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ORIGINAL PAPER

Sensitivity of tree ring growth to local and large-scale climate variability in a region of Southeastern Brazil

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Abstract We explored the relationship between tree growth in two tropical species and local and large-scale climate variability in Southeastern Brazil. Tree ring width chronologies of *Tectona grandis* (teak) and *Pinus caribaea* (Caribbean pine) trees were compared with local (Water Requirement Satisfaction Index—WRSI, Standardized Precipitation Index—SPI, and Palmer Drought Severity Index—PDSI) and large-scale climate indices that analyze the equatorial pacific sea surface temperature (Trans-Niño Index-TNI and Niño-3.4-N3.4) and atmospheric circulation variations in the Southern Hemisphere (Antarctic Oscillation-AAO). Teak trees showed positive correlation with three indices in the current summer and fall. A significant correlation between WRSI index and Caribbean pine was observed in the dry season preceding tree ring formation. The influence of large-scale climate patterns was observed only for TNI and AAO, where there was a radial growth reduction in months preceding the growing season with positive values of the TNI in teak trees and radial growth increase (decrease) during December (March) to February (May) of the previous (current) growing season with positive phase of the AAO in teak (Caribbean pine) trees. The development of a new dendroclimatological study in Southeastern Brazil sheds light to local and large-scale climate influence on tree growth in recent decades, contributing in future climate change studies.

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1 Introduction

The vascular cambium is the lateral meristem responsible for diametric growth (secondary growth) in trees. The activity of the cambium is governed by macro- and microclimatic and environmental factors present at the site where trees are growing, forming wood with distinct anatomical features according to growing conditions. The seasonal variation in these factors over a year is responsible for the annual tree ring formation in trees (Fritts 1976). In this context, the tree ring analysis supports the basis to explain the response of tree growth to climate, both locally (microclimate) as well as on continental scales (macroclimate) (Villalba et al. 2011).

Climate–tree relationships have focused on analysis of large-scale climate variability through the use of climatic indices in tropical and temperate forests to analyze the influence of global climate patterns, such as representing quantitative aspects of drought (e.g., Li et al. 2007; D'Arrigo et al. 2011a; Ram 2012), El Nino-Southern Oscillation (ENSO) (e.g., Christie et al. 2009; Fowler et al. 2012; Pompa-García and Jurado 2014), and Antarctic Oscillation (AAO) (e.g., Jones and Widmann 2003; Urrutia et al. 2011; Mundo et al. 2012). However, the climatic pattern analysis through tree ring growth is still unknown in some regions of Southeastern Brazil.

In dendroclimatic studies, drought indices are principally used because they include more than one variable besides soil layer moisture deficiencies (Cook et al. 2010). Temperature and precipitation are directly related to energy and water available to the plant for fundamental physiologic processes, such as photosynthesis and evapotranspiration. However, the relationship between these variables is not direct in agroclimatic studies and thus does not guarantee that there are sufficient quantities of ground water available for trees (Ribeiro et al. 2011). In dendroclimatology, the Palmer Drought Severity Index (PDSI) (Palmer 1965) is the most popular for reconstructing droughts (e.g., Liang et al. 2007; Li et al. 2007; Ram 2012), which reflects the duration and intensity of the long-term drought patterns, providing a reasonable approximation for the climate forcing of tree growth (Cook et al. 1999). Although the PDSI is widely used, its limitation as a climatological tool lies in the fact that it does not specify the time scale—it uses arbitrary rules in defining the drought periods—it has a delayed response to rainfall and is restricted to the geographical area for which it was developed (McKee et al. 1993; Hayes et al. 1999). To solve this problem, McKee et al. (1993) proposed an index based on rainfall, the Standardized Precipitation Index (SPI), currently considered one of the most popular precipitation indices used by meteorological and hydrological services all over the world (Wu et al. 2001; Khan et al 2008). However, the SPI equation only considers the precipitation variable, rather than other important variables such as temperature and water balance (Vicente-Serrano et al. 2010). To estimate the water fraction consumed and the amount that would be demanded by trees, ensuring its maximum productivity, the Water Requirement Satisfaction Index (WRSI) has been used specially in agrometeorological research and climate risk zone detection (Verdin and Klaver 2002; Senay and Verdin 2003; Assad et al. 2003; Brunini et al. 2007; Ribeiro et al. 2011). Although PDSI, SPI, and WRSI have been use as tree growth estimators in the tropics, there is no consensus on which index best explains the relationship between soil water availability and tree development.

