National Institute for Space Research

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Non-linear Interactions between Niño region 3 and the Southern Amazon

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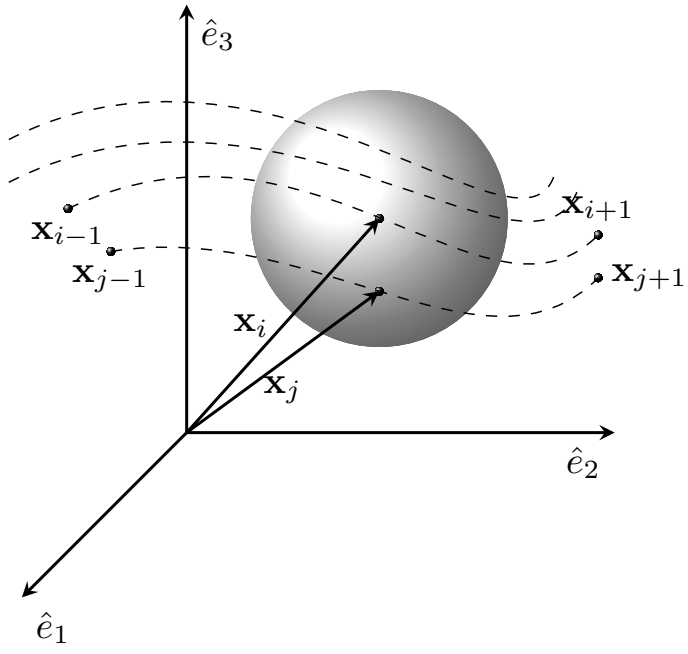
Outlines

1. We present a new tool called *Recurrence Measure of Conditional Dependence* (RMCD) to investigate causality.

2. RMCD is based on recurrence propeties of the system.

3. We show the efficiency of RMCD to establish temporal causal link by testing different coupled models and real data.

Recurrence Matrix



(a) reconstructed phase space

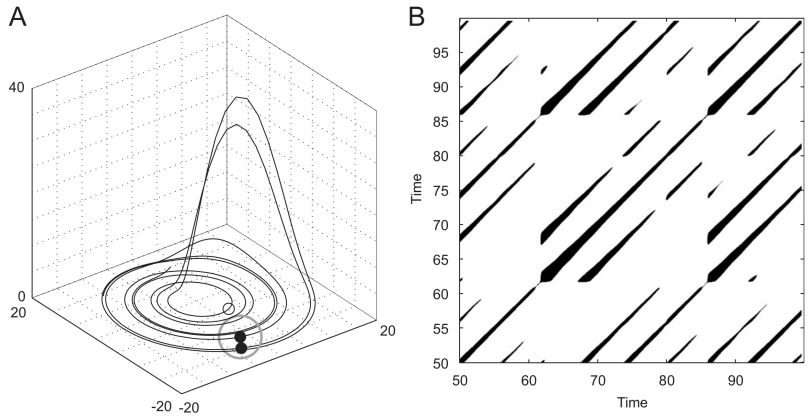
$$\mathbf{R}^X = \begin{array}{c} \\ i-1 \\ i \\ i+1 \\ j-1 \\ j \\ j+1 \end{array} \begin{array}{c} \begin{array}{ccccccc} i-1 & i & i+1 & & j-1 & j & j+1 \end{array} \\ \begin{pmatrix} 1 & \vdots & & & \vdots & 0 & \vdots \\ \vdots & 1 & \vdots & \cdots & 0 & 1 & 0 \\ & \vdots & 1 & & \vdots & 0 & \vdots \\ \vdots & 0 & \vdots & & 1 & \vdots & \\ 0 & 1 & 0 & \cdots & \vdots & 1 & \vdots \\ \vdots & 0 & \vdots & & & \vdots & 1 \end{pmatrix} \end{array}$$

