnitude and frequency of extreme events, develops state-of-the-art statistical tools for characterizing coincident extremes, and expands the scope of uncertainty quantification for detection and attribution. In terms of project goals, the investigation has several outcomes:

- Development of new machine learning approaches for generating huge ensembles of plausible weather scenarios for directly characterizing risk of the most extreme extremes.
- Systematically describe global changes in classes of extreme events.
- Provide localized information on both the changes in extremes and their causes.

Characterization of dominant sources of uncertainty in extremes: CASCADE is taking a systematic approach to consider dominant sources of uncertainty in research on extremes. These drivers include the chaotic behavior of the earth system (i.e., the butterfly effect), choices that model developers make about the structure of earth system models, uncertainty in underlying observations, and use of machine learning emulators—digital twins. CASCADE uses advanced statistical and experimental techniques to characterize the impact of these sources of uncertainty. This approach is designed to:

- Produce defensible scientific conclusions about how and why there are observed changes in extreme events.
- Advance fundamental understanding of extremes by reducing ambiguities that are caused by uncertainties.
- Produce data sets that the broader science community can use for similar research.

Understanding and simulating the physical behavior of extreme events: CASCADE advances understanding of the physical mechanisms that drive variability and change in the spatiotemporal characteristics of extreme events. This research enhances resiliency to extremes by:

- Quantifying how the probability distributions of multivariate extremes respond to trends and patterns of atmosphere-ocean variability.
- Identifying the thermodynamic and dynamic processes that drive extremes and their multi-scale interactions in the earth system.
- Evaluating the ability of earth system models and machine learning models to represent extremes.

Machine learning tools for analysis of LLHI extremes: CASCADE creates high-performance, open-source computational, statistical, and machine learning tools that can be shared, reused, and further developed for research beyond the project's central research challenges (see https://cascade.lbl.gov/software-products/). The effort is designed to produce significant new capabilities for climate science:

- Create high-fidelity machine learning and statistical tools for quantifying extremes.
- Develop in-situ approaches for analyzing and reducing the petabytes-to-exabytes of data produced by huge ensembles of machine learning simulations.
- Extend uncertainty quantification frameworks to treat a wide variety of extreme phenomena.

COLLABORATIONS

The CASCADE project is a collaborative work at Lawrence Berkeley National Laboratory (LBNL), University of California, Berkeley, University of California, Davis, Iowa State University, Indiana University, and NVIDIA. CASCADE scientists collaborate with related projects at LBNL and across Biological and Environmental Research's earth system modeling efforts, including Catalyst, WACCEM, and PCMDI. These projects include earth system modeling efforts—land, ocean, and atmosphere diagnostics projects and stakeholder-driven science projects. The resulting connections and related projects ensure tight integration of observations, experiments, and modeling of extreme events.

CONTACTS

Renu Joseph, Ph.D.
DOE Program Manager
Regional and Global Model Analysis
renu.joseph@science.doe.gov

William Collins, Ph.D.
Principal Investigator
Lawrence Berkeley National Laboratory
wdcollins@lbl.gov

Travis A. O'Brien, Ph.D.
Technical Co-Manager
Indiana University
obrienta@iu.edu