Some large-scale climate variability modes around the world that affect inter-annual climate variability are the El Niño-Southern Oscillation (ENSO) and Antarctic Oscillation (AAO). ENSO is a phenomenon characterized by unusual change in the sea surface temperature (SST) in the equatorial central/eastern Pacific Ocean that is warmed (cooled) during El Niño (La Niña) (Trenberth 1997). Although there are many studies linking tree growth response with ENSO (Mundo et al. 2012; Li et al. 2013), the search for ENSO-sensitive tree species and sites is still an ongoing activity (Christie et al. 2009). Characterization of ENSO's nature may be performed through analysis of SST anomalies in different regions of the tropical Pacific. Trenberth and Stepaniak (2001) proposed an optimal characterization of the evolution of El Niño or La Niña events by means of two indices: (1) N3.4 referred to SST anomalies in the Niño 3.4 region and (2) Trans-Niño Index (TNI) referred to the difference in normalized anomalies of SST between Niño 1+2 and Niño 4 regions.

Also referred as the Southern Annular Mode (SAM), the AAO has a dominant pattern of non-seasonal atmospheric circulation variations in the Southern Hemisphere (Thompson and Wallace 2000), and it occurs south of the 20° S parallel (Garreaud et al. 2009). Some studies have verified that the significant change in the Southern Hemisphere air pressure, which is well reflected by the increase of the positive phase of AAO over recent decades (Gillett and Thompson 2003; Marshall 2003), has been influenced by ozone-hole-induced changes that are reflected in tree growth (Villalba et al. 2012).

In this context, the main objective of this study is to analyze the tree growth sensitivity of two tropical species to local and large-scale climatic drivers in a region of Southeastern Brazil by means of drought indices (PDSI, SPI and WRSI) and global indices (TNI and AAO), respectively.

2 Methods

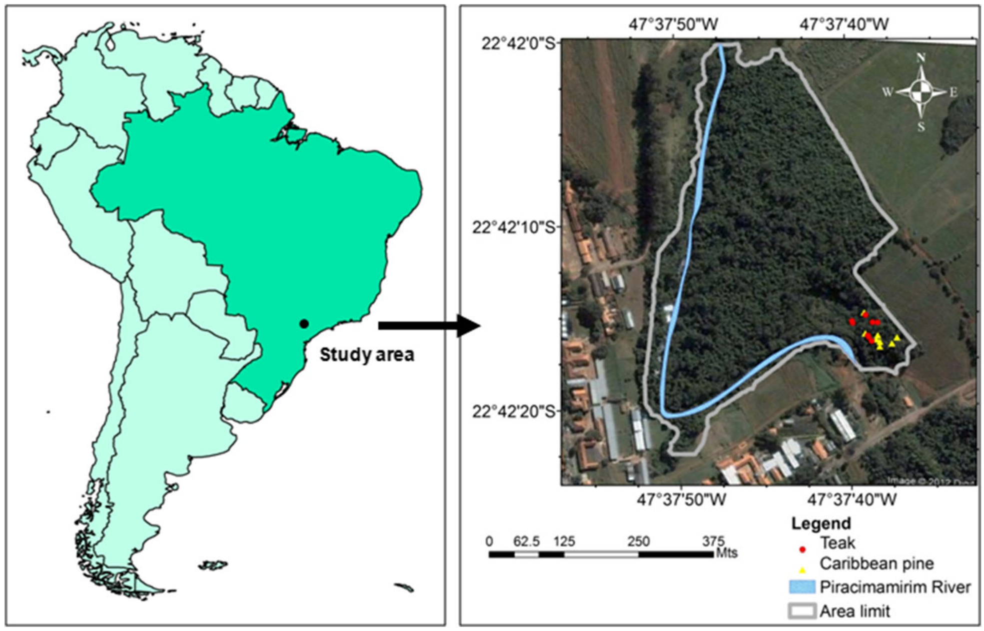
2.1 Study area

This study was conducted in a forest fragment in Piracicaba, São Paulo state, Brazil (22°42′ S, 47°37′ W, 546 m), that is part of the Atlantic Rainforest, considered one of the most fragmented and deforested Brazilian Biomes (Rodrigues et al. 2009). In this fragment, native species coexist with some introduced exotic tropical trees, highlighting *Tectona grandis* (teak) and *Pinus caribaea* var. *hondurensis* (Caribbean pine) (Fig. 1).