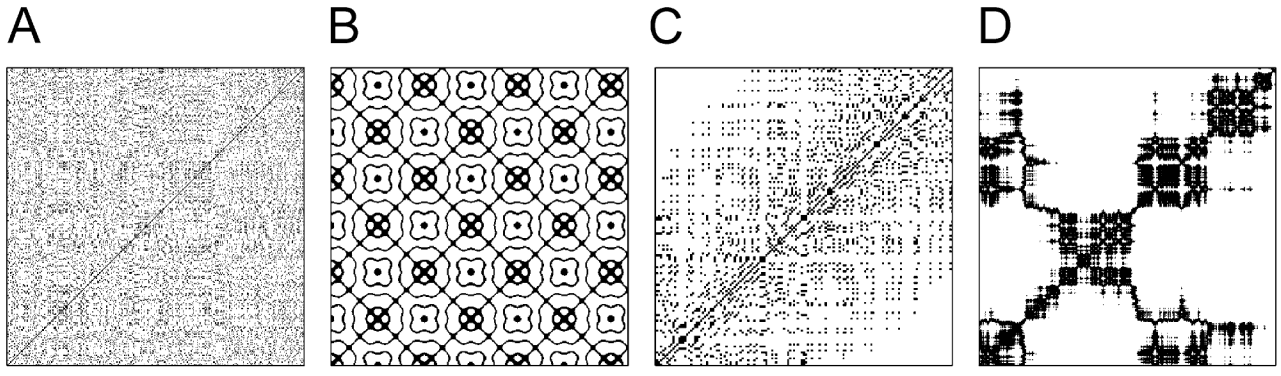
(b) Recurrence Matrix

$$R_{ij}^X = \Theta\left(\varepsilon - \| \mathbf{x}_i - \mathbf{x}_j \|\right), \quad i,j = 1,\ldots,N, \tag{1}$$

$$R_{ij}^{X,Y} = R_{ij}^X R_{ij}^Y = \Theta\left(\varepsilon_X - \| \mathbf{x}_i - \mathbf{x}_j \|\right) \Theta\left(\varepsilon_Y - \| \mathbf{y}_i - \mathbf{y}_j \|\right). \tag{2}$$

Recurrence Plot





Norbert Marwan, M. Carmen Romano, Marco Thiel, Juergen Kurths *Recurrence plots for the analysis of complex systems*; Physics Reports 438, 5–6, pag. 237 (2007)

Probability of Recurrence

$$\begin{pmatrix}
1 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\
0 & 1 & 0 & \textcircled{1} & 0 & \textcircled{1} & 0 & 0 & \textcircled{1} & 0 \\
1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 1 \\
0 & \textcircled{1} & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 \\
1 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 0 \\
0 & \textcircled{1} & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 \\
0 & 0 & 1 & 1 & 1 & 0 & 1 & 0 & 0 & 1 \\
1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\
0 & \textcircled{1} & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1
\end{pmatrix}$$

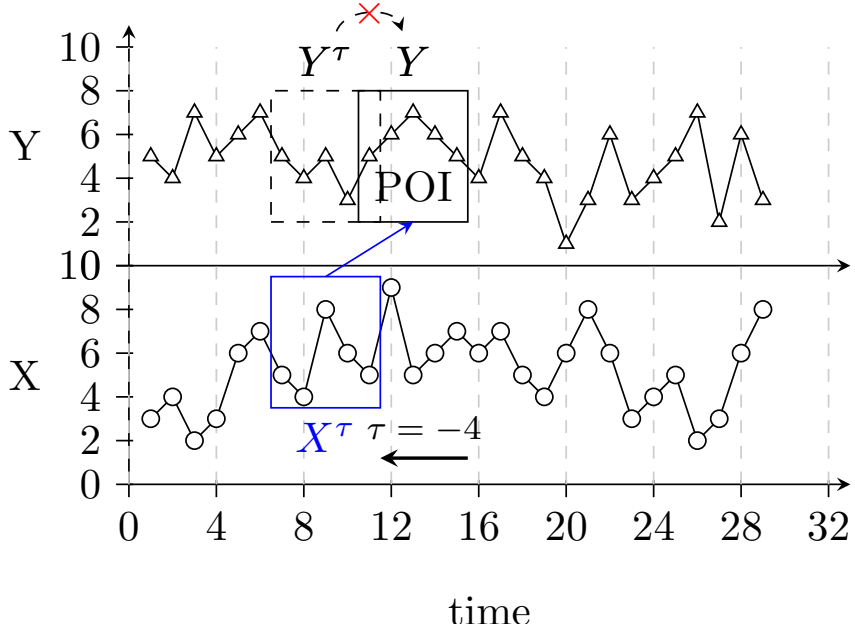
Probability of Recurrence at a given time $i = 2$

