Long-term relationships between climate oscillation and basin-scale hydrological variability during rainy season in eastern Northeast Brazil

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ABSTRACT
The high variability in the hydrological regime of the Eastern Hydrological Region (EHR) of Northeast Brazil often results in floods and droughts, leading to serious socio-economic issues. Therefore, this work aimed to investigate connections between spatiotemporal hydrological variability of the EHR and large-scale climate phenomena. Multivariate statistical techniques were applied to relate climate indices with hydrological variables within two representative river basins in the EHR. The results indicated a multi-annual relationship between the state of the sea surface temperature of the Atlantic and Pacific oceans and anomalous hydrological variability in the basins. In addition, the northern Tropical Atlantic conditions were shown to play an important role in modulating the long-term variability of the hydrological response of the basins, whilst only extreme ENSO anomalies seemed to affect the rainy season. This knowledge is an important step towards long-term prediction of hydrological conditions and contributes to the improvement of water resources planning and management in the EHR.

1 Introduction

Variability in climate conditions can lead to significant worldwide impacts on the hydrological regime, increasing the chances of extreme events such as floods or droughts (Labat 2010, Massei and Fournier 2012, Räsänen and Kummu 2013) causing damage to human activities and, consequently, economic losses. Therefore, efforts have been developed to identify the role of the large-scale atmospheric and oceanic circulations in the dynamics of hydrological variability in both the short and long term, as well as the relationship between hydrological anomalies and large-scale climate variability (Uvo 2003, Andreoli and Kayano 2005, Massei and Fournier 2012, Räsänen and Kummu 2013, Grimm and Saboia 2015, Tedeschi et al. 2016, Berton et al. 2017). The understanding of such relationship provides a major step towards predicting hydrological conditions weeks or months ahead. These predictions, even with relatively large uncertainties, may help to improve the strategic view, mitigate unwanted impacts and benefit from favourable conditions (Paz et al. 2011), by avoiding prescribing a near-pessimist long-term scenario as usually done in agriculture (Jones et al. 2000, Hansen 2002).

The region of Northeast Brazil (NEB) has been strongly affected by severe droughts, e.g. the recent drought between 2012 and 2015 described by Campos (2015), Cunha et al. (2015) and Marengo et al. (2017), or extreme flooding, e.g. the catastrophic flood of 2010, as mentioned by Kouadio et al. (2012), Hounou-Gbo et al. (2015) and Monte et al. (2016). It is well reported that NEB exhibits large inter-annual variability of precipitation and experiences a high intensity of hydrological extreme events (Uvo et al. 1998, Giannini et al. 2004). Moreover, NEB has different rainfall regimes with a variable and irregular spatio-temporal distribution of precipitation. Total annual precipitation may vary from less than 600 mm in the semi-arid part of NEB to up to 1600 mm along the coastal zones (Rao et al. 1993, Uvo et al. 1998, Amorim et al. 2014, Cunha et al. 2015).

In general, the rainfall regimes present precipitation concentrated in a few months a year (see Fig.1(a)). In northern Northeast Brazil (NNEB), the rainy season is mainly associated with the southward displacement of the Inter-tropical Convergence Zone (ITCZ), from March to May (Uvo et al. 1998, Grimm 2011, Amorim et al. 2014). In eastern Northeast Brazil...
(ENEB), the rainy season is concentrated in May–July and is closely related to anomalies of sea-surface temperature (SST) in the southern Tropical Atlantic Ocean, with maximum rainfall events and consequently flood episodes influenced by easterly wave disturbance (Amorim et al. 2014, Cunha et al. 2015, Gomes et al. 2015). In southern Northeast Brazil (SNEB), the rainy season is influenced mostly by cold fronts, from December to February (Kouadio et al. 2012, Gomes et al. 2015).

The understanding of integrated ocean–atmospheric conditions and their linkages with climate variability and impacts on precipitation over NEB has been the focus of many studies. For instance, anomalies during the rainy season (i.e. dry or rainy years) over NNEB have been associated with anomalous patterns of SST in the Tropical Atlantic Ocean and variations of the ITCZ displacement (Nobre and Shukla 1996, Uvo et al. 1998, Andreoli and Kayano 2004, 2006, Giannini et al. 2004). The SST state of the Tropical Pacific, related to the El Niño Southern Oscillation (ENSO), can influence the inter-annual variability of the precipitation over NNEB by acting in conjunction with the SST over the Tropical Atlantic, enhancing or damping the total amount of precipitation during the rainy season (Kane 1997, Saravanan and Chang 2000, Giannini et al. 2004, Lucena et al. 2011, Tedeschi et al. 2016).

