

Nonlinearity of teleconnections in paleoclimatological data

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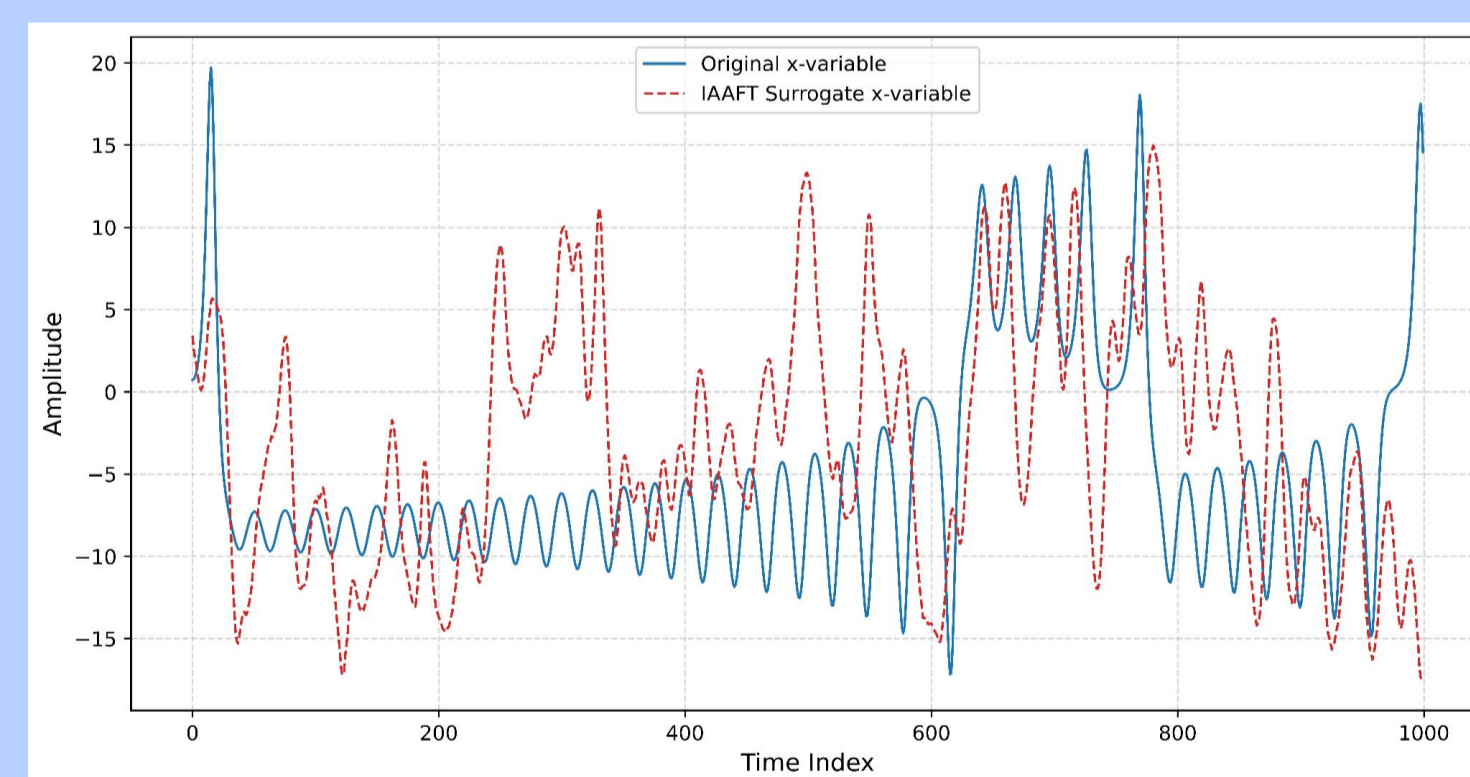
Section 1: Introduction

- The analysis of teleconnections in the climate system is usually carried out by using statistics sensitive to only to **linear** relationships, such as the Pearson correlation. The aim of this contribution is to investigate whether this assumption of linearity is valid.
- Our investigation is specifically focused on **paleoclimatological data**, coupled with a comparison to data from the **modern era**.
- We measure the significance of nonlinearity present in a 2D system of a fixed index time series describing an internal mode of variability, coupled with a temperature time series, for all grid points featured in the dataset.
- To carry out the analysis, we use the method of **surrogate data**, commonly used in the field on nonlinear time series analysis.
- We analyse teleconnections generated by two of the most prominent modes of internal variability - **El Niño–Southern Oscillation (ENSO)**, specifically characterized by the NINO3.4 and SO indices, and **North Atlantic Oscillation (NAO)**

Section 2: Methods

- As summarized in Lancaster (2018), we employ the IAAFT (Iterated Amplitude Adjusted Fourier Transform) algorithm to generate a **surrogate time series**, whose properties are as random as possible (compared to the original time series) while at the same time preserving the **linear** properties of the signal
- We then utilize a discriminating statistic, sensitive to the presence of nonlinearities in the time series. In our case, this is the **Mutual information** measure (MI)
- If the IAAFT transformation preserves the nonlinear statistic, we deduce that no information was lost \Rightarrow the system is linear
- On the other hand, if MI is reduced by the transformation, we expect a presence of nonlinearities in the individual time series, or in their coupling
- The procedure was tested on a number of synthetically generated systems, both linear and nonlinear