$$p_i(X) = \frac{1}{N} \sum_{j=1}^{N} R_{ij}^{X} = \frac{3}{10}. \tag{3}$$

Transfer Entropy approach

Transfer Entropy [3] is the reduction in the uncertainty of the *past* of X due to the knowledge of the *present* of Y when the *past* of Y is given.

$$I_{X\to Y} = I(X^\tau; Y|Y^\tau) = H(X^\tau, Y^\tau) + H(Y, Y^\tau) - H(Y^\tau) - H(X^\tau, Y, Y^\tau). \quad (4)$$



$$H(\cdot) = -\sum_{k=1}^{n} p_k(\cdot) \log_2 p_k(\cdot) \quad (5)$$

[3] Schreiber, T. Measuring information transfer. Phys. Rev. Lett. 2000, 85, 461464.

Recurrence Measure of Conditional Dependence

Following the definition of *Transfer Entropy*
Recurrence Measure of Conditional Dependence is defined as

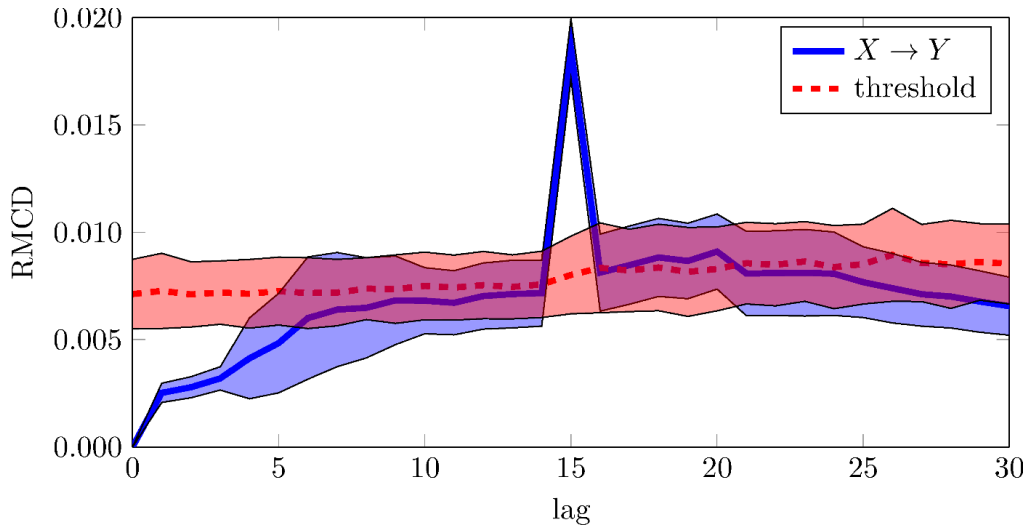
$$\mathrm{RMCD}(X^{\tau}, Y|Y^{\tau}) = \frac{1}{N}\sum_{i}\left[\frac{1}{N}\sum_{j} R_{ij}^{X^{\tau},Y,Y^{\tau}} \log_2\left(\frac{\sum_j R_{ij}^{X^{\tau},Y,Y^{\tau}} \sum_j R_{ij}^{Y^{\tau}}}{\sum_j R_{ij}^{X^{\tau},Y^{\tau}} \sum_j R_{ij}^{Y,Y^{\tau}}}\right)\right]. \quad (6)$$