Many studies have been carried out to address the dynamics of the inter-annual variability of precipitation over NEB, however, most of them focused on NNEB due to its vulnerability in the face of drought events (Krol et al. 2006, Campos 2015, Cunha et al. 2015). Efforts to understand the inter-annual variability of precipitation over ENEB have highlighted that the rainy season in ENEB is affected mainly by anomalous SST in the Tropical Atlantic (Rao et al. 1993, Kouadio et al. 2012, Amorim et al. 2014). Rao et al. (1993) also proposed that the South Atlantic Subtropical High plays a role in the rainfall variability over ENEB by modulating winds along the coast. Furthermore, the easterly wave disturbance (EWD), crossing the south Tropical Atlantic from West Africa to South America, is identified as one of the major causes of extreme rainfall events during the rainy season (Torres and Ferreira 2010, Kouadio et al. 2012, Amorim et al. 2014, Gomes et al. 2015). The interaction between the EWD and local circulations may significantly increase the number of rainfall events, and hence the amount of rainfall along the coast (Kouadio et al. 2012, Gomes et al. 2015).
2015). The EWD time scale is typically a few days from its inception on the African coast to triggering precipitation on ENEB (Kouadio et al. 2012, Gomes et al. 2015), and it may be used as an indicator to subside intra-seasonal forecast.

The Eastern Hydrological Region (EHR) is very susceptible to flooding during the rainy season (Fig. 1(a)), due to the EWD and other oceanic–atmospheric systems. An understanding of the connection between climate oscillations and the hydrological response at the EHR on an inter-annual to multi-annual time scale is, however, still lacking. Identifying connections between hydrological variations and climate indices may improve this lack of understanding. This work focuses on the study of such connections by using as a case study an area that covers two river basins within the EHR. It evaluates the long-term effects of the large-scale climate phenomena and climate patterns on the hydrological variability of the rainy season, using multivariate statistical techniques. A spatial analysis of the hydrological variability is also carried out. The knowledge obtained with this work is the first step towards the development of a long-term hydrological prediction. It is expected that this will contribute to the improvement of water resources planning and management in this region.

2 Materials

2.1 Study area

The EHR is composed of 16 watersheds with drainage areas ranging from 1200 to 20,000 km², which are mostly in ENEB (Fig. 1(a)). The main characteristics of these basins are shallow soils with a rapid response to rainfall events, a wet season with the rainiest months between May and July, and a climate gradient from the littoral towards the continental zones.

The study area consists of two neighboring river basins – Paraíba do Meio and Mundaú – that together have an area of 7283 km² (3157 and 4126 km², respectively), located in the southern EHR, between 8°30′00″S–10°00′00″S and 35°30′00″W–37°00′00″W (Fig. 1(b)).

The climatic and physiographic properties of the study area vary greatly from the outlets (coastal zone), characterized by a humid climate and covered by tropical forest, to the headwaters in a semi-arid region. The central part of the area is characterized by a transition climate and vegetation (Fig. 1(b)).

The average annual precipitation in the upper part of the basins is about 800 mm, while in the lower parts it is about 2000 mm (COTEC 2000). The annual precipitation regime is divided into a dry season between September and March, and a wet season from April to August during which more than 70% of the total annual precipitation falls. During the rainy season, frequent extreme rainfall events may occur, causing flash floods. Figure 2 presents the average annual precipitation for each climate region over the study area for the period 1950–2008.

The spatial and temporal features of precipitation in the study area are the same as those described by Rao et al. (1993) for the narrow zone of ENEB (Fig. 1(a)). Although the study area is small compared to the total area of ENEB, it might be representative of the climate of the EHR.

2.2 Data

Discharge data series for the study site are represented by two gauge stations located near the river outlets (Fig. 1(b)). The data cover a period from 1 January 1974 to 31 December 2008 for the station located on the Mundaú River, and from 1 January 1978 to 31 December 2008 for the station on the Paraiba do Meio River. Both gauge stations are operated by the Brazilian National Water Agency (ANA).

Precipitation data over the study area are represented by daily totals from 1 January 1950 to 31 December 2008, from a collection of 25 well-distributed rainfall gauges (Fig. 1(b)). Of the gauges, 15 belong to ANA and 10 to the Pernambuco Technology Institute (ITEP). All daily precipitation data were qualitatively checked and missing data filled by Costa et al. (2016). From daily precipitation data, monthly total time series were derived, as well as the accumulated precipitation for the wettest trimester, May to July (MJJ).

