Complex Network Analysis of Extreme Rainfall Synchronization in the South American Monsoon System

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ABSTRACT

Based on the theory of networks, a general framework is developed to study collective synchronization phenomena of extreme events in complex systems. The method relies on observational time series encoding the variability of the single parts of the system, and is intended to reveal emerging patterns of extreme event synchronization on the macroscopic level. For this purpose, the time series obtained from an interactive system under consideration are identified with network nodes, and the possibly delayed and non-linear interdependence of extreme events in different time series is represented by network links connecting the nodes. In this way, the complex internal synchronization structure of the system becomes accessible in terms of the topology of the network, which can be analyzed by introducing suitable network measures. The methodology can thus be seen as a tool for exploring empirical or simulation-derived data, and can form the basis for the development of scientific hypotheses concerning the physical mechanisms underlying the emergent synchronization patterns. But in addition to the pure analysis of a given system, this tool can also be used for statistical prediction of extreme events, given that the system exhibits sufficiently concise synchronization patterns.

The methodology is applied to satellite-derived rainfall time series of high spatiotemporal resolution in order to investigate the collective dynamics of extreme rainfall events in South America. The purpose of this application is threefold: First, it is shown how the methodology can be used for climatic analysis by revealing climatological mechanism from the spatial patterns exhibited by different network measures. This is partly intended to serve as a proof of concept, but also adds new insights into the functioning of the climate system in situations where traditional techniques to study spatial patterns of co-variability of climatic observables are not applicable. This is the case for spatial characteristics of extreme event synchronicity, which cannot be derived nor analyzed on the basis of linear covariance measures. Second, networks encoding the synchronization structure of extreme rainfall events are constructed in a way that resolves their temporal order. These directed networks are used to assess the predictability of extreme rainfall at the eastern slopes of the Andes, which are frequently exposed to rainfall-induced natural hazards in form of floods and landslides. By introducing the concept of network divergence, sink and source regions of extreme events can be identified, allowing to track their directed synchronization pathways through the network. On this basis, a climatological mechanism is revealed that causes large rainfall clusters to propagate from southeastern South America towards the Central Andes. A simple statistical forecast rule is finally derived from these insights, predicting substantial fractions of extreme rainfall events in the Central Andes. Third, the methodology and the insights developed in the first two steps are used to evaluate the dynamical representation of extreme events in different datasets, and in particular their dynamical implementation in three state of the art climate models.