

Embracing nature's heterogeneity - the challenge to infer dependences from paleoclimate data

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Abstract

Investigating past climate changes offers a unique key to understanding the future behavior of the Earth system under anthropogenic perturbation, because it is the only realization of the “Earth system experiment” accessible. Paleoclimate archives such as trees, stalagmites, or glacial deposits provide in their structure and composition time-dependent records of earlier climatic variability. Statistical analysis of dependencies amongst such time series helps to infer on the climatic processes reflected in the paleoclimate proxy data and then, ultimately, on the dynamics of the Earth system. Three inherent technical challenges need to be met: the datasets are heterogeneously sampled in (i) time and (ii) space, and time itself is a variable that needs to be reconstructed which (iii) introduces additional uncertainties.

To address these issues I developed the paleoclimate network framework, inspired by the increasing application of complex networks methodology in climate. I introduced estimators for Pearson correlation, mutual information and event synchronization that do not require time series sampled at regular intervals. The impacts of age uncertainty on such similarity estimates was assessed numerically, using ensembles of possible accumulation histories. A simple model for information flow in the Asian summer monsoon (ASM) was used to test the ability of (paleoclimate) network measures to detect spatio-temporal transitions from time series observed at heterogeneous locations in space. The Gaussian-kernel based estimators for Pearson correlation and mutual information were more efficient for irregular time series than standard estimators applied to interpolated time series. The proposed event synchronization function quantifies similarity between time series based on the relative timing of extreme events in the time series. In benchmark tests I found it especially suitable for irregular and age uncertain time series. In principle, also heterogeneously sampling in space did not preclude the detection of spatio-temporal transitions by the proposed paleoclimate network measures. Using ensembles of model realizations I found that measures such as the proposed cross-link ratio and regional node strength reflect these changes consistently, both when estimated from a grid-based realization and when the model was sampled at available paleoclimate archive locations. In contrast to this, shortest path betweenness, a popular measure for complex networks, did not reflect these transitions. I applied the paleoclimate network approach to investigate decadal scale dynamics in the Asian summer monsoon system for the last millennium. Specifically, I tested to what extent a possible temperature-induced spatio-temporal change in internal ASM dynamics could be discernible given that the dataset available is age uncertain, sparse, and irregularly sampled in time and space. For the given dataset I found that age uncertainty and data sparsity precludes robust estimation of dependencies at decadal resolution. The distribution of link strength in the network did not depend significantly on the type of paleoclimate archive from which the records came, or on the distance between their origin. This could indicate that global-scale teleconnections, rather than local convective dynamics, are reflected in these paleoclimate records.

The presented paleoclimate network approach is suitable to integrate methods that address the challenges in the reconstruction of paleoclimate dynamics. Future improvements could be sought by integrating directed measures of statistical association, for example to investigate the direction and strength of a potential coupling between the ASM and the El-Niño phenomenon in the past.