The influence of five climate phenomena on the precipitation of the study area was examined. They are the Atlantic Meridional Mode (AMM; Chiang and Vimont 2004), Atlantic Multidecadal Oscillation (AMO; Schlesinger and Ramankutty 1994), North Atlantic Oscillation (NAO; Hurrel et al., 1995), Pacific Decadal Oscillation (PDO; Mantua et al. 1997), and El Niño Southern Oscillation (ENSO/Southern Oscillation Index) (SOI; Trenberth 1997), and are represented by their indices. Monthly values of the climate indices were obtained from the database of the US National Center for Atmospheric Research (NCAR; http://www.cgd.ucar.edu/cas/catalog/climind/) and the US National Oceanic and Atmospheric Administration (NOAA; http://www.esrl.noaa.gov/psd/data/climateindices/list/) for the same period as the precipitation data.
Figure 2. Monthly variability of precipitation over the study area for (a) semi-arid region, (b) transition region and (c) tropical region, considering the average, minimum and maximum precipitation of the 25 selected rainfall gauges for the period 1950–2008 (the bars indicate ±1 standard deviation).
3 Methods

3.1 Spatial-temporal patterns of MJJ precipitation and homogeneous hydrological groups

Principal component analysis (PCA) was applied to an array with 59 years of total MJJ precipitation as rows and 25 rain gauges as columns. The PCA is useful for reducing the information of a large number of variables (25 in this case) into a smaller set of orthogonal variables (modes) that represent the major part of the overall data variance. The complete theory of PCA may be found in Jackson (1991), and some relevant applications in e.g. Uvo (2003), Munõz-Dias and Rodrigo (2004), Grimm (2011), Neto et al. (2015) and Rodriguez et al. (2016). Each PCA mode is composed by an eigenvector and an eigenvalue. The eigenvectors represent the covariability of each variable, whereas the eigenvalues express how much of the original variance is explained by each eigenvector.

The principal components (PC) of the array of eigenvectors, which together explain at least 80% of the total variance, were evaluated to identify spatial patterns of rainfall covariability. To relax the orthogonality constraint of the PCA and to improve possible physical interpretation of the spatial patterns, the PCs were rotated using varimax (Richman 1986). This technique is one of the most commonly employed rotation procedures (e.g. Bonnel and Sumner 1992, Uvo and Berndtsson 1996, Grimm and Saboia 2015). Physical factors that may explain the observed patterns in these components are discussed.

A cluster analysis was performed on the precipitation data to identify homogeneous hydrological groups (HG) of rainfall stations of the Paraíba do Meio and Mundaú river basins. Before this analysis, the data were filtered by PCA so that at least 80% of the original data variability was maintained. This filtering was made in order to minimize the interference of noise on the cluster analysis (Uvo and Berndtsson 1996, Uvo 2003). The method of Ward was applied to establish the numbers of HG (Munõz-Dias and Rodrigo 2004, Lyra et al. 2014, Rodriguez et al. 2016), and the clustering validation was based on the physical understanding of the geographical expression of the cluster in the study area. From the identified homogeneous groups, the MJJ time series of precipitation at each HG was calculated from the rainfall stations belonging to each HG. The series was based on the area of influence of each rainfall station at each HG.

3.2 Connections between climate indices and hydrological variability

As many watersheds in the EHR lack discharge measurements and/or only the spatio-temporal data for precipitation are available, the first step was to evaluate the inter-annual relationship between precipitation and average discharge over the study area using the Spearman rank correlation. Spearman correlation was also employed to investigate the relationship between MJJ precipitation at each HG and lagged climate indices (up to 6 months before the rainy season). Complementarily, the Spearman correlation was calculated between simultaneous average MJJ climate indices and the time series of the three first modes of the rotated PCA, i.e. rotated PCA scores. The Spearman correlation was preferred due to its capacity to measure both linear and somewhat nonlinear correlations between variables (Wilks 2006). The Monte Carlo method was applied for testing the statistical significance of the correlation coefficients obtained, considering the 95% confidence level.

In addition, a time–frequency analysis was performed to evaluate the temporal variability of MJJ precipitation and average discharge, as well as the MJJ precipitation and climate indices by continuous wavelet transform (CWT). The CWTs were calculated for each HG, considering only time series of MJJ precipitation and climate indices with statistical significance found by Spearman correlation.

In the wavelet analysis, both time and frequency variations can be investigated, decomposition of a time series into scale components allowing distinction between the oscillations that occur in different periods. Unlike other spectral techniques (such as the Fourier and Gabor transforms), wavelet analysis retains information about the occurrence of events in both time and frequency domains, highlighting localized intermittent periodicities (Morlet et al. 1982a, 1982b, Grossman and Morlet 1984). Moreover, it is possible to provide information about the level of significance by varying the period in accordance with short or long time-scale oscillations (Grinsted et al. 2004).

