Revisiting impacts of MJO on soil moisture: a causality perspective

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Abstract

Recent studies have documented that the Madden-Julian Oscillation (MJO) has impacts in extreme dry/wet conditions over tropical regions and in atmospheric state. They are based, however, in correlation analysis, and therefore do not consider non-linear interactions nor they establish cause-effect relationships.In this study we introduce a generalization of the non-linear Granger causality (GC) test to identify causal relations between MJO and hydrological extremes. The method is able to identify causal relations under noisy, nonlinear and non-stationary scenarios. A probabilistic extension is also introduced where the causal test operates directly on the marginal likelihood (also called evidence) of the observations, which is analytic. We apply our proposed method to MJO and satellite-based soil moisture (SM) data, and revisit the global teleconnection patterns induced by MJO events. Since El Ni\~no Southern Oscillation (ENSO) is a modulating factor that can result in abnormal SM global distributions, we also include it in the analysis as a potential driver of SM variability. Including ENSO allows us to differentiate the effect of the MJO and ENSO on the global SM anomalies and to learn the causal graph of their cause-effect relationships, and also the mutual relation between MJO and ENSO extreme events.

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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

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

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

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

  - 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

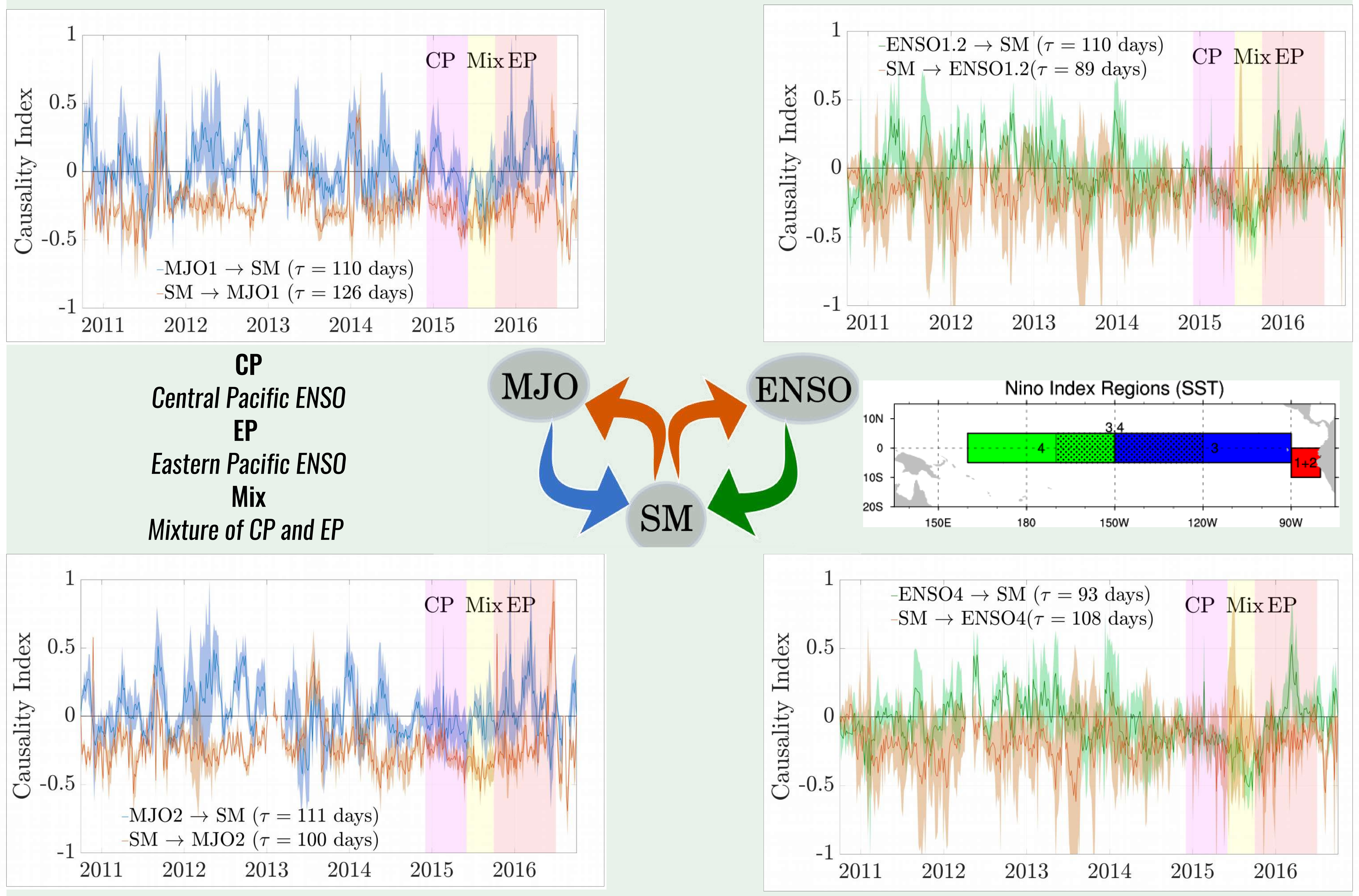
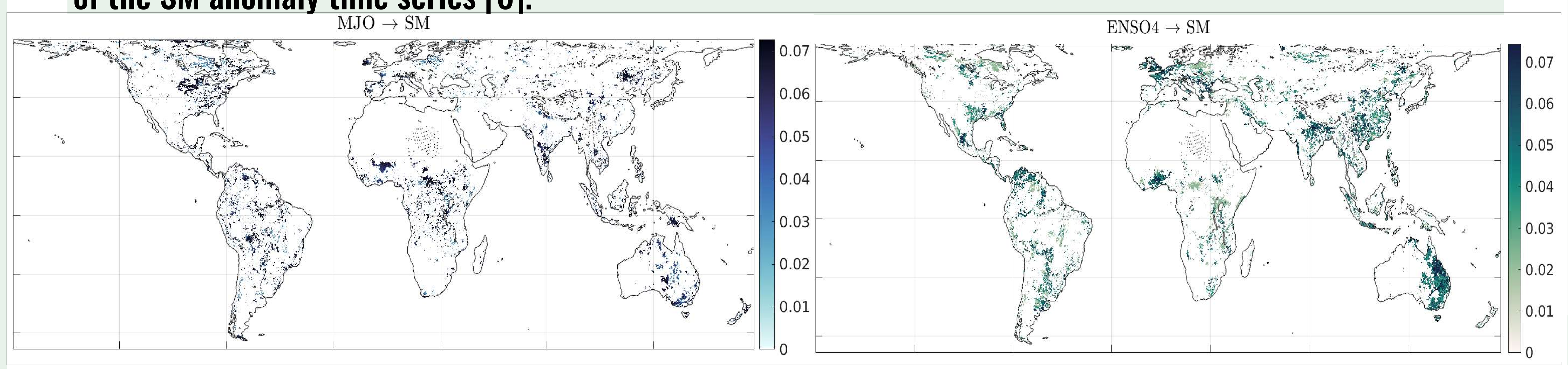


