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Atmosphere-Land Bridge between the Pacific and Tropical North Atlantic SST's through the Amazon River basin during the 2005 and 2010 droughts

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The present work uses a new approach to causal inference between complex systems called the Recurrence Measure of Conditional Dependence (*RMCD*) based on the recurrence plots theory, in order to study the role of the Amazon River basin (AM) as a land-atmosphere bridge between the Niño 3.0 region in the Pacific Ocean and the Tropical North Atlantic. Two anomalous droughts in the Amazon River basin were selected, one mainly attributed to the warming of the Tropical North Atlantic (2005) and the other to a warm phase of El Niño–Southern Oscillation (2010). The results of the RMCD analysis evidence the distinctive behavior in the causal information transferred between the two oceanic regions during the two extreme droughts, suggesting that the land-atmosphere bridge operating over the AM is an active hydroclimate mechanism at interannual timescales, and that the *RMCD* analysis may be an ancillary resort to complement early warning systems. *Published by AIP Publishing.* https://doi.org/10.1063/1.5020502

The present work studies the role of the Amazon River basin (AM) as a land-atmosphere bridge between the Niño 3.0 region in the Pacific Ocean (PAC) and the Tropical North Atlantic (TNA). The analysis was carried using a new approach to causal inference between complex systems called the Recurrence Measure of Conditional Dependence (*RMCD*) based on the recurrence plots theory. Two anomalous droughts in AM were selected, one mainly attributed to the warming of the TNA (2005) and the other to a warm phase of El Niño–Southern Oscillation (ENSO) (2010). The results of the RMCD analysis evidence the distinctive behavior in the information transferred between the two oceanic regions during the two extreme droughts. During the 2005 drought there were indications of a strong connection between TNA and AM and not so with PAC, confirming the findings of previous studies. During 2010, the influence of PAC over AM was found to be significant for 5 to 7-month lags, and also the AM exerted a significant influence on the TNA, thus indicating that the proposed land-atmosphere bridge was active during the 2010 El Niño. The study also addresses the direct influence of tropical PAC over TNA during 2010 and found a significant causal relationship between the two oceans. *RMCD* proves to be remarkably consistent regarding the information transfer from the tropical PAC to the AM six major sub-basins, but also for the Andes and the low lying Amazonia, the influence being stronger between 5 and 7-month lags in 2010 and also the Andes receives the information transfer from PAC one month before Amazonia. During the 2005 drought, two results differ from the entire Amazon River basin: (i) there is a two-month temporal gap in the information transfer from the tropical Pacific to each one of the regions and (ii) the Andes receives the information transfer from PAC one month earlier than Amazonia. Presented results confirm that the land-atmosphere bridge operating over the AM is an active hydroclimate mechanism at interannual timescales, and the *RMCD* analysis may be an ancillary resort to complement early warning systems.

I. INTRODUCTION

The influence of ENSO events in the tropical Pacific on the global hydroclimatic variability is well documented.[1–3] Most regional and local impacts associated with ENSO are mediated by both direct influences and ocean-atmosphere teleconnections that drive continental, regional, and local hydroclimate processes and weather conditions, related to droughts (floods) in regions as far as the Yangtze basin or South Africa,[4–9] and changing patterns in winter (summer) temperatures in oceans such as the North and Tropical Atlantic, Caribbean, and Antarctic.[10–13] With respect to northern South America and the Amazon River basin (AM), diverse studies have linked ENSO with extreme hydroclimatic events.[14–34] Figure 1 shows the worldwide impacts of El Niño on rainfall and temperature during the DFJ and JJA seasons.

The connections between the tropical Pacific Ocean (PAC) and the Tropical North Atlantic (TNA) sea surface temperatures (SSTs) during ENSO have been a research topic for several decades, and there is evidence of Atlantic SST anomalies change during El Niño events. These alterations have been typically explained through a vertical stabilization of the tropical troposphere that may induce such feedbacks to a delay related to weaker trade winds and fluxes over the Atlantic due to an anomalous Walker circulation,[35,36] through an "atmospheric bridge"[37–39] and by a Gill-type response to the ENSO zonally compensated

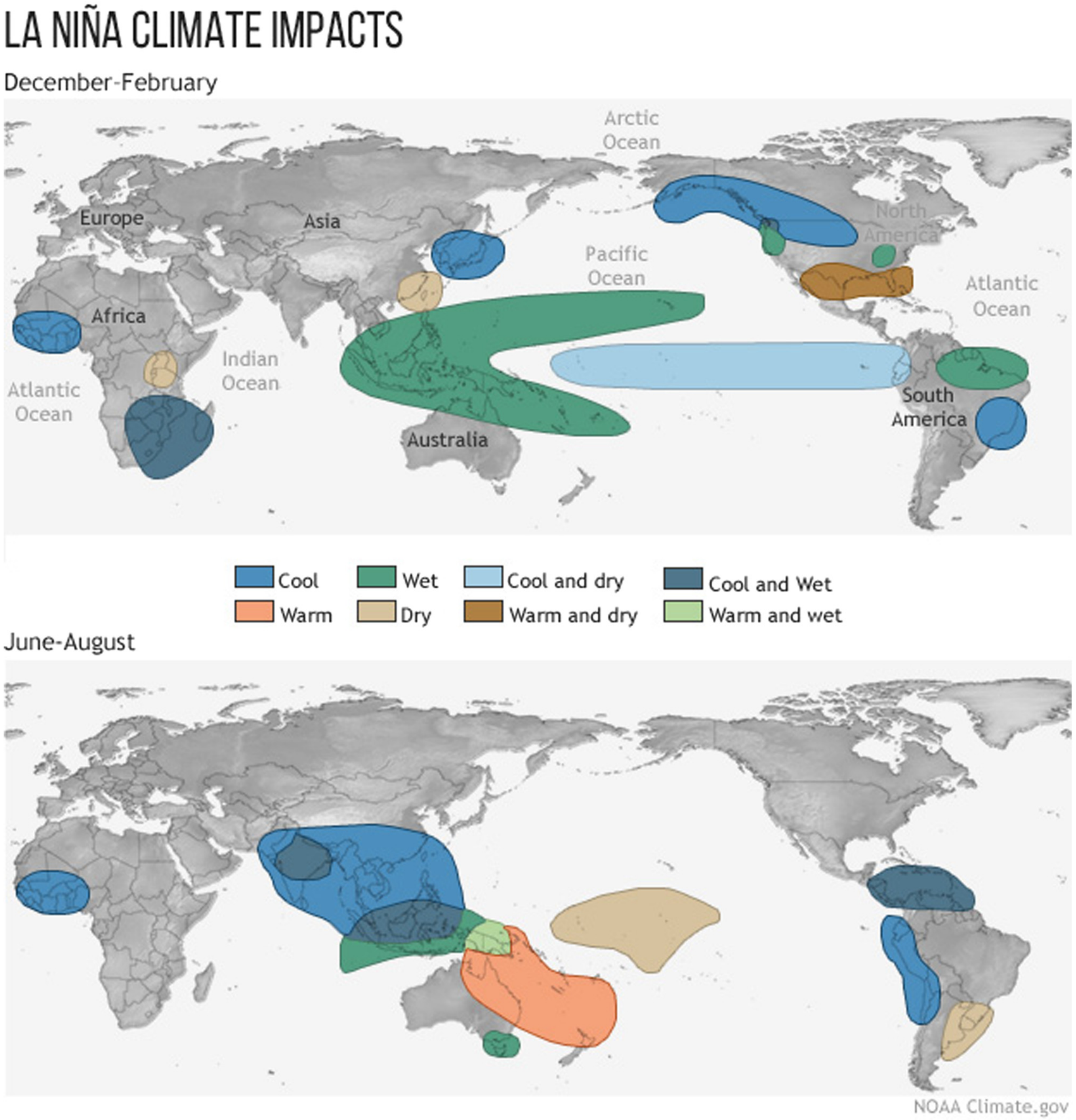

FIG. 1. Geographical locations where La Niña events may impact during the northern summer (DJF) and winter (JJA). Image Credit: NOAA Climate.gov, http://bit.ly/2hI8XLm.

heat source over the Amazon as proposed recently in Ref. 40.