The Morlet wavelet ($\Psi_s$) was chosen in this analysis since it is efficient in extracting features, maintaining a good balance between time and frequency resolution (Grinsted et al. 2004, Liu et al. 2011). It is defined as:

$$\Psi_s(\eta) = \pi^{-1/4}e^{i\omega_0 \eta - \eta^2/2}$$

(1)
where $\eta$ and $\omega_c$ are time and frequency, respectively, both non-dimensional. Thus, the CWT of a time series of data $X$ may be defined as:

$$W_X(t, s) = (X(t) \times \Psi_s(t))$$  

(2)

where $t$ is the time and $\Psi_s$ is the Morlet mother wavelet at the scale $s$. The wavelet spectrum is then defined as the square of the amplitude of the transform: $|W_X(t, s)|^2$ (Torrence and Compo 1998).

To evaluate the covariance of two time series from their CWT time–frequency signal, the cross-wavelets transform (XWT) was employed. The XWT is a tool that can reveal areas with a high common power and relative phase between two time series in their time–frequency domain (Jevrejeva et al. 2003, Grinsted et al. 2004, Liu et al. 2011). The cross-wavelet spectrum ($W_{XY}(t, s)$) is defined as:

$$W_{XY}(t, s) = W_X(t, s) W_Y(t, s)$$  

(3)

where * denotes complex conjugation of $W_Y(t, s)$. Furthermore, the wavelet coherence (WTC) was applied to measure how coherent the power spectrum could be in a XWT analysis (Labat 2010) and avoid pitfalls identified by Maraun and Kurths (2004). The WTC was described by Torrence and Compo (1998) as the square of the smoothed cross-spectrum, normalized by smoothed spectra of the two time series, and it can be thought of as the local correlation between the wavelet transform of each time series used in the XWT, i.e. it gives a quantity between 0 and 1 in their time–frequency space. Therefore, while a XWT identifies periods and times when the two variables are oscillating, the WTC enhances the periods and time when the variables are locally correlated. The WTC is defined as:

$$R^2(s, t) = \frac{|\mathcal{S}(s^{-1} W_{XY}(s, t))|^2}{\mathcal{S}(s^{-1} |W_X(s, t)|^2) \ast \mathcal{S}(s^{-1} |W_Y(s, t)|^2)}$$  

(4)

where $\mathcal{S}$ is the smoothing operator (Grinstad et al. 2004, Liu et al. 2011).

The results of these analyses are presented as diagrams of period vs time with colours representing the power intensity and arrows representing the relative local phase. Horizontal arrows pointing to the right indicate that the climate phenomena and MJJ precipitation variability are in phase (i.e. positive relationship in the time–frequency space), while arrows pointing to the left means that they are in anti-phase (i.e. negative relationship). Vertical arrows pointing up (down) indicate that the climate phenomenon is leading MJJ precipitation with a lag (i.e. phase difference) of 270° (90°).

All calculations were performed using the software MatLab®. The output maps were produced in ArcGIS® 10.2. The CWT was performed by the software provided by Torrence and Compo (http://atoc.colorado.edu/research/wavelets/) and the cross-wavelets and wavelet coherence analysis were performed by a software package provided by Jevrejeva et al. (2003), at: http://www.pol.ac.uk/home/research/waveletcoherence/.

### Table 1. Explained variance for the first four rotated principal components of the MJJ time series.

| Principal component, PC | 1° PC | 2° PC | 3° PC | 4° PC |
|------------------------|------|------|------|------|
| Explained variance (%)  | 28.7 | 26.2 | 14.2 | 11.4 |

### 4 Results

#### 4.1 Spatial-temporal patterns of MJJ precipitation and homogeneous hydrological groups

The first four modes of the rotated PCA together explain 80.5% of the total variance of the MJJ precipitation, with 69.1% being explained by the three first modes (Table 1), which presented characteristics clearly connected to spatial distribution of the local climate.

The eigenvectors of the first mode consist of positive values for the entire domain (Fig. 3(a)), with the highest values (above 0.5) mainly concentrated from the coastal zone to the central part of the basins, which is the region classified as tropical climate.

The eigenvector values of the second mode are predominantly negative (Fig. 3(b)), and stronger values (below ~0.6) are concentrated over the semi-arid climate on the upper basins. The values of the third mode are also mostly negative (Fig. 3(c)), and this mode mainly highlights the central part of the basins, i.e. the transition climate area.

The cluster analysis applied to the reconstructed data using the four first PCA models (Fig. 4(a)) divided the 25 time series of MJJ precipitation into three homogeneous hydrological groups (HG1, HG2 and HG3). The HGs identified by the cluster analysis are coherent with the spatial patterns presented by the rotated PCA and with the climate classification over the region. The stations that make up HG1 are mostly located in the upper basins, over the semi-arid climate, similar to the features pointed out by the second mode of the rotated PCA (Fig. 3(b)). The HG3 comprises stations located at the central and lower parts of the basins, i.e. the tropical climate area, following the characteristics of the first mode of the rotated PCA (Fig. 3(a)). Finally, HG2 comprises stations located on the central to upper basins that coincide with the transition...
Figure 3. Isolines of the eigenvectors of the covariance matrix of the (a) first, (b) second and (c) third rotated PCA components of MJJ precipitation.

