Detecting and Quantifying Causality from Time Series of Complex Systems

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Abstract

Today's scientific world produces a vastly growing and technology-driven abundance of time series data of such complex dynamical systems as the Earth's climate, the brain, or the global economy. In the climate system multiple processes (e.g., El Nino-Southern Oscillation (ENSO) or the Indian Monsoon) interact in a complex, intertwined way involving teleconnections and feedback loops. Using the data to reconstruct the causal mechanisms underlying these interactions is one way to better understand such complex systems, especially given the infinite-dimensional complexity of the underlying physical equations.

In this thesis, two main research questions are addressed: (i) How can general causal interactions be practically detected from multivariate time series? (ii) How can the strength of causal interactions between multiple processes be quantified in a well-interpretable way?

In the first part of this thesis, the theory of detecting and quantifying general (linear and nonlinear) causal interactions is developed alongside with the important practical issues of estimation. To quantify causal interactions, a physically motivated, information-theoretic formalism is introduced. The formalism is extensively tested numerically and substantiated by rigorous mathematical results.

In the second part of this thesis, the novel methods are applied to test and generate hypotheses on causal interactions in climate time series covering the 20th century up to the present. The results yield insights on an understanding of the Walker circulation and teleconnections of the ENSO system, for example with the Indian Monsoon. Further, in an exploratory way, a global surface pressure dataset is analyzed to identify key processes that drive and govern interactions in the global atmosphere. Finally, it is shown how quantifying interactions can be used to determine possible structural changes, termed tipping points, and as optimal predictors, here applied to the prediction of ENSO.