The impacts of ENSO on the Amazon River basin are well documented, and are mainly related to the interannual anomalies in precipitation triggered by a displacement of the Walker circulation over South America, which may lead to droughts (floods) all over the basin.[16,23,26,27,29,41–44] The increase of anomalous extreme events that may be induced by climate change[22] could be related to a possible change in the Amazonian ecosystems and in the equilibrium state of the Amazon from forest to savannah.[45–52] At seasonal time scales, the main forcing mechanisms of the Amazon River basin hydroclimatology are the TNA, the Intertropical Convergence Zone (ITCZ), and the South Atlantic Convergence Zone (SACZ), influencing the availability of moisture, surface air temperatures, and extreme hydrological events.[14,27,53–61] The importance of the TNA on hydroclimatic processes over the Amazon River basin is well documented.[54,56,62–71]

On the other hand, owing to its size (more than 6.2×10^6 km^2), cross equatorial location, land-cover types, and hydroclimatic dynamics, the Amazon River basin has been considered as a green ocean and a hotspot of Earth's climate dynamics.[49,72] The strong role of soil moisture and evapotranspiration on precipitation recycling over the Amazon River basin has been known for decades,[73–77] and, therefore, the region's hydroclimatic dynamics plays a major role in the large-scale ocean-atmospheric phenomena. For instance, there is evidence that deforestation in Amazonia severely reduces rainfall in the lower U.S. Midwest during the spring and summer seasons and in the upper U.S. Midwest during the winter and spring.[78] Furthermore, land surface and hydro-climatic processes taking place in the Amazon River basin have been shown to affect the Tropical North Atlantic and Caribbean Sea SSTs.[79,80] Those studies found evidence that convection anomalies in the Amazon induce the displacement of the ITCZ and SSTs in the Caribbean. Ref. 79 showed evidence of the presence of coupled convective waves emerging from Amazonia and traveling over the TNA to the African coast.

The study of Poveda and Mesa[25] put forward and provided statistical evidence of the existence of a land-atmosphere bridge acting over northern tropical South America at interannual timescales (during El Niño) that connects SST anomalies over the Tropical Pacific and Tropical North Atlantic Oceans through a suite of physical mechanisms discussed and depicted in Ref. 27. More recently, Ref. 81 provided further evidence about the existence of such a land-atmosphere bridge mechanism over the Amazon River basin connecting the tropical Pacific and TNA at interannual timescales, and explains the functioning of a two-way feedback physical mechanism between the TNA SSTs and the Amazon River basin hydrology during El Niño events, and also during neutral years. The two-way interactions between the Amazon River basin and the Tropical North Atlantic are mainly driven by changes in the surface pressure difference between the two regions that may be induced by anomalies in land surface-atmospheric processes and convection in the Amazon.

The present work aims to further understand the dynamics of such land-atmospheric bridge linking the Tropical Pacific (PAC) and Tropical North Atlantic (TNA) oceans, with particular emphasis on the two “droughts of the century” that occurred in the Amazon River basin (AM) during 2005 and 2010.[82–87] To that end, we use tools from non-linear dynamical systems and information theory in the search for evidence about the transfer of information from PAC to TNA SSTs. Our study will investigate the linkages between both oceanic regions with and without considering the presence of the Amazon River basin (AM) to shed light about the role of the Amazon River basin hydrology in the land-atmosphere bridge mechanism. We investigate the influence of the Pacific Ocean in the main six sub-basins of the Amazon, namely, Madeira, Solimoes, Tapajos, Xingu, Purus, and Negro. We also study the Pacific influence in the Andes and in the low-lying portion of the Amazon River basin, hereafter denominated simply as Amazonia. Our study aims to provide further insights into the physical processes involved in the dynamics of the land-atmosphere bridge connecting two of the most important oceanic basins for the tropical climate.[88] Towards those ends, a novel approach from complex and non-linear dynamical systems called *Recurrence Measure of Conditional Dependence* (RMCD) was used in this study. The tool is based on the framework of recurrence and allows inferring causality among dynamic variables.[89]

The paper is organized as follows: Sec. II presents the methods and data used for the analysis, Sec. III shows the results and discussions dealing with the Pacific to Atlantic feedback and the Atlantic to Amazon feedback (Sec. III A), the information transfer from PAC to TNA through AM (Sec. III B), information transfer from TNA to AM (Sec. III C), direct information transfer from PAC to TNA, (Sec. III D), information transfer from PAC to the major AM sub-basins, and (Sec. III E) information transfer from PAC to the Andes and Amazonia regions. Finally, Sec. IV provides concluding remarks of the present study.

II. METHODS AND DATASETS

A. Recurrence measure of conditional dependence

Some dynamical systems, including climate, present a recurrent behavior in the phase space, which constitutes a fundamental property of the systems.[90] This property can be easily visualized by the so-called Recurrence Plot (*RP*).[91] In order to calculate an *RP* from a unidimensional time series, $X = \{x_i\colon i = 1, 2,\ldots, N\}$, it is necessary to reconstruct the m-dimensional phase space of the underlying system X. In the case of a single time series, the dynamics has to be artificially reconstructed using the time delay embedding technique,[92,93] whereby the phase trajectories $\vec{x}_i$are defined as

$$\vec{x}_i = [x_i + x_{i+\omega}, \ldots, x_{i+\omega(m-1)}], \quad \vec{x}_i \in R^m, \tag{1}$$

where m is the embedding dimension and ω is the time delay embedding. To determine the embedding dimension, m, the method of false neighbors[94] is used, and to determine the embedding delay, ω, the mutual information function procedure[95,96] is used. Once the parameters are set, the *RP* can be estimated as the pair-wise proximity test such that

$$R^X_{i,j} = \Theta(\varepsilon - \|\vec{x}_i - \vec{x}_j\|)i, \quad j = 1, \ldots N', \tag{2}$$

where $N' = N - (m-1)\omega$ is the number of phase space vectors, ϵ is the threshold defined for the proximity between the phase space vectors, $\|\vec{x}_i - \vec{x}_j\|$ is the spatial distance between vectors in phase space, and $\Theta(\ )$ is the Heaviside function: $(\Theta < 0\ ) = 0$, $(\Theta \geq 0\ ) = 1$. The plot of the R^X recurrence binary matrix provides the *RP* of X. The probability that one system recurs to a certain state $\vec{x}_i$ is equal to the column-average of the recurrence matrix:[97]

$$p(\vec{x}_i) = \frac{1}{N'} \sum_{j=1}^{N} R^X_{i,j}. \tag{3}$$

Joint recurrence plots (*JRP*) are used to study the possible influence between two physically different systems,[90,98] as they provide a measure of the simultaneous recurrence. The *JRP* matrix is defined as the Hadamard product of the *RP*s of systems X and Y:

$$JR^{X,Y}_{i,j} = \Theta(\varepsilon - \|\vec{x}_i - \vec{x}_j\|) \times \Theta(\varepsilon - \|\vec{y}_i - \vec{y}_j\|)i, \quad j = 1, \ldots N'. \tag{4}$$