Figure 4. Cluster analysis of the spatial-temporal similarity of the MJJ precipitation, considering (a) three cluster groups and (b) two cluster groups.
climate, enhanced by the third mode of the rotated PCA (Fig. 3(c)). Other cluster classifications were also tested. The cluster classification with two HGs (Fig. 4(b)) classified most of the series in HG1 and HG3 in one group, and preserved HG2 as a second group. Cluster classification with four HGs (not shown) was disregarded in comparison to the clear physical characteristics of the three-cluster division.

4.2 Connections between climate indices and hydrological variability

The CWT analysis (Fig. 5) performed for each HG separately shows that the average MJJ precipitation of each HG varies differently in the time–frequency spectrum. The CWT displayed mainly high power at low frequency (8–16-year period) during the 1970s and 1980s in HG3 (Fig. 5(c)), somewhat similar to HG1 (10- to 16-year period, Fig. 5(a)). However, no such low-frequency power was captured in the HG2 time series (Fig. 5(b)). Significant power at high frequencies (2- to 3-year period) is also noticed for all HGs in the 1970s.

The correlation coefficient between MJJ precipitation and average discharge is 0.85 for the Mundaú River and 0.79 for the Paraíba do Meio River, both with 99% statistical significance. The time–frequency analysis between MJJ precipitation and average discharge of the Mundaú and Paraíba do Meio river basins are presented in Figure 6. The XWT analysis highlights that MJJ precipitation and discharge have common power in different periods in both basins, from high to low frequencies (2- to 4-year period and 4- to 8-year period, respectively), being stronger at the Mundaú River basin (Fig. 6(a,b), left column). Moreover, high coherence values across all frequencies on the wavelet coherence spectrum (WTC) confirm the significant common power in XWT (Fig. 6(c,d), right column), indicating that the series are locally correlated at both high and low frequencies. The relative phase of the arrows in Figure 6 is predominantly pointing to the right, indicating an in-phase relationship between precipitation and discharge (i.e. positive local correlation), supporting the Spearman correlation. These results confirm that the region has a rapid response for rainfall events. As the precipitation dataset spans a longer time period than the average discharge one, MJJ precipitation data were chosen to be used as the hydrological variable of reference to investigate teleconnection patterns between climate and hydrological variability.

The Spearman rank correlation between the MJJ precipitation for each HG and lagged climate indices are presented in Table 2. Note that, among the five investigated indices, only AMM, NAO and SOI showed statistically significant (magnitude about 0.3) correlation with the MJJ precipitation of any HG.

Regarding the AMM index, negative statistically significant correlations were obtained between February and April indices and precipitation for all HG, which means one or three months before the start of the rainy season (Table 2). Such correlations suggest the influence of the Tropical North Atlantic on the MJJ precipitation. For the NAO index, a negative statistically significant correlation was found between the December index of the previous year and precipitation at each HG, i.e. five months before the start of the rainy season, supporting the idea that the conditions in the northern Atlantic might affect the MJJ precipitation. The state of the Pacific Ocean also affects the MJJ precipitation, as the SOI presented a significant correlation between the index in December of the previous year and the precipitation during the rainy season for all HGs.

Based on Table 2, the XWT was performed and the WTC calculated between the time series of MJJ precipitation and the time series of climate indices that presented significant correlations, namely, AMM\textsubscript{FEB}, AMM\textsubscript{APR}, NAO\textsubscript{DEC} and SOI\textsubscript{DEC}. The diagrams of the

![Figure 5. Continuous wavelet power spectrum for the average MJJ precipitation at (a) HG1, (b) HG2 and (c) HG3. The thick black contours highlight the 95% confidence level.](image)
cross-wavelet and wavelet coherence analyses are shown in Figures 7, 8 and 9, for HG1, HG2 and HG3, respectively.

The results from XWT analysis highlight that MJJ precipitation and AMM, NAO and SOI indices have common power mostly at low frequencies (8- to 16-year period to AMM and NAO, 12- to 16-year period to SOI), especially in HG1 and HG3 for the 1960s to 1990s (Figs. 7 and 9, left column). Moreover, high coherence values on the WTC spectrum (Figs. 7 and 9, right column) confirm the significant common power in XWT, supporting the obtained Spearman correlation by indicating that the series are locally correlated at low frequencies, and suggesting a long-term influence of both Atlantic and Pacific oceans on the wet season of HG1 and HG3.