Figure 2: Spatio-temporal analysis of ENSO and MJO impacts on SM anomalies. Causality index maps obtained from the neutral period (2010-2015). Spatial distribution extracted from the spatial component of the SM anomaly time series [6].



Data

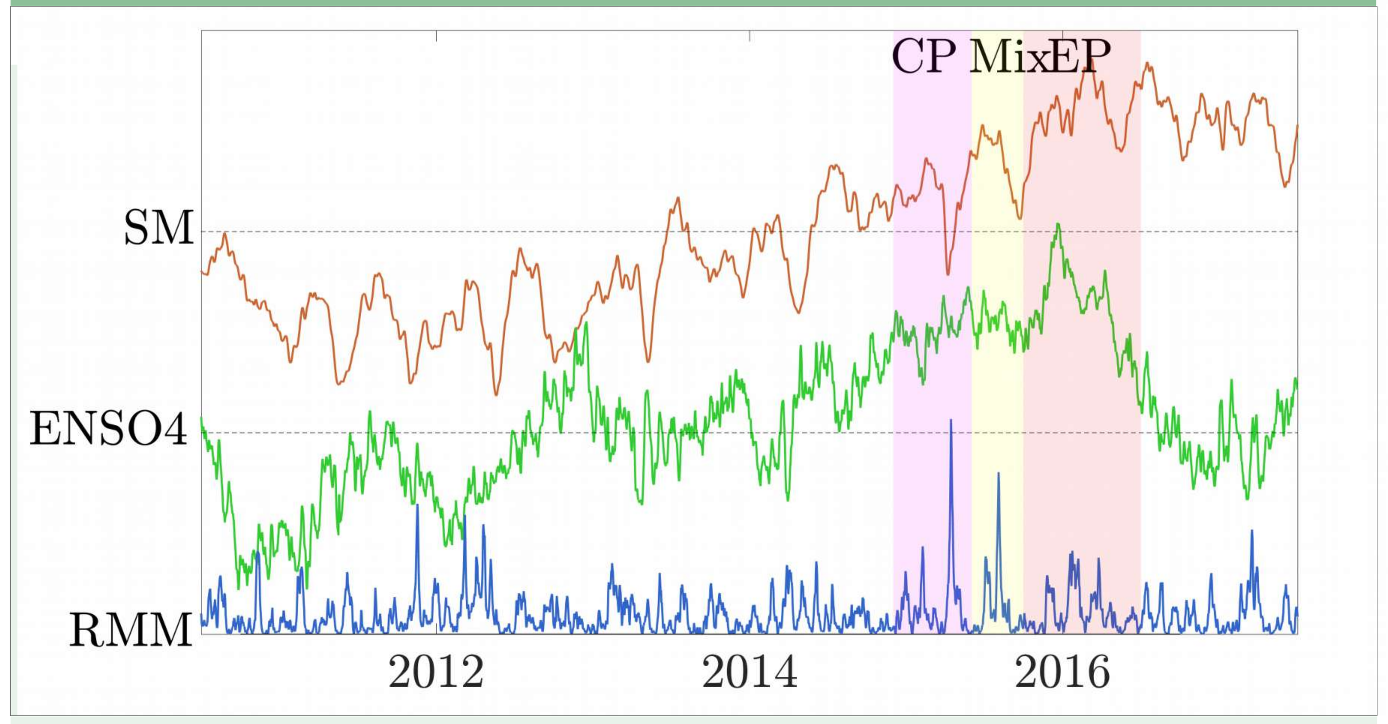


Figure 3: Time series of main variables.

- **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

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