The probability of finding a simultaneous recurrence at time i in both systems X and Y at time i is equal to the column-average of the JR^{XY} matrix:

$$p(\vec{x}_i, \vec{y}_i) = \frac{1}{N'} \sum_{j=1}^{N} JR^{X,Y}_{i,j}. \tag{5}$$

It is possible to calculate the conditional probability of the system X recurring conditioned to Y in a given time i such that

$$p(\vec{x}_i|\vec{y}_i) = p(\vec{x}_i, \vec{y}_i)/p(\vec{y}_i) = \left(\sum_{j=1}^{N} JR^{X,Y}_{i,j} \middle/ \sum_{j=1}^{N} JR^{Y}_{i,j} \right). \tag{6}$$

The concept of Transfer Entropy[99,100] is used to assess the recurrence relation between two variables by excluding the past self-influence of the driven variable and thus inferring causality. The extension in this concept using recurrence quantifiers is called *Recurrence Measure of Conditional Dependence* (RMCD).[89] It evaluates the recurrence between systems X and Y gave Z, so that

$$RMCD\ (X, Y|Z) = \frac{1}{N'} \left[p(\vec{x}_i, \vec{y}_i, \vec{z}_i) \log \left[\frac{p(\vec{x}_i, \vec{y}_i|\vec{z}_i)}{p(\vec{x}_i|\vec{z}_i).p(\vec{y}_i|\vec{z}_i)} \right] \right]. \tag{7}$$

With *RMCD* it is possible to quantify the causal dependence of system X on system Y based on the joint recurrence between the past of the driver system X^T and the present of the driven system Y, discarding the past contributions Y^T such that

$$RMCD\ (X^\tau, Y|Y^\tau) = \frac{1}{N'} \sum_{i=1}^{N} \left[\frac{1}{N'} \sum_{j=1}^{N} JR^{X^\tau, Y, Y^\tau}_{i,j} \right. \\ \left. \times \log \left(\frac{\sum_{j=1}^{N} JR^{X^\tau, Y, Y^\tau}_{i,j} \ \sum_{j=1}^{N} JR^{Y^\tau}_{i,j}}{\sum_{j=1}^{N} JR^{X^\tau, Y^\tau}_{i,j} \ \sum_{j=1}^{N} JR^{Y, Y^\tau}_{i,j}} \right) \right], \tag{8}$$

where τ represents the lag by which the system is shifted back in the past, and analogously to other recurrence based measures[101] *RMCD* is nonnegative, in particular, $RMCD = 0$ when $Y^T = X^T$ or $Y^T = Y$, or when X^T, Y, and Y^T are mutually independent.

B. Significance testing

For a finite hydro-climatic time series, we have to rely on a null hypothesis test to define the statistical significance of the *RMCD* measure in determining the possible causal relation between systems X and Y. The null hypothesis assumes that all trajectories in the embedding space are independent realizations of the system with different initial conditions. The statistical significance is tested then using a twin surrogate hypothesis,[102,103] which produces a number of surrogates or copies defined as N_{surr} with the same dynamical properties as the original sample, but with a different recurrence structure. The 99th percentile of the distribution of the surrogates *RMCD* values is defined as the confidence interval.

The *RMCD* value of the original set of time series is then compared with its respective confidence interval (threshold) at all lags τ. If the *RMCD* is higher than the confidence interval, we reject the null hypothesis, i.e., the variables are not independent with respect to the surrogate test with a significance of 0.01. Otherwise, the hypothesis is accepted, meaning that the variables are independent in the recurrence sense. Therefore, rejection of the null hypothesis for a particular lag τ indicates a possible causal interaction at the time scale τ. Finally, a multiple comparison analysis (M.C.A.) was carried out between all lags investigated using the Dunn-Sidák test.[104] The significance of comparison for the Dunn-Sidák test, $\alpha = 0.001$, yields a family-wise error rate around 0.03.

C. Data

Three main geographical regions shown in Fig. 2 were defined to study the role of the land-atmosphere bridge established over the Amazon River basin (AM) connecting PAC and TNA (Fig. 2). The regions are NIÑO 3.0 (90°W-150°W and 5°S-5°N), TNA (75°W to 10°W and 5°S to 29°N), and the Amazon River basin that comprises 146 sub-catchments as defined by the Observation Service SO-HYBAM (formerly Environmental Research Observatory ORE-HYBAM available at http://www.ore-hybam.org/). The six major sub-basins of the Amazon River were also added to the study: Madeira, Solimoes, Tapajos, Xingu, Purus, and Negro, as defined by ORE-HYBAM, as well the Andes and Amazonian regions of AM.

Daily precipitation data for the whole AM and its main sub-basins, and over the Andes-Amazonia regions, were obtained from the Tropical Rainfall Measuring Mission (TRMM) whose product 3B42 provides satellite measured precipitation corrected with rain gauge information.[105–107] Daily time series were averaged for the regions within the Amazon River basin, and daily anomalies were computed with respect to the climatology from 1998 to 2014. Daily SST data were obtained from the NOAA OI SST High-Resolution Dataset with a spatial resolution of 0.25° × 0.25° and spanning from 1985 to 2014.[108] The daily time series

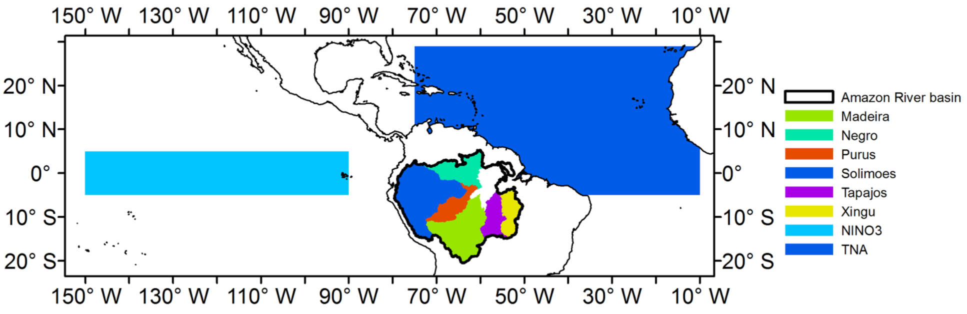

FIG. 2. Spatial domains of the regions involved in the present study.

were averaged over the NIÑO 3 and TNA regions. The SST anomalies were obtained removing the seasonal effect, in turn estimated from the climatology from 1982 to 2014. The daily river flows time series at *Obidos* (last river gauging station before the Amazon River delta) were obtained from SO-HYBAM and spans from 1968 to 2011. River flow anomalies were computed with respect to the 1968 to 2010 climatology. On all datasets, a 3-day filter is performed to time series in order to remove the synoptic effect present at daily time scales.