Coupled ARMA[53] Model

$$x_i = \frac{4}{25}\sum_{k=1}^{5} x_{i-k} + \frac{4}{25}\sum_{k=1}^{3} \xi^x_{i-k}$$

$$y_i = \frac{4}{25}\sum_{k=1}^{5} y_{i-k} + \frac{4}{25}\sum_{k=1}^{3} \xi^y_{i-k} + \eta x_{i-15} \qquad (7)$$

where $\eta = 0.9$ is the coupling parameter and ξ is an uniformly distributed random number.

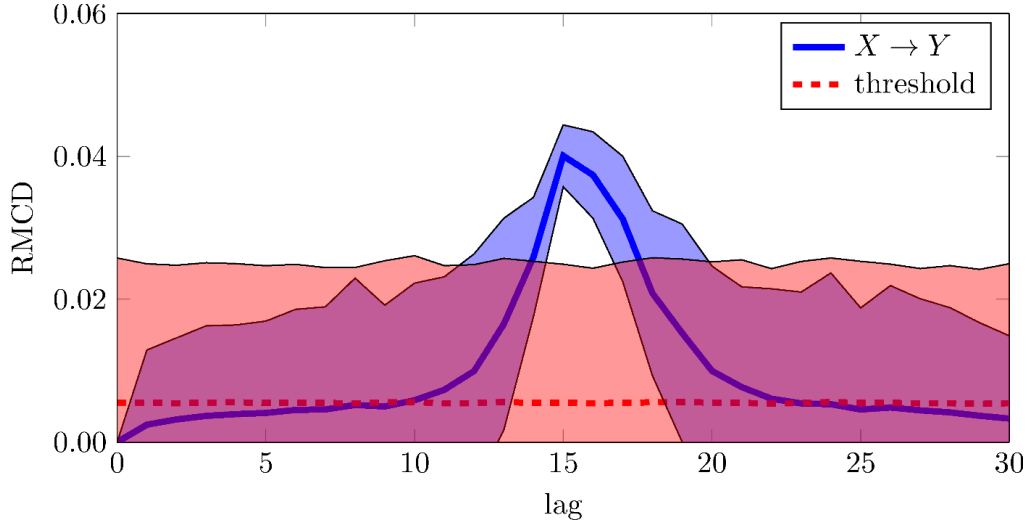


Embedding parameters: dimension 2 and delay 9. 100 twin surrogates ar

Coupled Logistic Map

$$x_i = (1-\eta) r x_{i-1}(1-x_{i-1}) + \eta y_{i-15},$$
$$y_i = (1-\eta) r y_{i-1}(1-y_{i-1}) + \eta x_{i-15}. \quad (8)$$

where the coupling or migration parameter is $\eta = 0.5$ and the growth rate is $r = 3.7$



Embedding parameters: dimension 2 and delay 1. 100 twin surrogates and 100 runs.

Gyllenberg and Gunnar, *Does migration stabilize local population dynamics? analysis of a discrete metapopulation model*, Mathematical Biosciences, 1993

