Revisiting impact of MJO on soil moisture: a causality perspective

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Introduction

- Madden-Julian Oscillation (MJO) and El Niño Southern Oscillation (ENSO) impact extreme dry/wet conditions over tropical continental land [1-2]
- Granger Causality (GC) is widely used in geosciences
  - Useful and interpretable
  - Strong assumptions made: linearity and stationarity
- Our cross-kernel Granger causality (XKGC) [3]
  - Nonlinear relations
  - Kernel function for nonstationary processes
- We use XKGC to uncover the effect of the MJO and ENSO on global SM anomalies

Cross-information Kernel Granger Causality (XKGC)

- **Granger Causality (GC):**

Unrestricted Regression

$$y_{t+1} = \sum_{k=0}^{p} a_k y_{t-k} + \varepsilon_t^y$$

Causality Index

$$\delta_{x\to y} = \log(\mathbb{V}[\varepsilon_t^y]^2 / \mathbb{V}[\varepsilon_t^{y|x}]^2)$$

Restricted Regression

$$y_{t+1} = \sum_{k=1}^{p} a_k y_{t-k} + \sum_{l=1}^{q} b_l x_{t-l} + \varepsilon_t^{y|x}$$

- **Kernel Granger Causality (KGC)** $\mathbf{z}_t = [\mathbf{y}_t, \mathbf{x}_t] \in \mathbb{R}^{p+q}$
  - Concatenate [X,Y] data in the restricted regression
  - Standard kernelization

$$\begin{aligned} y_{t+1} &= \mathbf{a}_H^T \phi(\mathbf{y}_t) + \varepsilon_t^y \\ y_{t+1} &= \mathbf{b}_H^T \psi(\mathbf{z}_t) + \varepsilon_t^{y|x} \end{aligned} \Rightarrow \begin{aligned} y_{t+1} &= \boldsymbol{\alpha}^\top \mathbf{k}_t + \varepsilon_t^y \\ y_{t+1} &= \boldsymbol{\beta}^\top \boldsymbol{\ell}_t + \varepsilon_t^{y|x} \end{aligned}$$

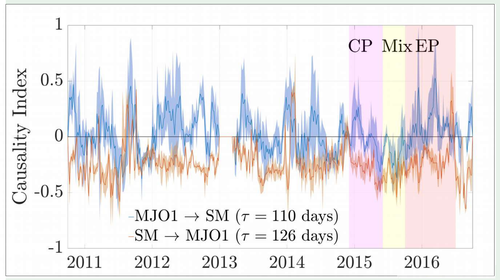
  - Simple & neat
  - One kernel param. to fit all & no cross-relation
- **Cross-Kernel Granger Causality (XKGC):**
  - Define a new feature map to generalize KGC

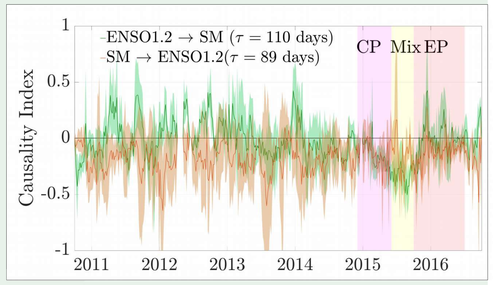
$$\psi(\mathbf{x}_t, \mathbf{y}_t) = [\phi_1(\mathbf{y}_t), \phi_2(\mathbf{x}_t), \phi_3(\mathbf{y}_t) + \phi_3(\mathbf{x}_t)] \Rightarrow K = \psi^T \psi$$
$$K(\mathbf{x}_t, \mathbf{y}_t) = K_{xx} + K_{yy} + K_{xy} + K_{yx}$$

  - Generalizes KGC for more complex X-Y relations
  - Separates kernel parameters for each relation
  - Can find different scales on the non-linear relations

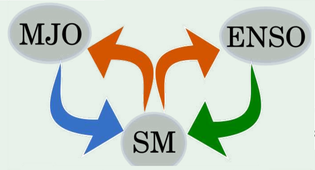
MJO impact on soil moisture anomalies: An ENSO disruption

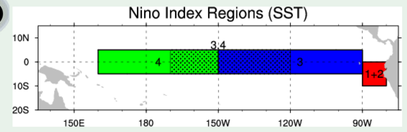
Figure 1: ENSO atmospheric disruption, MJO and SM anomalies. Estimation of causality indices using XKGC with a (half year) moving window. Mean and deviation of each index come from a sensitivity analysis of the autoregressive models [4], where values > 0 indicate causality. Three regimes are identified [5]:
1. Neutral period: both ENSO and MJO induce variability (Granger Causality) on the SM anomalies till the start of the 2016 ENSO event (El Niño Godzilla).
2: Disruption: the link breaks at the CP ENSO phase and remains till the EP ENSO phase.
3: Transition period: during the peak of the ENSO event, highest variability induced on SM anomalies