III. RESULTS AND DISCUSSION

To gain further insights into the role of the land-atmosphere bridge connecting the PAC and TNA regions through the Amazon River basin, the study is focused on two once-in-a-century droughts in the Amazon River basin that occurred within 5 years.[85] The first one was mainly driven by the Atlantic Ocean (2005), and the second one was related to an El Niño episode (2010).[44,85,86,109–111] Up to 210 day lags (7 months) were tested to evaluate the influence of SSTs on precipitation over land. The rationale behind the use of those two contrasting years is to evaluate with one experiment not only the possibility of a causal connection between both oceanic regions through the Amazon River basin but also the capability of the *RMCD* measure to pinpoint the differential influence over the Amazon River basin during the 2005 and 2010 droughts. For estimation purposes, the following embedding parameters were used: $m = 3$, $d = 15$, and ε is 20% the size of the phase space based on a criterion of maximizing the *RMCD* value as proposed and used in Refs. 89 and 112 to study the coupling between PAC and Southwest Amazonia.

This section is organized into four subsections presenting results and analyses about the transfer of information: (1) from the Tropical Pacific to the Amazon River basin to the Tropical North Atlantic (PAC → AM → TNA), and from the Tropical North Atlantic to the Amazon River basin (TNA → AM); (2) from PAC → TNA without the mediation of the Amazon land-atmosphere bridge; (3) from the PAC to the main sub-basins of AM; and (4) from the PAC to the Andes and Amazonia. Results will be presented with a schematic diagram illustrating the significance of the results. Figure 3 shows two panels with the results obtained through the *RMCD* analysis; the upper panel shows in red the time evolution of the *RMCD* values for each one of the lags (days), and in grey the confidence interval constructed with the surrogates. The bottom panel shows the results of the significance test, with red dots depicting the lags where the *RMCD* values cross the confidence interval (rejecting the null hypothesis, thus denoting transfer of information and a causal relationship), and blue dots representing the significant lags according to the Dunn-Sidák M.C.A. test. The example in Fig. 3 shows the information transfer from PAC to AM according to the *RMCD* analysis for the 2010 drought; red dots denote the lags of significant information transfer, that for this particular example represents 55 out of 210 lags analyzed (26%), and blue dots denote the lags with significant information transfer for which the M.C.A. test indicate a positive result, 17 out of those 55 lags (30%). For the sake of simplicity, the results section will be presented only with the panel showing the significant results (Fig. 3, bottom).

A. Information Transfer from the Pacific Ocean to the Tropical North Atlantic through the Amazon River basin (PAC → AM → TNA)

This section investigates the role of the Amazon River basin as a land-atmosphere bridge in connecting the PAC and TNA during the 2005 and 2010 droughts. We study separately the pathways between PAC and AM, and between AM and TNA [Fig. 4(a)]. In Fig. 4(b), we show results of the *RMCD* analysis regarding the information transfer from PAC to AM during 2005 and 2010. During 2005 there is significant information transfer from PAC to AM between 30 and 40 day-lags (1 to 2-months), and from 150 to 210 day-lags (5 to 7-months), although the significant *RMCD* behave intermittently [Fig 4(b), top], during 12% of the lags. During the 2010 drought, the influence of PAC over AM is more intense and almost steady from 150 to 210 day-lags (5 to 7-months) [Fig 4(b), bottom], with crossings at 26% of the lags. The information transfer from PAC to AM in 2010 is not only more intense but also more consistent, as it gets through both the confidence interval crossing and the M.C.A., as evidenced in Fig. 4(b) (bottom panel) by a larger number of blue dots.

Results of the M.C.A. test show that 30% of the crossings pass both tests. Accordingly, during both 2005 and 2010 droughts there is information transfer from PAC SSTs to AM precipitation, the influence being stronger during the occurrence of the 2010 El Niño event, with a 5 to 7-months lag. The

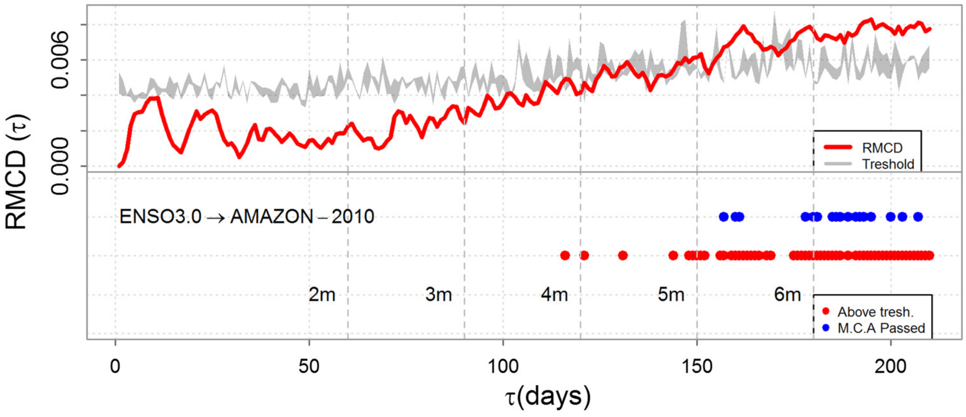

FIG. 3. Results obtained with the *RMCD* analysis for the information transfer from tropical Pacific (PAC) to the Amazon River basin (AM). The upper panel shows the *RMCD* values (red) and the confidence interval (grey). Red dots in the bottom panel denote those lags for which the *RMCD* values cross the uncertainty threshold, for the relation between the Pacific Ocean SST anomalies and rainfall anomalies over the Amazon River basin during 2010, thus rejecting the null hypothesis, thus denoting a significant transfer of information or causality. Blue dots represent the lags with a significant value of the M.C.A. test.