An example of a surrogate time series generated from the Lorenz 3D system x-variable

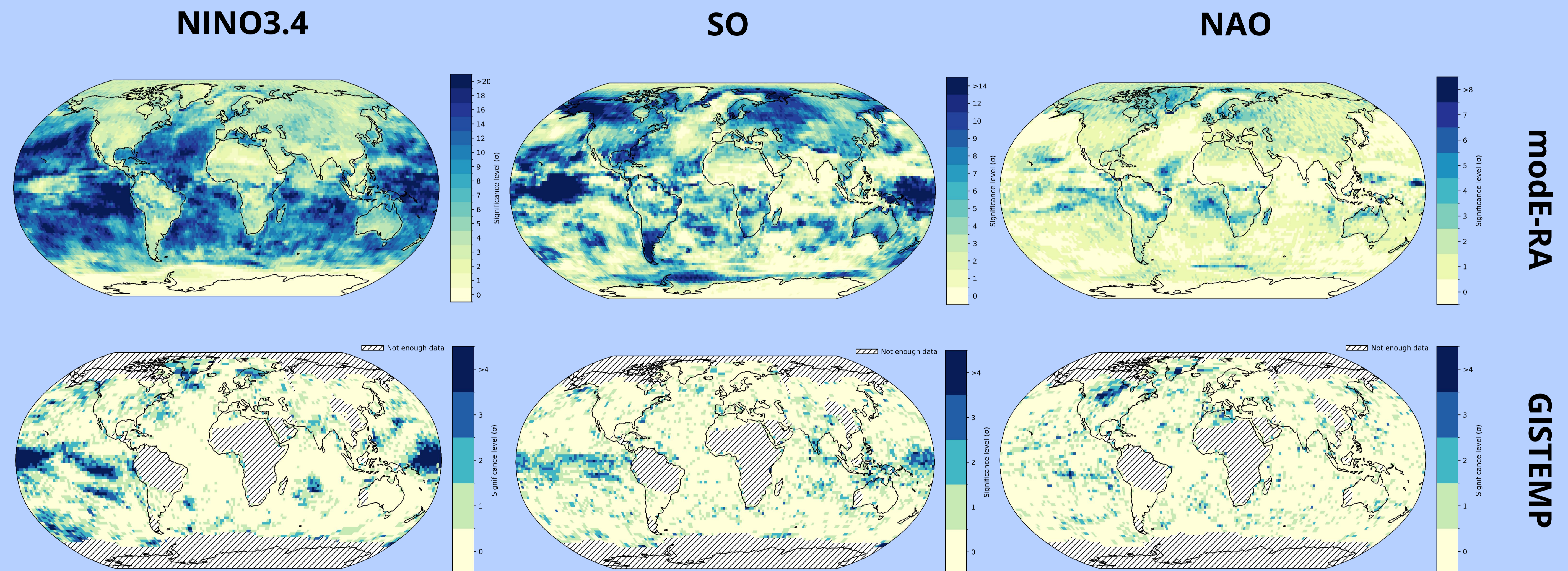


Section 3: Data

- For the paleoclimatological record, we used the **2-m temperature** and **sea level pressure** data from the m01 run of the modE-RA reanalysis (Valler et al., 2024) for the years 1439-1849
- From this dataset, we also derived the index time series for the respective internal variability modes (NINO3.4, NAO)
- For the modern day analysis, we used the GISTEMP dataset (years 1880-2024), along with with indice time series taken from Climate Explorer

Section 5: Practical implementation and results

- The figures show significance scores representing the number of standard deviations the original MI value takes with respect to a Gaussian-fitted distribution of the surrogate MI values
- Note the varying scales of significance scores
- For GISTEMP, grid points with missing data were not included



Section 4: Findings

- Significant nonlinearity was observed in all analysed teleconnections, albeit with varying spatial structures
- We generally observe that coupled ocean-atmosphere modes of variability induce teleconnections with higher nonlinearity compared to purely atmospheric modes of variability
- In the paleoclimatological modE-RA data, nonlinearities from NINO3.4 propagate globally over the oceans
- The ModE-RA data generally exhibit more significant nonlinearities compared to modern day data, which may be a statistical artifact caused by greater length of the paleoclimate time series
- However, not only the significance, but also the spatial structures of the observed nonlinearities vary, which could be an indicator of either change in the physical mechanisms or insufficiencies in the representations of the variability modes in modE-RA

Section 6: Future directions and questions to clarify

- Repeating the analysis for different runs of modE-RA and comparing results
- Addressing nonhomogeneities and nonstationarities in the data
- Rigorously defining the meaning of nonlinearity
- Is it possible to quantify the strength of the present nonlinearity, or in other words measure the extent to which a correlation is invisible to linear statistics?
- Based on these findings, what can we say about the quality of representations of internal modes of variability in modE-RA?

Section 7: References

Surrogate data: Lancaster et al. (2018), <https://doi.org/10.1016/j.physrep.2018.06.001>
modE-RA: Valler et al. (2024), <https://doi.org/10.1038/s41597-023-02733-8>
GISTEMP: Hansen et al. (2010), <https://doi.org/10.1029/2010RG000345>
KNMI Climate Explorer, (2022), Koninklijk Nederlands Meteorologisch Instituut

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