Hastings, *Complex Interactions Between Dispersal and Dynamics*, Ecology, 1993

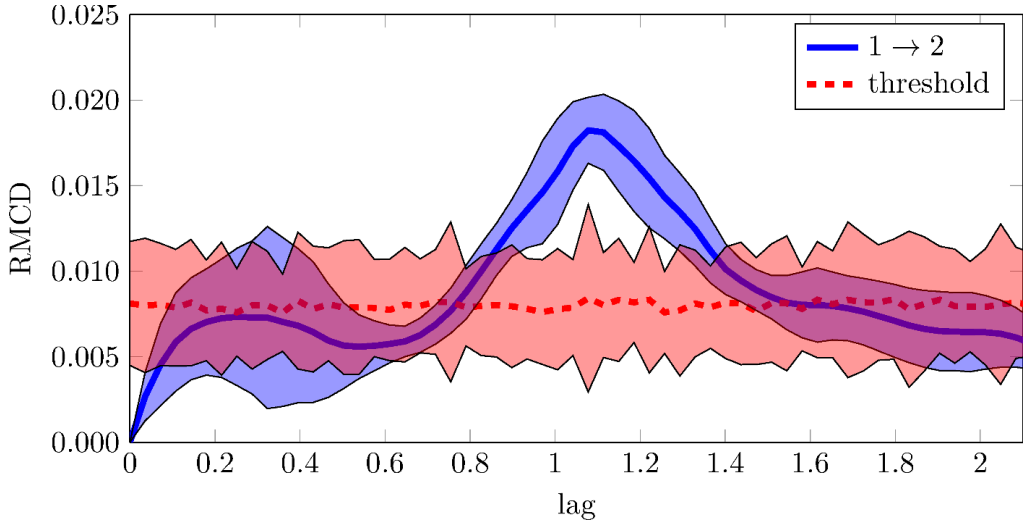
Coupled Lorenz Model

$$\dot{x}_i(t) = \sigma\,[y_i(t) - x_i(t)]\,,$$

$$\dot{y}_i(t) = r\,x_i(t) - y_i(t) - x_i(t)z_i(t) + \sum_{j\neq i} K_{ij}y_j^2(t-\tau_{ij}),$$

$$\dot{z}_i(t) = x_i(t)y_i(t) - b\,z_i(t), \qquad (9)$$

with $i, j = 1, 2$ and Lorenz systems parameters are $\sigma = 10$, $r = 28$, $b = 8/3$; the coupling parameters are $k_{21} = 1.2$ and $k_{12} = 0$, this way 1 influences 2 but not the other way around.



Embedding: dim. 3 and delay 1, lag of between 1 and 2 is 1 unid. time. 200 twin surrogates and 10 runs.

Frenzel, Stefan and Pompe, Bernd; *Partial Mutual Information for Coupling Analysis of Multivariate Time Series*, v 99, p.204101; Phys. Rev. Lett.; 2007

Extreme Events in Amazonia

- Drought in 2005 and 2010

Review

Extreme seasonal droughts and floods in Amazonia: causes, trends and impacts

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[a] *Centro Nacional de Monitoramento e Alerta de Desastres Naturais, Ministério da Ciência, Tecnologia e Inovação, Sao Paulo, Brazil*

[b] *Subdirección de Ciencias de la Atmósfera e Hidrósfera (SCAH), Instituto Geofísico del Perú, Lima, Peru*

2005*	Drought	Warm TNA	Marengo *et al.* (2008), Marengo *et al.* (2011), Zeng *et al.* (2008), Espinoza *et al.* (2011), Cox *et al.* (2008), Tomasella *et al.* (2011), Yoon and Zeng. (2010), Aragão *et al.* (2007), Coelho *et al.* (2013)
2010*	Drought	EN + Warm TNA	Lewis *et al.* (2011), Marengo *et al.* (2011), Espinoza *et al.* (2011), Coelho *et al.* (2013)

EN, El Nino; LN, La Niña; TNA, Tropical North Atlantic; TSA, Tropical South Atlantic; SSA, Subtropical South Atlantic; IP, Indo-Pacific Ocean.
*Events characterized at the time as 'once in a century'.