The relationship between climate indices and MJJ precipitation may be seen by the local relative phase of the arrows in Figures 7 and 9. At low frequencies along the significant XWT and WTC (8- to 16-year period), the arrows of the AMM index predominantly point up, suggesting that the physical processes connected to AMM oscillation at those frequencies lead the precipitation over HG1 and HG3 lagged by 270° (i.e. three-quarters of the oscillation period). As to the NAO index, arrows are pointing down on the 8- to 12-year period, which means that NAO may lead the MJJ precipitation lagged by 90° (a quarter of the oscillation period) at this period interval, whilst on the 12- to 16-year period, arrows point to the left, which indicates that the MJJ precipitation over the HG1 and HG3 is in anti-phase with the NAO index (i.e. local negative correlation).

### Table 2. Spearman rank correlation between MJJ precipitation and lagged climate indices (1–8-months prior MJJ). Values in bold indicate 95% statistical significance and in italic bold, 99% statistical significance.

| Climate Index | Sep. | Oct. | Nov. | Dec. | Jan. | Feb. | Mar. | Apr. |
|---------------|------|------|------|------|------|------|------|------|
| HG1 AMM       | -0.02| -0.25| 0.22 | 0.10 | 0.10 | -0.28| -0.23| -0.36|
| AMO           | 0.12 | 0.12 | 0.12 | 0.11 | 0.11 | 0.10 | 0.11 |      |
| NAO           | 0.01 | -0.22| 0.14 | 0.31 | 0.10 | 0.23 | 0.16 | 0.10 |
| PDO           | 0.01 | -0.10| -0.03| 0.05 | -0.03| 0.20 | 0.20 | 0.20 |
| SOI           | 0.02 | 0.12 | 0.25 | 0.34 | 0.01 | 0.10 | 0.01 | 0.21 |
| HG2 AMM       | -0.02| -0.10| 0.24 | 0.20 | 0.14 | -0.31| -0.21| -0.30|
| AMO           | 0.03 | 0.02 | 0.01 | 0.01 | 0.01 | -0.01| -0.01| -0.01|
| NAO           | 0.02 | 0.03 | 0.12 | 0.32 | -0.10| -0.16| -0.20| 0.10 |
| PDO           | 0.04 | -0.20| 0.08 | 0.03 | -0.04| 0.17 | 0.10 | 0.20 |
| SOI           | 0.06 | 0.11 | 0.20 | 0.33 | 0.10 | 0.07 | 0.03 |      |
| HG3 AMM       | -0.02| -0.19| 0.24 | 0.19 | 0.04 | -0.42| -0.22| -0.25|
| AMO           | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 |
| NAO           | 0.11 | -0.08| -0.06| -0.33| 0.11 | -0.02| 0.01 | 0.05 |
| PDO           | 0.03 | -0.20| -0.16| -0.04| 0.01 | -0.05| -0.06| -0.06|
| SOI           | 0.05 | 0.15 | 0.24 | 0.28 | 0.13 | 0.08 | 0.02 | 0.03|

Figure 6. Cross-wavelet transform (left) and wavelet coherence (right) between MJJ precipitation and average discharge to Mundaú River (a) and (c), and Paraíba do Meio River (b) and (d). The thick black contours highlight the 95% confidence level. The arrows show the relative phase relationship between MJJ precipitation and average discharge (in-phase pointing right, anti-phase pointing left, and 90°/270° out of phase for vertical arrows).
correlation). The arrows on the SOI XWT point down along the 12- to 16-year period, characterizing that the SOI leads the MJJ precipitation lagged by 90° at HG1 and HG3.

Differently from the previous HG, the XWT spectra of precipitation on HG2 and climate indices do not display significant areas with common power at low frequencies, coherent with the lack of power at CWT of HG2 (Fig. 5(b)). The significant power at low frequency present in the XWT with the SOI (12- to 16-year period) for 1960s to 1990s (Fig. 8, left column, lower diagram) is the result of the SOI CWT power at that period (not shown), since the XWT is essentially the multiplication of two CWTs (Maraun and Kurths 2004).

The absence of a consistent XWT spectrum on an inter-annual scale in all HGs is due to the used dataset being composed of annual values, that is, a time step (δt) of 1 year. Here, the frequency scale at CWT (S₀) starts from a 2-year period, as S₀ is a function of the time step multiplied by two, i.e. S₀ = 2δt (Torrence and Compo 1998, Santos and Morais 2013). Thus, no signal is captured before the 2-year period in this XWT analysis. This is an important remark that clarifies the differences found between XWT analysis and the statistically significant correlations presented in Table 2.

Figure 7. Cross-wavelet transform (left) and wavelet coherence (right) between climate indices and MJJ precipitation in HG 1. See Figure 6 caption for explanation.
5 Discussion

The physiographic features of the study area seem to have a leading role in the structure of the spatial variation of the precipitation during the rainy season, as shown by the first three rotated PCA modes of MJJ precipitation. The three homogeneous hydrological groups of precipitation variability defined by cluster analysis follow the characteristics highlighted by the first three modes of the rotated PCA and coincide closely with the patterns of the climate classification and the average rainfall distribution over these river basins, as shown in Figure 2.