According to Köppen's classification, the climate is Cfa (humid subtropical) with hot summer and an annual mean temperature of 20.5 °C (Alvares et al. 2013a). Mean temperatures of the hottest and coldest months are 23.3 and 16.7 °C, respectively (Alvares et al. 2013b). The mean annual rainfall is 1281 mm, with 50 % occurring during summer (Dec to Feb). Soil is classified as Red Nitosol of clayey texture (Alfisoil) with high fertility (Torrado et al. 2004), undergoing a water deficit from July to September, with maximum value in August (Fig. 2).

The dendroclimatological quality of teak has been revealed by relationships with precipitation (Pumijumnong et al. 1995; Ram et al. 2008; Deepak et al. 2010; Borgaonkar 2011; D'Arrigo et al. 2011a), the Palmer Drought Severity Index (PDSI), and large-scale ENSO data (Borgaonkar et al. 2010; Ram 2012). Caribbean pine has also been used to conduct dendroclimatic and dendroecological studies in tropical forest (Worbes 1999; Melandri et al. 2007; Olajide et al. 2010).

Fig. 1 Study area and spatial distribution of the trees sampled.



2.2 Dendrochronological analysis

For tree ring analysis, increment four cores, approximately, were collected from 18 trees, 10 Caribbean pines and 8 teaks (Table 1). Wood cores were glued into wooden holders, and the cross-sections were polished with a sandpaper gradient varying between 80 and 600 grains mm^{-2} until the anatomical features related to ring boundaries were clearly identified. The cross-sections were examined under a stereomicroscope (×10 magnification), and the tree ring patterns, characteristic of each species, were identified. Wood cross-sections were scanned at 1200-dpi resolution with a reference scale, and tree ring widths were measured using the Image Pro Plus software, version 4.5.0.29 (Media Cybernetics Inc, Rockville, MD, USA). The cross-dating quality was checked with the software COFECHA (Holmes 1986), which calculates correlation coefficients between individual tree ring series as a way to identify absent or false rings.

The tree ring width measurements were standardized to remove the biological age trend of individual trees and any other non-climate-related growth variation through double detrending by using the Arstan software (Cook and Holmes 1996). Tree ring width measurements were detrended using negative exponential or a linear regression of any slope. The second detrended series was fitted to a cubic spline with a 50 % frequency response cutoff equal to 67 % of the series length, reducing the non-climatic variance by preserving high-frequency climatic information (Cook and Peters 1981) and generating residual and standard chronologies. The residual index series were prewhitened by autoregressive modelling of the standardized index series to remove autocorrelation, generating dimensionless indices that represent independent records of annual growth for each measured series.

The chronologies were characterized using the classic statistic parameters in dendrochronology (Fritts 1976), i.e., average and standard deviation of tree ring width, mean sensitivity (MS) and series intercorrelation (r_{bt}). MS describes the mean percentage change of year-to-year growth variability, and r_{bt} is the mean value of all possible correlations between individual series. The sample quality was verified by means of the expressed population signal (EPS) and Running Bar (RBar). EPS represents the hypothetical chronology or a chronology

Fig. 2 Climograph (*P* precipitation, *T* temperature) and water balance of Piracicaba, Brazil, for the period between 1970 and 2011