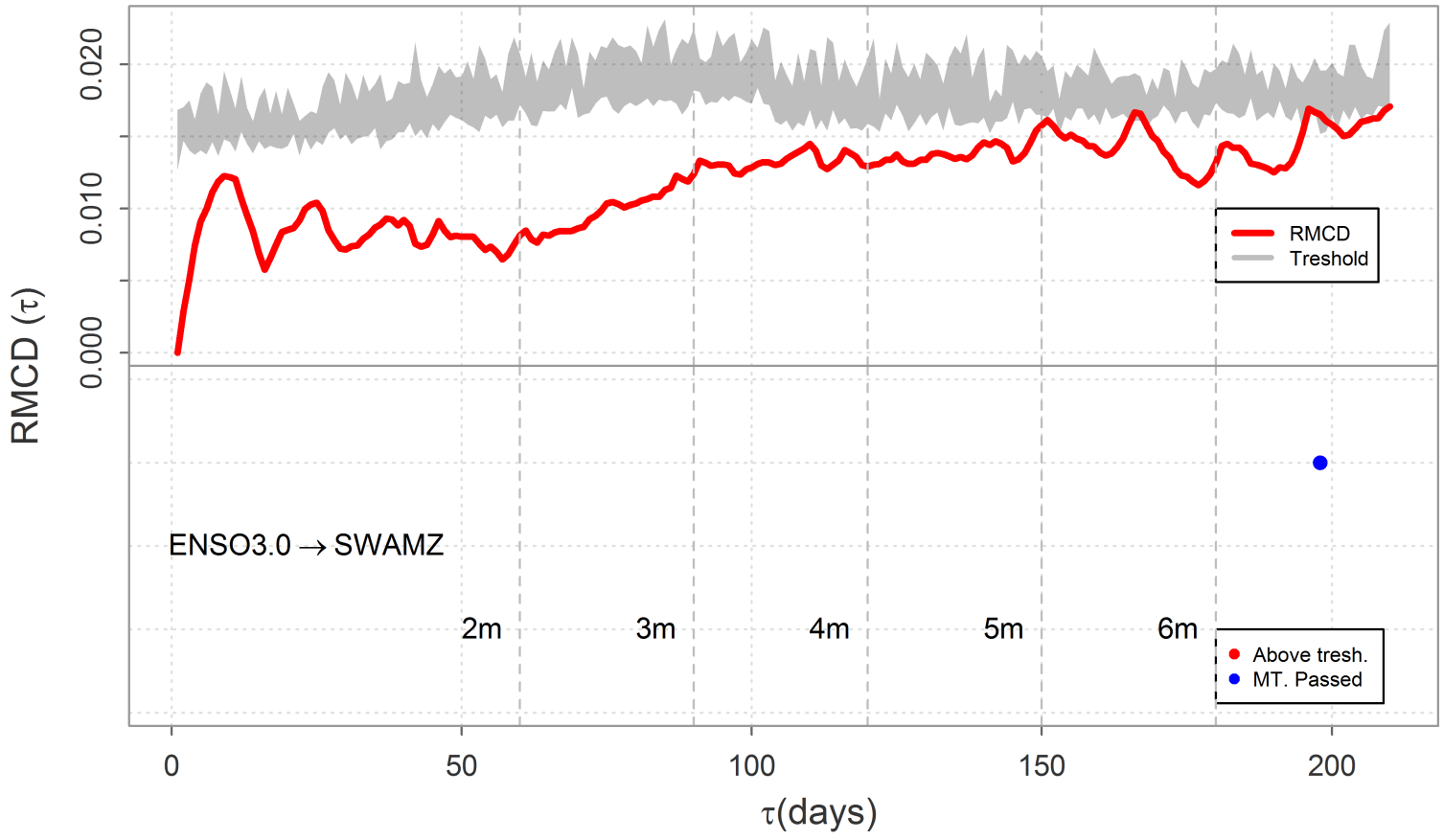
Extreme Events in Amazonia

How long does it takes for an anomalous temperature in the Ocean causes an anomaly in the precipitation of Amazon?

What are the differences between the droughts of 2005 and 2010 ?