Regarding the temporal variability of the MJJ precipitation, the wavelet analysis indicated that HG1 and HG3 present low-frequency variability (Fig. 5(a) and (c), respectively), different from HG2 (Fig. 5(b)), which does not show any low-frequency variability. This difference is captured by the cluster classification if a division into only two groups is chosen (Fig. 4(b)). An indication of this difference is also given by the third mode of the rotated PCA (Fig. 3(c)).

The temporal variability of the precipitation also appears to be influenced by large-scale climate
conditions, since the simultaneous Spearman correlation (not shown) indicates that there are significant correlations between the modes of the rotated PCA and climate indices. The first mode is significantly correlated with the NAO and AMM, the second mode with the SOI and the third mode with the PDO. The PDO has a well-known multi-decadal variability, and its significant correlation with the third mode of the PCA might suggest signals of low frequency on the HG2 with a time scale longer than the multi-annual 16-year period (the 16-year period was the maximum time-frequency period captured by wavelets due the limitation of the dataset extension used here). In general, these correlations are in agreement with Grimm and Saboia (2015), which showed that, during austral summer (which coincides with the start of the rainy season in parts of SNEB and NNEB), the third and fourth rotated modes of the precipitation over northeastern South America are significantly correlated with the Atlantic and Pacific ocean conditions. Therefore, those conditions might have a later influence on the rainy season over ENEB.

The correlation coefficients calculated between MJJ precipitation for the different HG and AMM, NAO and SOI climate indices, as well as the XWT and WTC spectra, indicate that these indices are connected

Figure 9. Cross-wavelet transform (left) and wavelet coherence (right) between climate indices and MJJ precipitation in HG 3. See Figure 6 caption for explanation.
to the precipitation of the three HGs, even if with different intensities and on different time scales, suggesting a teleconnection between the state of the SST in the Atlantic and Pacific oceans and anomalous precipitation over the EHR-ENEB, in agreement with previous studies (Palmer 1986, Nobre and Shukla 1996, Uvo et al. 1998, Giannini et al. 2004, Andreoli and Kayano 2006, Grimm and Saboia 2015).

The significant correlation between AMM and MJJ precipitation in February and April may represent the early displacement southward of the ITCZ, commonly observed during wet years over NEB. Uvo et al. (1998) showed that anomalous warm SST conditions in the Tropical Atlantic during February are connected to an early start of the rainy season in that region due an early southward migration of the ITCZ. Moreover, they pointed out that the SST conditions in April, which may define whether the ITCZ remains in its southernmost position or returns northwards, are one of the most important indicators of the inter-annual variability of precipitation in NEB.

Such a SST anomaly is related to the phase of the AMM (Chiang and Vimont 2004) so that, during the negative (positive) phase of the AMM, the SST in the northern Tropical Atlantic is colder (warmer) than normal and the SST in the southern Tropical Atlantic is warmer (colder). Thus, a negative correlation between AMM and MJJ precipitation in ENEB is expected, suggesting that the state of the AMM could impact the precipitation over the EHR, especially at the beginning of the rainy season. Moreover, in years when the SST over the Tropical South Atlantic is warmer than normal, the ITCZ may reach latitudes further south than normal and remain in its southernmost position during an anomalous long period that can be as long as May (Uvo 1989, Nobre and Shukla 1996, Chiang et al. 2002, among many others).

This pattern is supported by the common power of the XWT and local correlation of the WTC, where the AMM leads MJJ precipitation at low frequencies. The lack of significant correlation between the AMM in March and MJJ precipitation (Table 2) corroborates the findings from Uvo et al. (1998) for the rainy season in NNEB. They argue that, differently from the Atlantic SST anomalies in February and April, the March SST anomalies (here represented by the AMM) “do not systematically alter the climatological progression” of the tropical trough and of the ITCZ, which, climatologically, reach their southernmost positions during that month in near-normal precipitation years. March is the month when the precipitation normally decreases in NNEB. Such near-normal influence of the ITCZ over March precipitation may also be seen in the EHR, where precipitation also start to increase, with the occurrence of maximum extreme events mainly outside the coastal zone (i.e. semi-arid and transition climate in Fig. 2(a) and (b) for HG1 and HG2, respectively).

The results obtained in this study indicate that the NAO also plays a role in the variability of the MJJ precipitation. The relationship found between the NAO in December of the previous year and MJJ precipitation is consistent in occurring during the period when the NAO is most active (Greatbatch 2000). Palmer (1986) suggested some evidence that the NAO could be related to dry or rainy years in NEB, because negative (positive) events of NAO tend to be associated with warm (cold) SST in the northern Tropical Atlantic (Palmer 1986, Czaja et al. 2002). Moreover, the NAO could lead the state of the AMM and influence the SST in the southern Tropical Atlantic through an inter-hemispheric relationship (Robertson et al. 2000, Mo and Hakkinen 2001, Chiang and Vimont 2004), so that the NAO could remotely affect the variability of precipitation over NEB during the rainy season.