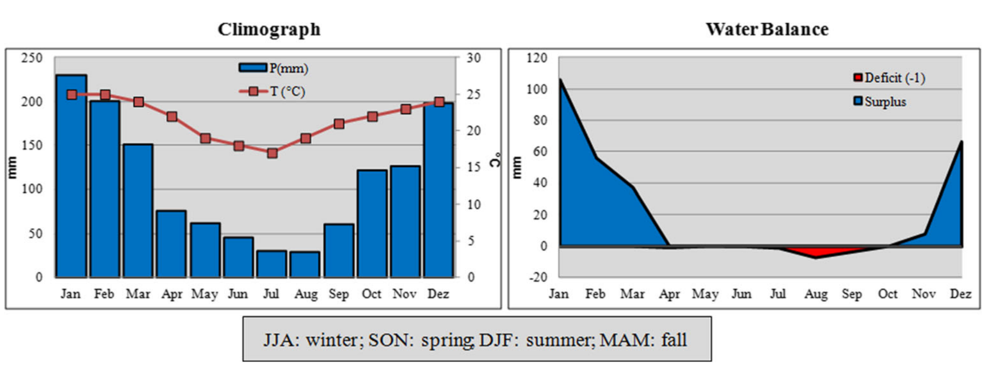


Table 1 Descriptive statistics of the chronologies of *P. caribaea* var. *hondurensis* and *T. grandis*

Specimen	Record period	MRW±σ[a]	r_{bt}[b]	MS[c]	EPS[d]
P. caribaea	1971–2011	6.46±4.49	0.689	0.324	0.95
T. grandis	1976–2011	4.95±2.60	0.642	0.395	0.93

[a] Mean ring width ± standard deviation (mm)

[b] Mean correlation between trees

[c] Mean sensitivity

[d] Expressed population signal

that has been infinitely replicated and is sensitive to both variations in the series intercorrelation and sample size, and RBar represents the mean correlation coefficient for all possible pairings of ring width series over a common time, both of which were computed using a 10-year moving window with a 5-year overlap. The reliable time span was defined by a threshold of EPS≥0.85 (Wigley et al. 1984).

2.3 Local (SPI, PDSI and WRSI) and large-scale (TNI and AAO) climate indices

SPI and PDSI monthly series were calculated for the Piracicaba region between 1917 and 2001 (Sansigolo 2004) and between 1917 and 2011 (Sansigolo 2012), respectively.

For WRSI, monthly time series from 1970 to 2011 were obtained from the meteorological station located at the College of Agriculture "Luiz de Queiroz"/University of São Paulo, which is 250 m away from the study area. WRSI represents the ratio between actual and potential evapotranspiration (AET/PET), so we used the following data input of the meteorological station: temperature (°C), rainfall (mm), wind ($m\ s^{-1}$), solar radiation ($MJ\ m^{-2}\ day^{-1}$), relative humidity (%), sunshine ($h\ day^{-1}$) and day of year to calculate these variables. Daily PET values were calculated and subsequently transformed into monthly values according to the parameterization proposed by Allen et al. (1998). Monthly AET was estimated from the water balance method proposed by Thornthwaite and Mather (1955). This index was calculated only for 33 years (1978–2011) because since 1978 the solar radiation measurements were beginning.

The relationship between tree growth and the El Niño-Southern Oscillation was analyzed through the Trans-Niño Index (TNI) and Niño-3.4 (N3.4) (Trenberth and Stepaniak 2001). TNI is the difference, in normalized anomalies of SST, between Niño 1+2 and Niño 4 regions, while N3.4 is the SST anomalies in the Niño 3.4 region. We applied the series available from the website of Climate and Global Dynamics of the National Centre for Atmospheric Research (www.cgd.ucar.edu/cas/catalog/climind/TNI_N34/index.html).

The influence of the tropospheric circulation south of 20° S was analyzed through the Antarctic Oscillation (Thompson and Wallace 2000; Marshall 2003), which is based on the principal component of the geopotential height anomalies of 850 HPa (Garreaud et al. 2009). We used the series available from the website of British Antarctic Survey (www.nerc-bas.ac.uk/icd/gjma/sam.html). The period employed for TNI and AAO was 1970–2011.

2.4 Tree ring response to climate

Correlation functions were constructed between the residual tree ring index chronologies of Caribbean pine and teak and monthly values of local and large-scale indices through the common period (Blasing et al. 1984). Since a tree ring is partially considered an integration of climate influences occurring over an extended period (current and prior growth periods; Fritts 1976), the correlations were performed for the period between spring of the previous growth year (September to November: SONp) to fall of the current growth year (March to May: MAMc), in months that have precipitation higher than 60 mm, a condition that according to Worbes (1995) ensures no stoppage of cambium activity in tropical tree species. To estimate the association between radial growth and circulation patterns associated to the pressure differences and ENSO events, we built a correlation map between tree ring chronologies and 850-hPa geopotential height and SST for the 20° N–90° S/20° W (E)–160° E (W), with 2.5×2.5 gridded cells from the NCEP re-analysis global dataset (Kalnay et al. 1996). To verify the relationship between tree rings and large-scale climate, we analyze whether there was correlation between large-scale index and precipitation using lagged climatic conditions of 1 year.