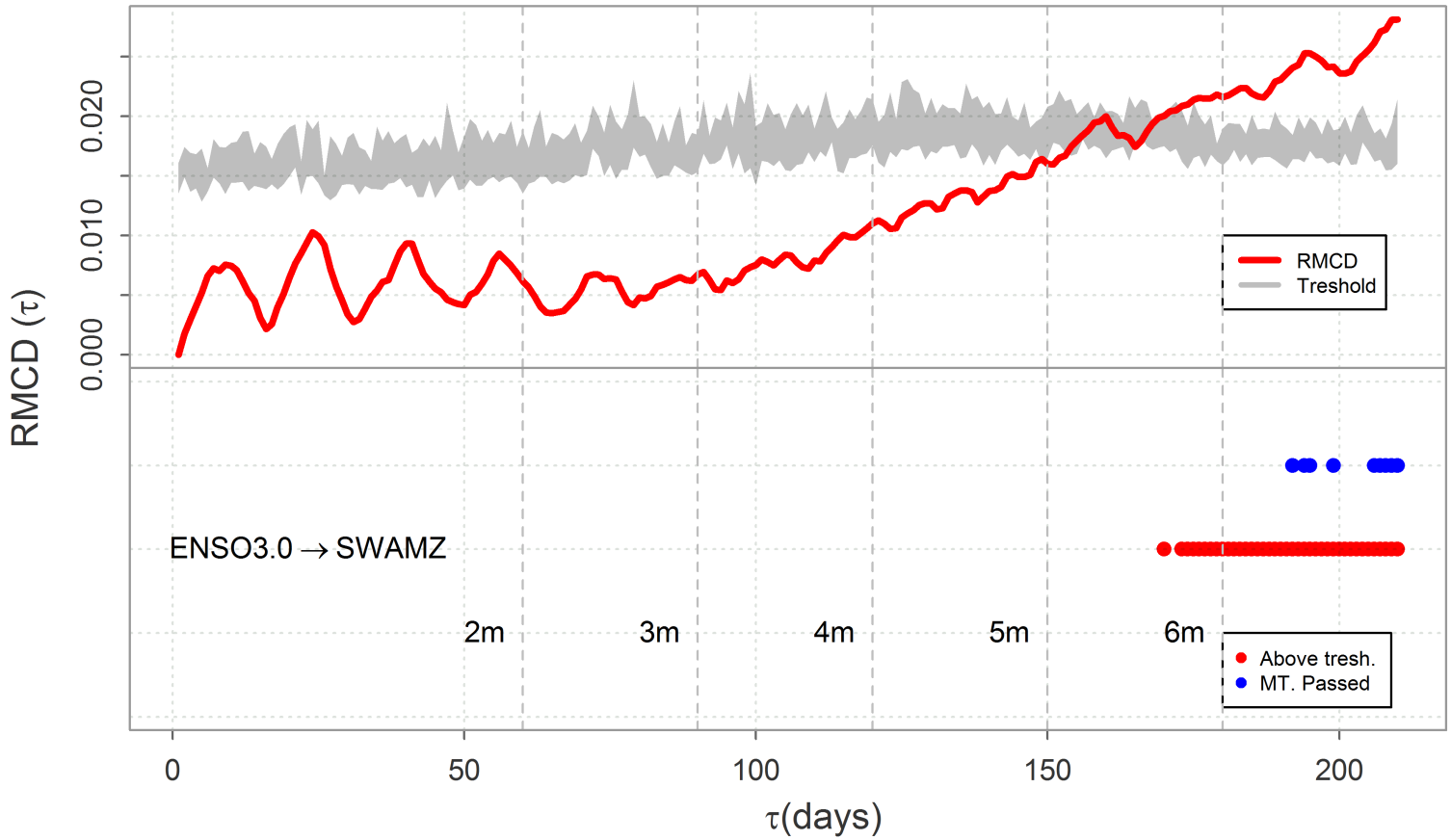
Real Data

Time lag influence of temperature anomaly of the Pacific Ocean (ENSO30) over the precipitation anomaly in the South Amazon during **2005**.



Real Data

Time lag influence of temperature anomaly of the Pacific Ocean (ENSO30) over the precipitation anomaly in the South Amazon during **2010**.



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