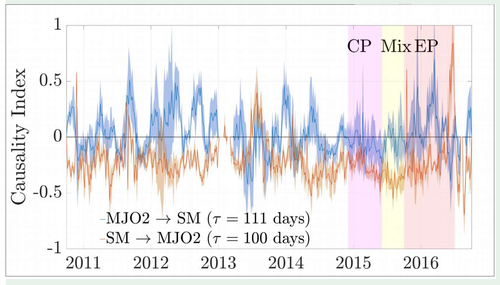




CP
Central Pacific ENSO
EP
Eastern Pacific ENSO
Mix
Mixture of CP and EP







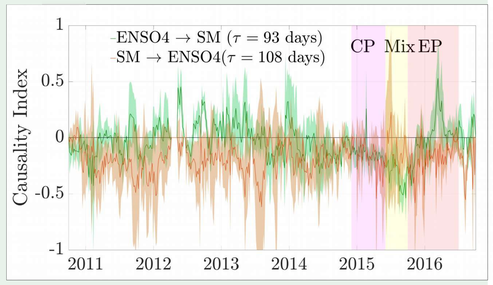
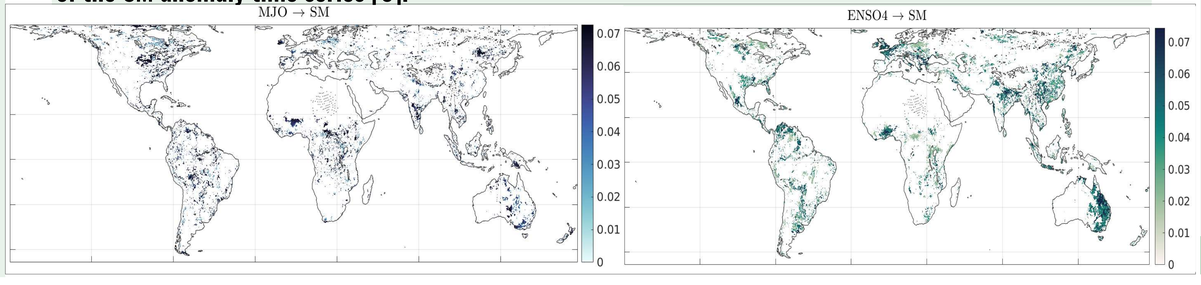


Figure 2: Spatio-temporal analysis of ENSO and MJO impacts on SM anomalies. Causality index maps obtained from the neutral period (2010-2015). Spatial distribution extracted from the spatial component of the SM anomaly time series [6].



Data

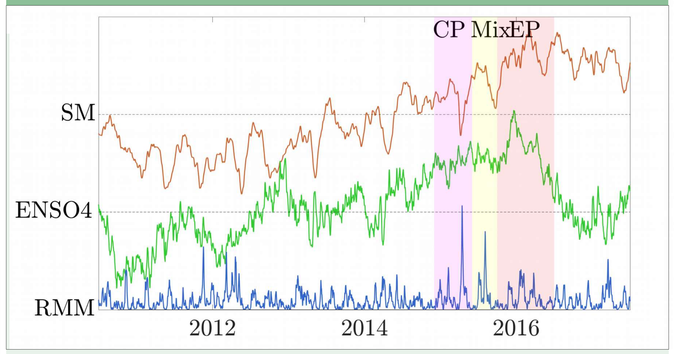


Figure 3: Time series of main variables.
- **ENSO:** SST anomalies of the equatorial Pacific Ocean.
- **Real-time Multivariate MJO (RMM):** First two EOF of 850 and 200 hPa zonal wind average over the Equator.
- **SM:** data extracted from ESA's SMOS (Soil Moisture Ocean Salinity) mission. Independent and complex valued Spatio-temporal features have been extracted using a nonlinear dimensional reduction method for different time scales [6].

Conclusions

- New XKGC method generalizes GC & KGC
- Reconstructing the ENSO atmospheric disruption, breaking the causal link between MJO and ENSO and the SM anomalies
- Common causal mediators revealed
- Causality maps reveal different MJO and ENSO impacts on SM anomalies

References

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