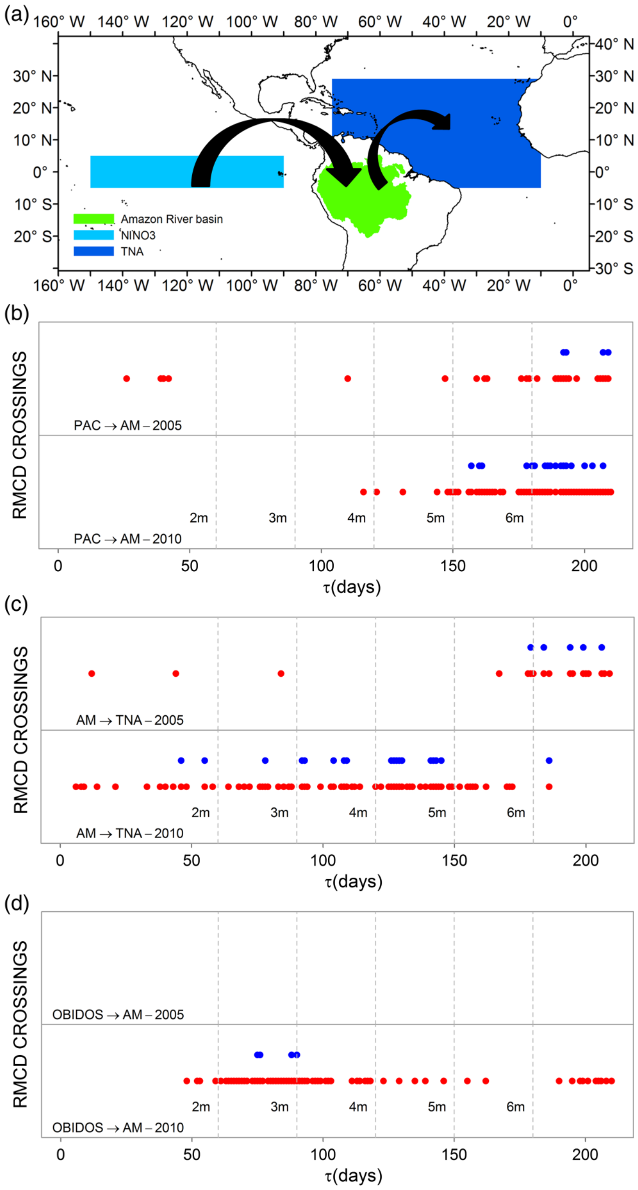

FIG. 4. Results about information transfer: (a) the schematic diagram of the PAC-AM-TNA influence or the Pacific Ocean to Tropical North Atlantic feedback mediated by the Amazon River basin. (b) Results of the *RMCD* crossings as a function of lag (days) between the Pacific Ocean SST anomalies and rainfall anomalies over the Amazon River basin during 2005 (top) and 2010 (bottom). (c) Similar to (b) for the influence between the Amazon River basin precipitation and the Tropical North Atlantic, during 2005 (top) and 2010 (bottom). (d) Similar to (b) for the influence between the Amazon River basin river flows and the Tropical North Atlantic, during 2005 (top) and 2010 (bottom). Red dots depict the crossing of the confidence interval constructed for the *RMCD* values and blue dots denote significant lags according to the M.C.A. test.

timing of the influence from PAC to AM is in concordance with the well-known dynamics of El Niño, which starts in MAM and reaches its maximum extent and anomalies 5 to 7 months later in DJF, and also with the timing of the influence of the particular 2010 event on AM.[44,87]

Figure 4(c) shows the results of the *RMCD* analysis for the information transfer from AM precipitation to TNA in 2005 and 2010. For 2005 [Fig 4(c), top], there are some individual crossings during the first month's lags, and significant crossings from 180 to 210 day-lags (6 to 7 months), that might be related to the response of PAC to AM perturbations starting at 150 day-lags (5 month lag [Fig. 4(b), top], and a propagation towards the TNA [Fig 4(c), top], although the confidence bands are crossed only at 8% of the lags. The panorama is quite different during the 2010 drought, which is a strong indication of AM feedback over the TNA that spans from 5 to 180 day-lags (0 to 6 months), covering 30% of lags, and being more significant between 120 and 150 days (4 to 5 months), according to the M.C.A. test [Fig 4(c), bottom].

Figure 4(d) shows the results of the *RMCD* analysis for the information transfer from AM river flows to TNA SSTs in 2005 and 2010. The rationale behind the use of river flows is that this variable acts as a physical and mathematical filter of the high frequency variability inherent to rainfall, and, therefore, it summarizes all land-surface processes taking place within river basins. As a matter of fact, the land-atmosphere bridge theory that links PAC and TNA at interannual timescales was put forward by *Poveda and Mesa*[25] using Andean river flows. For 2005, there is no information transfer from AM river flows to TNA [Fig. 4(d), top], given the lack of *RMCD* crossings or positive results from any of the significance tests, whereas in the case of the 2010 drought the crossings of the confidence interval represent 30% of the lags and the information transfer is strong from 60 to 120 day-lags (2 to 4 month-lags), and have some intermittency in between 200 and 210 day-lags (the 7 month-lag) [Fig. 4(b), bottom].

These previous results indicate that during the 2010 El Niño event, AM was more active in transferring information to the TNA. As for the 2010 drought, the influence of AM over TNA tends to be strengthened through an increase of air temperature in AM induced by the displacement of the Walker circulation in association with El Niño in PAC, and also activating diverse processes involved in the feedback mechanism recently proposed in Ref. 81, whereby changes in convection in the AM may induce the warming of the TNA SSTs due to changes in the surface atmospheric pressure gradient, which in turn disrupts the patterns of moisture advection to the AM basin.

B. Information Transfer from the Tropical North Atlantic to the Amazon River basin (TNA → AM)

Figure 5 shows the results of information transfer from the Tropical North Atlantic (TNA) to the Amazon River basin rainfall (AM) (panel a). For 2005 and 2010, the *RMCD* reveals that the influence of TNA in AM has started in early June and lasted until late November of the previous year, respectively. Results regarding the crossing of the threshold are from 40 to 210-day lags (2 to 7-month lags) [Fig. 5(b), red dots in top and bottom panels]. These results agree with the well-known fact that the TNA is of utmost importance to influence the AM hydroclimatic regime.[54,56–58,69–71,113] During the 2005 drought more indications of significance are observed than during 2010 along the studied lags, with less scattered red dots and crossings of the confidence interval covering 28% of the lags [Fig. 5(b), top], while those found in 2010 only cover 16% of the lags, which means that the TNA → AM feedback was much stronger in 2005. The drought of 2005 has been attributed mainly to an anomalous warming of

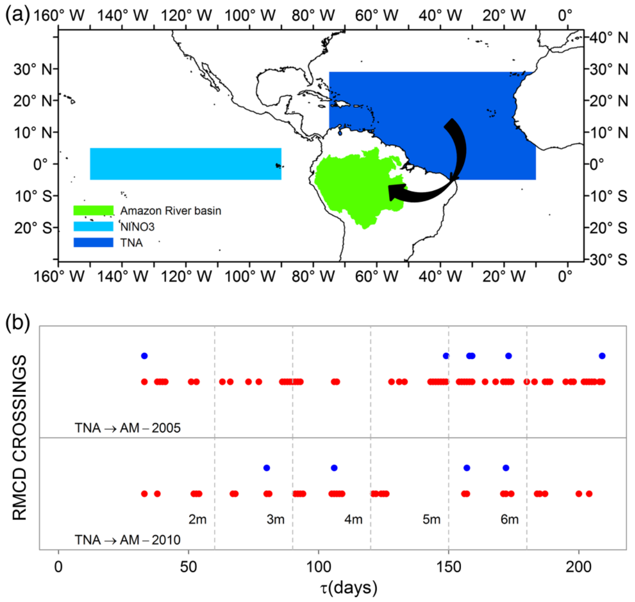

FIG. 5. Results about information transfer: (a) the schematic diagram of the TNA-AM influence. (b) Results of the *RMCD* crossings as a function of lag (days) between the TNA SST anomalies and rainfall anomalies over the Amazon River basin during 2005 (top) and 2010 (bottom). Red dots depict the crossing of the confidence interval constructed for the *RMCD* values and blue dots denote significant lags according to the M.C.A. test.

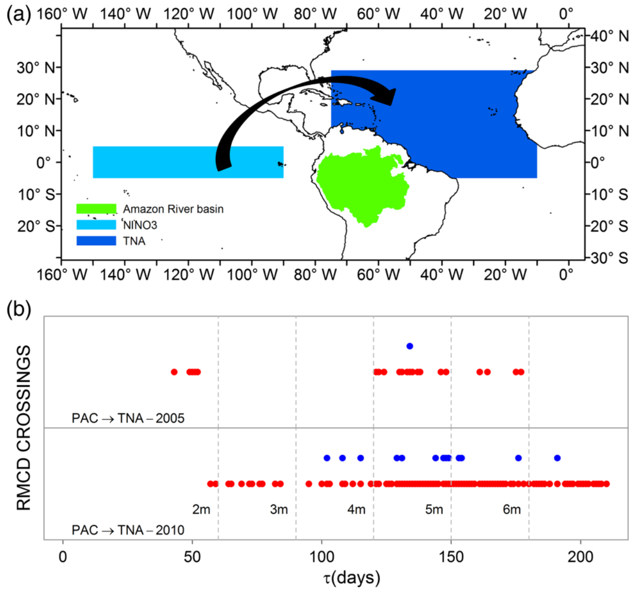

FIG. 6. Results about information transfer: (a) the schematic diagram of the PAC-TNA influence. (b) Results of the *RMCD* crossings as a function of lag (days) between the PAC SST anomalies and TNA SST anomalies during 2005 (top) and 2010 (bottom). Red dots depict the crossing of the confidence interval constructed for the *RMCD* values and blue dots denote significant lags according to the M.C.A. test.

the TNA,[22,86,109] and our results confirm more information transfer during the 2005 drought than the 2010 one which has been attributed mainly to PAC, thus supporting the TNA origin of the 2005 AM drought.