3 Results

3.1 Tree ring width chronologies

The mean tree trunk radial increase was 4.95 mm $year^{-1}$ for teak and 6.46 mm $year^{-1}$ for Caribbean pine. There was high correlation within series (r_{bt}) for both species (greater than 0.64). The mean sensitivity was greater than 0.30 and showed that trees react to the environment through their annual growth variability (Grissino-Mayer 2001) (Table 1). The teak and Caribbean pine chronologies had registration periods from 1976–2011 and 1971–2011, respectively. Caribbean pine showed lesser sample quality than teak, demonstrated by EPS values across the chronology (Fig. 3); however, the expressed population signal was greater than 0.85 in the entire period for both species, showing that sampling replication is adequate according to Wigley et al. (1984) (Table 1).

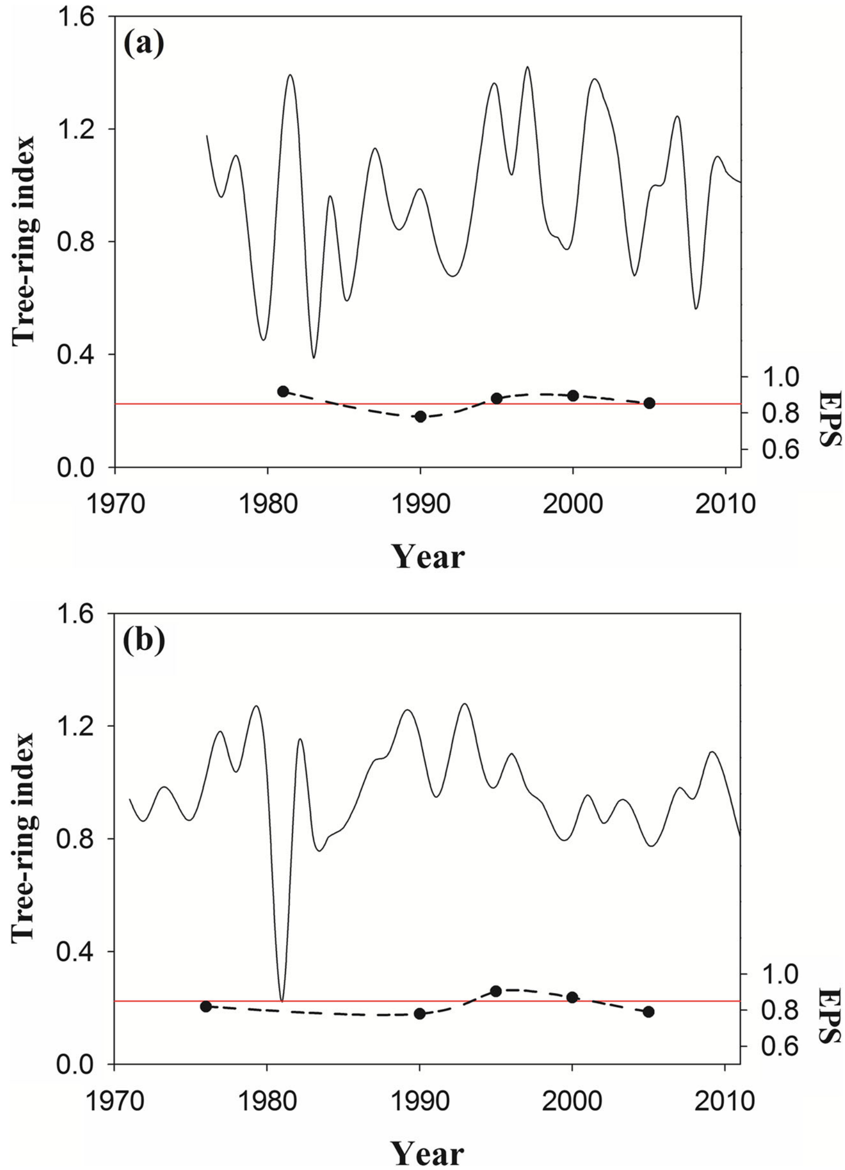


Fig. 3 Chronologies of *T. grandis* for the 1971–2011 period (**b**) and *P. caribaea* var. *hondurensis* for the 1978–2011 period (**a**). EPS for 10-year windows with a 5-year overlap. The *horizontal line* in EPS indicates the 0.85 value which represents adequate samples, according to Wigley et al. (1984)