Based on this evidence, the negative correlation between the NAO and MJJ precipitation found in our results seems to be unexpected, as the correlation between the NAO and AMM/SST in the northern Tropical Atlantic is negative (Chiang and Vimont 2004). The cross-wavelet analysis and wavelet coherence spectrum between the NAO and AMM (not shown) present a significant local correlation between the NAO and AMM in anti-phase (as represented by most of the arrows pointing to the left) mainly between 1960 and 2000 and at a 4- to 10-year period, which is in agreement with the negative correlation proposed by Chiang and Vimont (2004). However, Lucena et al. (2011) observed that after the 1970s, when the PDO and NAO presented positive phases, their opposite impacts on precipitation in the northern parts of NEB annulled each other, so that their typical characteristics of increasing or decreasing precipitation over NNEB were not observed. Thus, there is a possibility that the negative Spearman correlation obtained here (Table 2), as well as the indication that the NAO leads MJJ precipitation at the low-frequencies period on the XWT/WTC spectra, despite being statistically significant, is the result of some similar counterbalance among different climate phenomena or that the source of this correlation is related to atmospheric dynamics and not to the SST, as remarked by Grimm and Saboia (2015).

Belanger et al. (2014) suggested that the frequency of easterly waves has a strong covariability with the AMM, associated with the dipole of mid-troposphere
vorticity in western Africa. Therefore, the relationship between the NAO and MJJ precipitation needs to be investigated more deeply in further research.

The conditions of the Pacific Ocean, mainly reported as ENSO (here represented by the SOI index), are frequently associated with inter-annual variability of precipitation over NNEB (Nobre and Shukla 1996, Uvo et al. 1998, Saravanan and Chang 2000, Giannini et al. 2004, Andreoli and Kayano 2006). The results of this work also shows that MJJ precipitation might be influenced by the Pacific Ocean, either by the statistically significant values of correlation (Table 2) with SOI-December conditions or by the significant common power and local correlation at low frequencies on the XWT and WTC, respectively. It has been observed that during ENSO events the SST anomalies in the northern Tropical Atlantic tend to show anomalies of the same sign as the Tropical Pacific SST (Uvo et al. 1998, Czaja and Frankignoul 2002), which could also influence the position of the ITCZ (Saravanan and Chang 2000, Andreoli and Kayano 2006, Tedeschi et al. 2016) and hence affect the inter-annual precipitation over NNEB. Furthermore, the inter-annual precipitation over NNEB. However, precipitation anomalies over NNEB associated with ENSO have been noted only during strong events of the Tropical Pacific SST (Rao et al. 1993, Amorin et al. 2014), when episodes of El Niño (La Niña) might occur concomitantly with positive (negative) AMM (Lucena et al. 2011). This might also be a consequence of which phase of ENSO is influencing the Tropical Atlantic SST, and therefore explain the common power at low frequencies identified here, with the SOI leading MJJ precipitation.

Notably, the inter-annual MJJ precipitation variability over ENEB is influenced by different ocean and atmospheric processes, as previously shown (Rao et al. 1993, Andreoli and Kayano 2006, Kouadio et al. 2012, Amorin et al. 2014, Gomes et al. 2015). Besides the well-known inter-annual patterns, this work has also shown the occurrence of a multi-annual teleconnection between climate oscillations and precipitation at the EHR–ENEB. The multi-annual connection highlighted that the state of both the Tropical Atlantic and Tropical Pacific oceans has a long-term effect on the rainy season of the region, since most significant common power and local correlations were identified at low frequencies.

The yearly frequency of the dataset created a limitation for wavelet analysis to capture signals in high frequencies of variability. Nevertheless, such variability is indicated on Table 2 by statistically significant values of correlation with climate indices. In addition, the temporal variability of the rotated modes of the PCA seems to be influenced by the inter-annual oscillation of global climate phenomena, as suggested by their correlation.

The findings achieved by this work revealed that global climate oscillations have a non-stationary relationship with the rainy season of the EHR, impacting the hydrology of the study area at different temporal scales, but mainly a long-term mode of variability was identified (intervals of 8- to 16-year period), influenced by climate indices such as the AMM and SOI. The work also clarified that precipitation may be used as a proxy for hydrological forecasts on the studied basins, due to their rapid precipitation–discharge response. These results create a robust basis for the development of a long-term hydrological forecast over the EHR on ENEB in the face of anomalous large-scale climate conditions, contributing to the enhancement of water resources management in ENEB.

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