Understanding Changes in Environmental Time Series with Time-Frequency Causality Analysis

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Research Objective

Can we detect and attribute anomalous events based on the analysis of changes in the causal effect relationships?

The high magnitude wavelet coherence of sea level pressure (SLP) and wind speed (W) correlates well with the date and time-scale (9-16 days) of the historic hurricanes in year 2012.

Method

- Variables: Air Temperature (T), Vapor Pressure Deficiency (VPD), Net Ecosystem Exchange (NEE), Latent Energy (LE), Sea Level Pressure (SLP), Wind Speed (W), Latent Heat (LH), Evapotranspiration (ET), Precipitation (PR)
- Observations: Data from a buoy located near the Bahamas in the Atlantic Sea (23.838° N, 68.335° W)
- Duration: Hurricane Rafael (12-26 Oct. 2010), Hurricane Sandy (Oct. 22 – Nov. 02, 2012)

Challenges in Causality Analysis

- Nonstationary
- Presence of periodic components
- Multi-scale cause effect relations
- Nonlinearity
- Presence of hidden cofounders

Time Domain Vector Autoregressive (VAR) Granger Causality

\[
\begin{align*}
    x_1(n) & = \sum_{i=1}^{p} A_{1i} x_i(n-1) + \epsilon_1(n) \\
    x_2(n) & = \sum_{i=1}^{p} A_{2i} x_i(n-1) + \epsilon_2(n) \\
    \vdots & \notag
\end{align*}
\]

The causal relation from \( x_i \) to \( x_j \) conditioned on other variables is \([1](2)\)

\[
\begin{align*}
    \gamma_{i\rightarrow j} & = \frac{1}{\sum_{j=1}^{m} \sum_{i=1}^{n} A_{ij}}
\end{align*}
\]

Frequency Domain VAR-GC: The generalized Partial Directed Coherence (gPDC)

\[
g_{PDC}(f) = \frac{1}{\sum_{k=1}^{m} \frac{1}{\| A_k(f) \|^2}}^2 A(f) = \sum_{i=1}^{m} A_{ij} z^{-\tau} |_{z=\pm f}
\]

Nullity of \( g_{PDC}(f) \) indicates an absence of Granger causality from \( x_i \) to \( x_j \) at normalized freq. \( f \)

Experimental Results


How ecosystem functioning is affected during unusual hydro-meteorological conditions?

Variables:
- Hourly data measured at the flux tower of Puechabon-France

Event Detection in Marine Climate Time Series [4]

During the heatwave of August 2003 in France, we can notice deviation of the causal effect intensities (blue solid line) from the average ones during similar summer periods within years 2001-2013 (red dashed line): clear increase in the causal intensity of VPD on NEE at the low frequency range (long term change) pointing towards an increase in water stress on ecosystem functioning. Note also the increased effect of T on VPD as short term change (high freq.). The threshold for statistical significance estimated using permutation test and the FT surrogate test is shown in the dashed-dotted line and gray area respectively.

Conclusions & Future Work

- An anomalous event can be detected as the one where the causal intensities between the variables differ from the average causal intensities.
- Time frequency analysis allows for causality analysis at different frequency components and different time scales. Further details can be found in [4].
- The analysis of the spectral causal effect patterns allows for understanding these events and define the time scale on which changes occur.
- Further work: 1. Extension to state space model with latent variables, 2. Extension to spatiotemporal data, and 3. Adaptive window size selection based on stationarity test.

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References