3.2 Climatic influence on tree ring formation

Correlation between both chronologies and the drought indices for the common period can be visualized in Fig. 4. For teak, SPI, PDSI, and WRSI indices were positively correlated with tree ring index in summer and fall of the current growing seasons, highlighting a stronger relationship of SPI in DJF and PDSI in MAM ($p<0.01$). For Caribbean pine, the climate–tree relationship showed that there was a weaker response to the three moisture indices, unlike the relationships observed for teak. The results showed that Caribbean pine trees had only a significant correlation with WRSI in the driest quarter period before beginning of the growing season (JJAp) and a significant marginal correlation with SPI in the same period.

We observed that the first 5 years of teak chronology had lower correlation with SPI and PDSI in the two quarter periods analyzed, becoming stronger in the following years. This result could be associated to problems with ontogenetic trends because young trees may suffer other limitations for their growth. WRSI values had better correlation with tree ring width of Caribbean pine in middle period (between 1984 and 2000) (Fig. 5).

There was reduced radial growth in teak trees as response to increasing TNI before the growing season (MAMp was significant with $r=0.34$, $p<0.05$; DJFp and JJA are marginally significant with $r=-0.27$, $p=0.1$ and $r=-0.29$, $p=0.08$), indicating the influence of large-scale climate variables of ENSO events on tree growth. There was no significant response between both chronologies and N3.4. AAO–growth relationship results showed a significant positive correlation for the previous summer in teak trees, while in the current growing