C. Information Transfer from the Tropical Pacific the Tropical North Atlantic without mediation of the Amazon River basin (PAC → TNA)

In order to test the transfer of information from PAC to TNA without including the proposed land-atmosphere bridge acting on the Amazon River basin, the *RMCD* analysis was carried out between the SSTs time series on both oceanic regions, as shown in Fig. 6. When AM is removed, more active influence of the PAC over the TNA in 2010 (44% of lags) is observed than in 2005 (10% of lags), although there is evidence of information transfer during both years. In 2010, the signal starts to be significant from 60 to 210-day lags (2 to 7-months lags) [Fig. 6(b), bottom], while for 2005 the signal is intermittent between 120 and 180-day lags (4 to 6-month lags) [Fig. 6(b), up]. According to the M.C.A. test, there is more confidence in 2010 than in 2005 about the influence of PAC on TNA.

Up to this point, the results support the role of the land-atmosphere bridge acting on the Amazon River basin to enhance the influence of the tropical Pacific over the Tropical North Atlantic. Diverse studies have suggested an atmospheric pathway from PAC to TNA[37–40] at play during El Niño events [Fig. 5(a)]. For ENSO neutral years such as 2005, there is evidence of an influence from the Pacific Ocean to the Atlantic Ocean and South American climate,[114,115] although it is not so easy to estimate and disentangle the Pacific's from other influences as the one from the Indian Ocean. ENSO events force the TNA SSTs via the weakening of the northeasterly trade winds as a result of the vertical stabilization of the tropical atmosphere related to a tropic-wide warming.[35,116] A recent study has found evidence of an indirect path through the continent due to the influence that the AM has over the TNA, thus supporting the existence of the land-atmosphere bridge and also the presence of an AM → TNA physical mechanism[81] during El Niño.

The results presented until this point indicate that both processes have a significant influence on TNA's interannual dynamics (crossings of the confidence interval and the M.C.A. test): the direct atmospheric pathway from PAC → TNA, and the indirect PAC → AM → TNA mediated by the Amazon River basin surface processes (precipitation and river flows).

D. Information Transfer from the Tropical Pacific to Major Amazon River Sub-Basins

This section quantifies the transfer of information from PAC to the major sub-basins of the Amazon River basin. It is well-known that different sub-basins exhibit distinctive hydrological patterns depending on their location, land cover, and land use change (deforestation). There are well-known north-south hydrological differences in the Amazon River basin,[117–119] as well in the behavior of the droughts and lengths of dry periods depending on location in the AM region.[55,120–122] In order to understand the way in which PAC may affect the major sub-basins of the AM, the *RMCD* was computed between the PAC SSTs and precipitation in the six major AM sub-basins: Madeira, Solimoes, Tapajos, Xingu, Purus, and Negro, whose results are presented in Fig. 7.

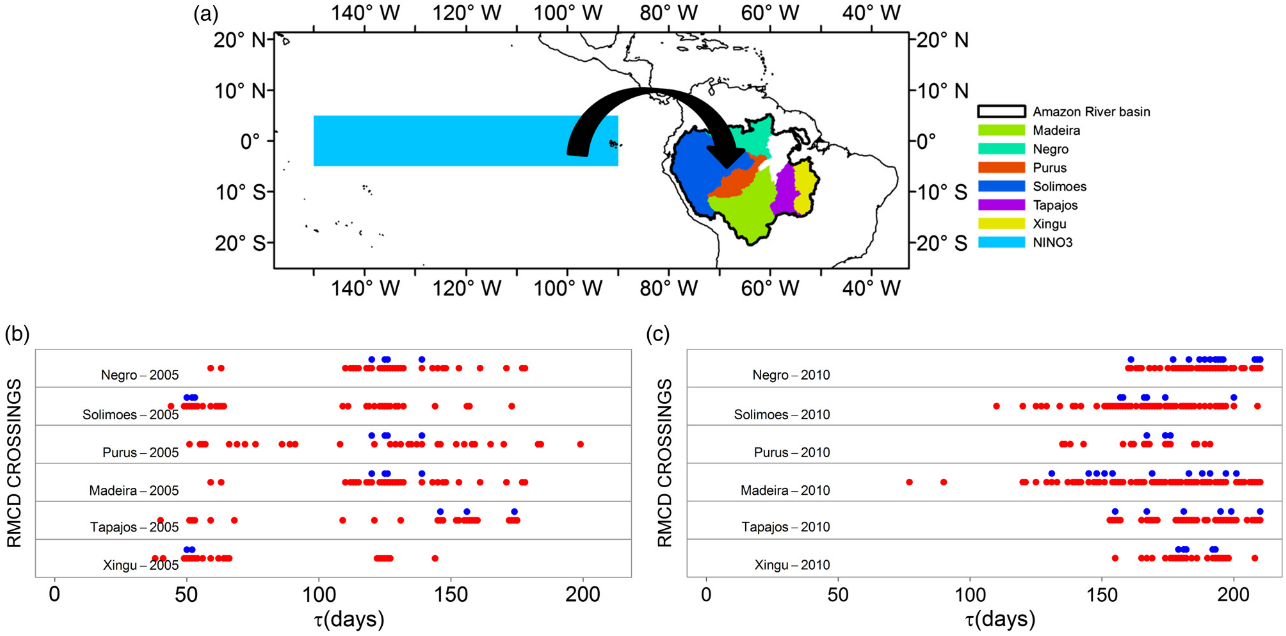

FIG. 7. Results about information transfer: (a) the schematic diagram of the PAC-six major sub-basins in the Amazon River basin influence. Results of the *RMCD* crossings as a function of lag (days) between the PAC SST anomalies and rainfall anomalies over the six major amazon sub-basins during 2005 (b) and 2010 (c). Red dots depict the crossing of the confidence interval constructed for the *RMCD* values, and blue dots denote significant lags according to the M.C.A. test.

Figure 7(b) shows the *RMCD* analysis for the transfer of information from PAC to each one of the sub-basins in 2005. Results show that the Xingu River basin receives a significant influence from PAC (10% of the crossings) at 40 and 60 day-lags (2 and 3-month lags) [Fig. 7(b), sixth row]. The Tapajos River basin [Fig. 7(b) fifth row] had an early influence of PAC in 2005 (11% of the lags) like the one found for Xingu, but it lasted almost up to 180-day lags (month 6th). The Madeira River basin (Fig. 7, fourth row) had a strong signal of influence between 110 and 180-days lags (4 and 6-month lags) for 2005 (14% of the lags). The influence in the Purus River basin [Fig. 7(b), third row] in 2005 started around the previous 210 days (7-month lag) and continued until 50 days (2-month lag) before the period of interest (15% of the lags). The Solimoes River basin [Fig. 7(b), second row] received a strong influence from PAC around 40 and 60 day lags (2 and 3-month lags), and later on from 110 to 180-day lags (4 to 6-month lags) (14% of the lags). For the Negro River basin [Fig. 7(b), first row], the influence of PAC is found from 120 to 180-day lags (4 to 6-month lags) (15% of the lags).