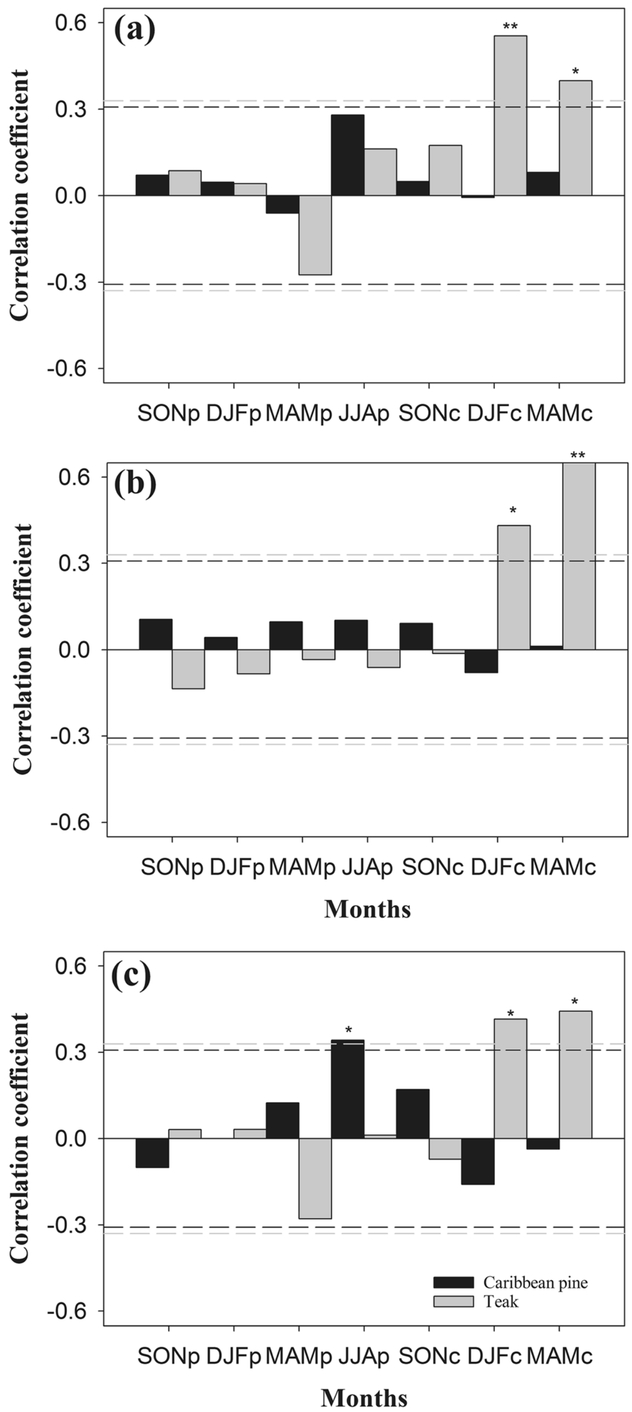


Fig. 4 Climate–growth relationships between residual chronologies of both species and **a** SPI, **b** PDSI and **c** WRSI. *Letters* by the months indicate growth periods (*p* previous year, *c* current year). Period of months with significant correlation (*$p<0.05$ and **$p<0.01$). *Dashed horizontal lines* indicate statistical significance at the 95 % confidence level; *black line* for Caribbean pine and *gray line* for teak trees

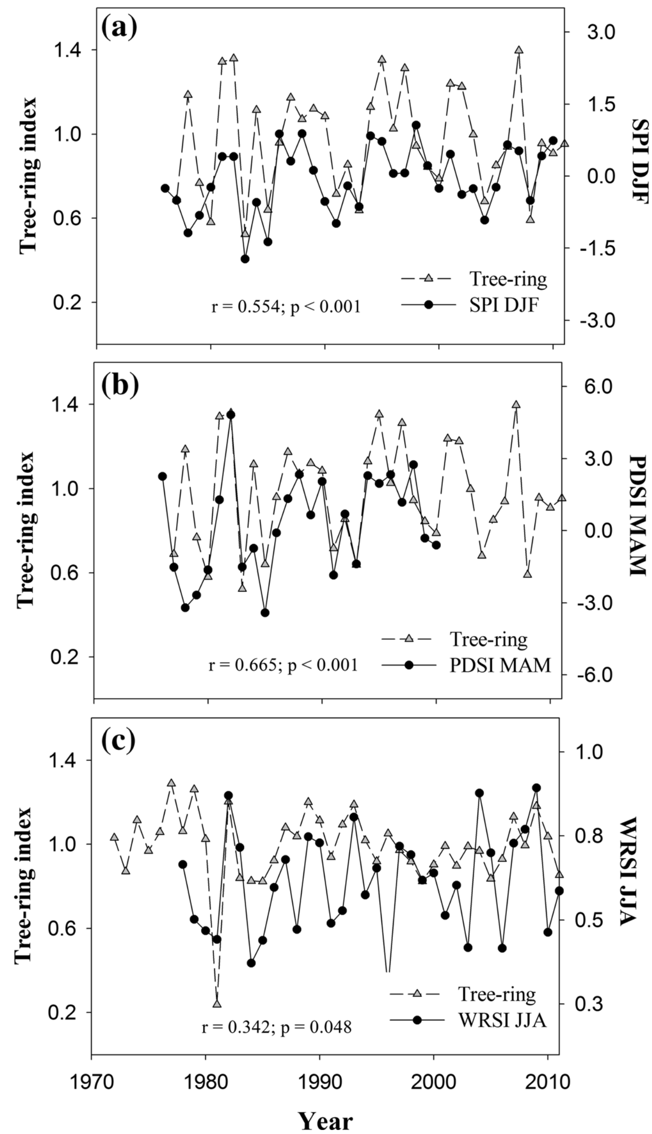


Fig. 5 Correlation between drought indices and radial growth in the seasons with highest correlation between residual chronologies and drought indices for both species: **a** teak vs. mean SPI of December to February, **b** teak vs. mean PDSI of March to May and **c** Caribbean pine vs. mean WRSI of June to August

season there was a marginal positive association with fall. In Caribbean pine trees, there was a stronger relationship with positive phase of the AAO ($p<0.01$), from March to May, during growing season (Fig. 6).

Spatial correlation verifies the significant relationship results between teak chronology and TNI/AAO, and Caribbean pine and AAO (Fig. 7). For teak trees, we observed a positive (negative) association with SST anomalies in the Niño 4 region (Niño 1+2) during previous fall and a negative relationship with geopotential height 850 hPa in the Antarctic region during previous summer. There was a positive association between Caribbean pine trees and geopotential height 850 hPa in the Antarctic region during current fall.