Figure 7(c) shows the results of the *RMCD* analysis for the transfer of information from PAC to each one of the major AM sub-basins in 2010. A remarkable consistency of the influence of PAC on all sub-basins is observed throughout the lags for 2010. For instance, the Xingu, Tapajos, Madeira, and Negro river basins receive the influence from 150 to 210-day lags (5 to 7 months-lags) (with 11%, 17%, 29%, and 15% of lags, respectively). The influence on the Solimoes River basin also starts earlier than in other sub-basins from 110 to 210-day lags (4 to 7-month lags) (24% of the lags). Finally, the Purus River basin receives a lagged influence from 140 to 180-day lags (4 to 6-month lags) (8% of lags). The early signals of coupling during 2010 and the percentage of crossings of the confidence interval in that same event in the Madeira River basin are consistent with previous studies showing that the 2010 drought was especially strong over southwestern AM.[87,120]

These results of the *RMCD* allow us to conclude that during the 2010 El Niño event, the influence of PAC on the major Amazon sub-basins was stronger from 5 to 7-month lags, regardless of the location of the sub-basin. This finding is in tune with the timing of ENSO dynamics and with our previous results presented in Sec. III A. Also, PAC had an influence on the major sub-basins during the 2005 drought, though with a different timing that cannot be generalized for all the basins as it was found for 2010. The particular drought of 2005 shows a distinctive feature reflected in a temporal gap in the PAC influence from the end of month 2 that lasted almost one month, perfectly visible for 5 of the 6 sub basins [Fig. 7(b)]. The way and the timing in which PAC transfer information on to each of the major sub-basins of the Amazon River are mediated not only by location and land cover but also by the influence on the Walker circulation and by the teleconnections from PAC to South America via wave trains.[123,124]

Regarding the information transfer from PAC to TNA, one interesting feature about the *RMCD* results for the 2010 drought is the increasing pattern in the *RMCD* values that starts around the 150th day lag [Fig. 6(b), red dots]. On the same token, Fig. 8 shows the *RMCD* values in the 2010 event up to 210-day lags (7 months) for the six major AM sub-basins. For all sub-basins, the values of *RMCD* start to cross the confidence interval around the 150-day lag, and for 5 of them (Xingu, Purus, Solimoes, Tapajos, and Negro) the increasing trend starts around the 100-day lag, while for Madeira the trend starts around the 10-day lag. Another characteristic of the metric values is that after reaching the point

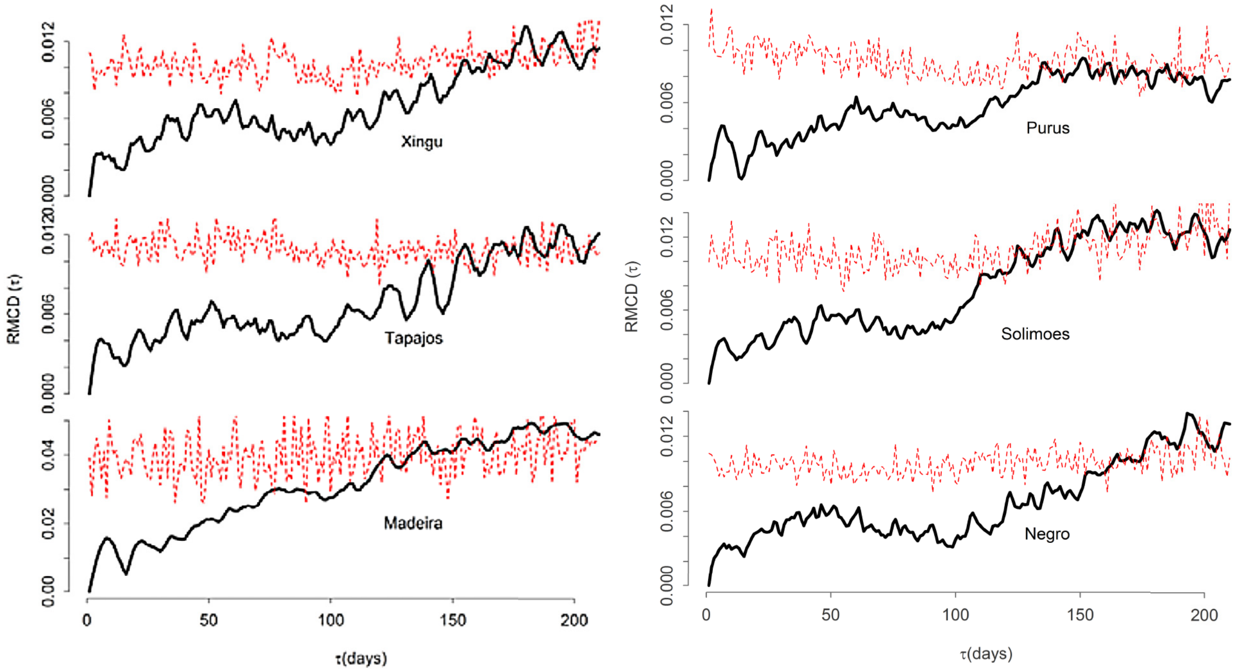

FIG. 8. RMCD values during the 2010 drought from 0 to 210-day lags (black line), and confidence interval (red dashed line); regarding the information transfer from PAC to the major AM sub-basins. Crossings of the confidence interval are evident around the 150th month-lag.

where the confidence interval is crossed, the metric tapers off (with no trend). Such increasing trends before reaching the confidence level in the *RMCD* values for the 2010 event suggest the need for further investigating the behavior of the measure in other ENSO events. Such results may be pretty valuable in order to propose *RMCD* as a robust early warning system ancillary measure in the Amazon River basin.

E. Information Transfer from the Tropical Pacific to the Andes and Amazonia regions

This section investigates the information transfer from PAC to the Andes, defined as the portion of the Amazon River basin that comprises regions located above 500 m a.s.l., and from PAC to the low-lying Amazonia, whose results are

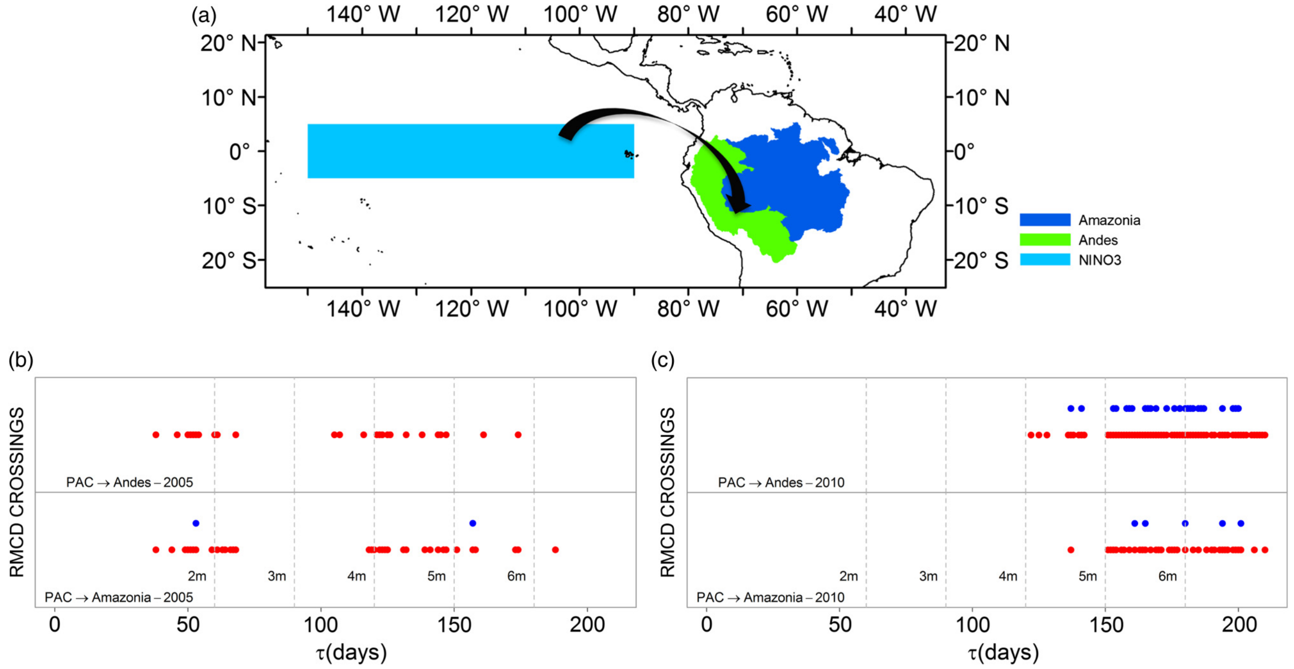

FIG. 9. Results about information transfer: (a) the schematic diagram of the PAC-Andes and Amazon influence. Results of the *RMCD* crossings as a function of lag (days) between the PAC SST anomalies and rainfall anomalies over Andes and Amazonia during 2005 (b) and 2010 (c). Red dots depict the crossing of the confidence interval constructed for the *RMCD* values and blue dots denote significant lags according to the M.C.A. test.

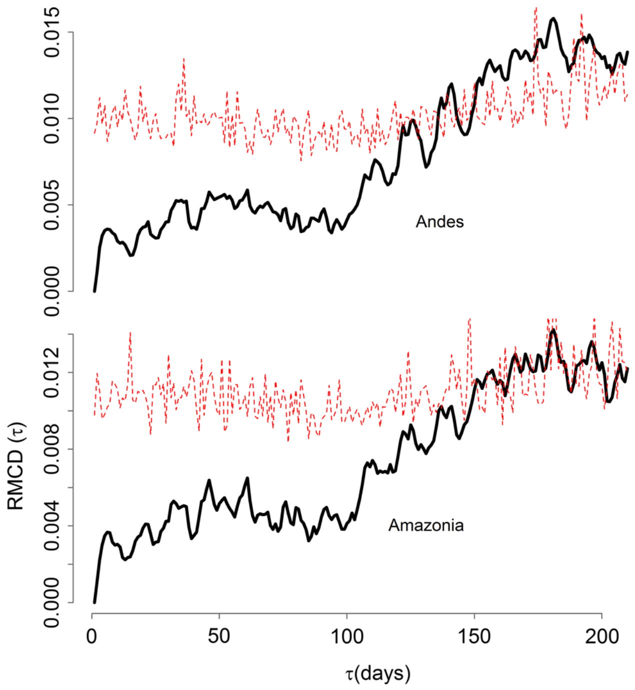

FIG. 10. Same as Fig. 8 for the information transfer from the Pacific Ocean to the Andes and Amazonia regions.

shown in Fig. 9. During the 2005 drought [Fig. 9(b)], the influence of PAC on both regions has a distinctive timing in the second month and a second strong influence during the fourth and fifth months. This temporal gap in the influence of PAC in 2005 is similar to the one found in the PAC to sub-basins analysis (Sec. III C). The second period of influence starts earlier in the Andes, and it may be explained in terms of the geographical proximity of Andes to the Pacific Ocean. The influence found in 2005 covers 16% of the lags for Amazonia and 12% of the lags for the Andes.

On the other hand, during the 2010 drought [Fig. 9(b)] the influence of PAC shows up after the fourth month and more significantly from 5 to 7-month lags. The signal of significant information transfer over the Andes reaches up to 30% of the lags (40% of which passes also the M.C.A. test); while for Amazonia it represents 17% of the lags. During the 2010 drought, PAC exerts a larger influence on the Andes, and the information transfer starts almost one month earlier than in Amazonia, such as in the 2005 drought. The Andes may represent only 13% of the total AM basin, but the region is the most important source of surface water (runoff), nutrients, and sediments to the whole basin.[27,125,126] Our results indicate that the Andes receives stronger influences from El Niño (30% of lags have a significant signal) starting one month earlier than that in the low lying Amazonia. The cascading of the ENSO influence on both regions has been already reported and analyzed as one of the most distinctive features of the 2010 drought.[83] As it was found for the PAC to sub-basins analysis, there are increasing trends in the *RMCD* values for the information transfer from PAC to Andes and to Amazonia regions, that taper off around the 150th day lag (Fig. 10).

IV. SUMMARY AND CONCLUSIONS

Using a novel approach to quantify nonlinear causality between hydro-climatic systems, the present work has provided further support for the existence of a land-atmosphere bridge connecting the Tropical Pacific and the Tropical North Atlantic, and disentangled different aspects of the role that the Amazon River basin plays in such a bridge during the two extreme droughts of 2005 and 2010. The identified land-atmosphere bridge mechanism is captured with the causal analysis when using two different hydrological processes in the Amazon River basin (precipitation and river flows). Our results confirm the presence of information transfer from the AM basin to the TNA, which is intensified by the impact of the El Niño event of 2010 in the hydrological regime of the Amazon River basin.

The results show the complex interaction between the two oceanic regions and the Amazon River basin. This interaction was found to be significantly active during the 2010 El Niño event, whereas in 2005 it was intermittent and was significant only through the influence of AM precipitation. Our results also show an active transfer of information from the Amazon River basin to the Tropical North Atlantic, which confirms the Amazon hydrology feedback on the Tropical North Atlantic climate variability. The causal measure proved to be a suitable tool to disentangle the importance of PAC and TNA in the 2005 and 2010 historical droughts of the Amazon River basin. Our results are in agreement with previous studies that pointed out TNA as a major influence in the 2005 drought and PAC in the 2010 one.

The information transfer from the Tropical Pacific to the major AM sub-basins and from Andes to Amazonia regions was also analyzed. Results show that the information transfer from PAC to these regions is present in both study periods, and exhibits different timings for the 2005 drought event. With regards to the 2010 drought, the pattern of coupling between PAC and the regions inside the Amazon is characterized by a higher significance, given by an increase in crossings of the confidence interval and positive values of the M.C.A. test, starting around the 150-day lag (5 months). This consistent signal during an El Niño event shows the classical timing of El Niño events reaching their peak 5 to 7 months after the beginning of the anomalous warming of the Pacific.

Our results denote increasing trends in the *RMCD* values in the presence of a strong climate forcing as El Niño. These kinds of patterns may suggest a further use of the causality measure to develop or to test early warning systems for extreme ENSO events. An early signal of information transfer between PAC and Andes may be useful for the communities that rely on water supply from the high lands of the AM River basin or that are prone to floods.

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