TNI/AAO–trees relationship was verified in Fig. 8, where the accumulated rainfall of MAM was associated with mean TNI values of MAM of the previous year ($r=-0.32$; $n=41$,

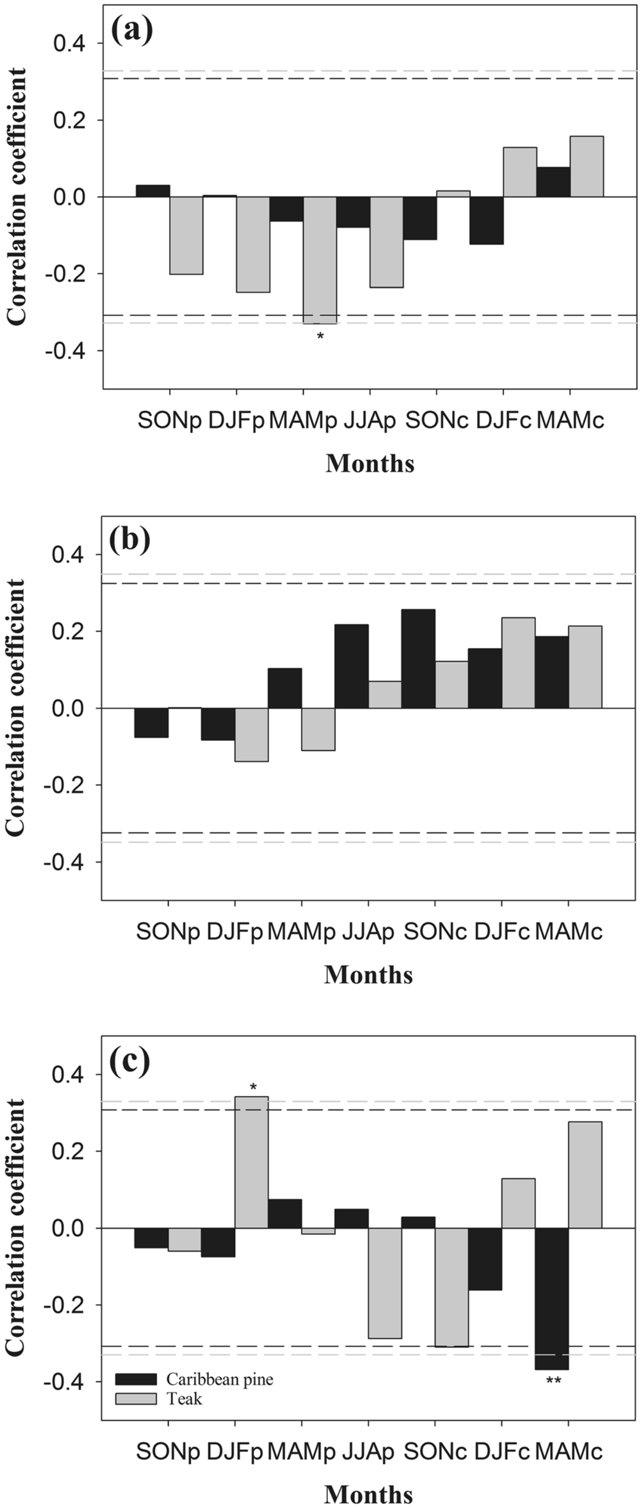


Fig. 6 Climate–growth relationships between residual chronologies of both species and **a** Trans-Niño Index, **b** Niño 3.4 and **c** Antarctic oscillation. *Letters* by the months indicates growth periods (*p* previous year, *c* current year). Period of months with significant correlation (*$p<0.05$ and **$p<0.01$). *Dashed horizontal lines* indicate statistical significance at the 95 % confidence level; *black line* for Caribbean pine and *gray line* for teak trees

$p<0.05$), while there was a significant correlation between AAO values and precipitation during DJF in the same year ($r=0.42$; $n=41$, $p<0.05$).

4 Discussion and conclusion

Climatic change is the weather pattern modification on a global scale, with consequences to the local climate in different time scales (Fowler et al. 2012), so proxy records are needed to represent climate variability at different temporal scales in regions with short or discontinuous climatic records, and even without weather stations (Mundo et al. 2012). Tree rings are the only annual resolution scale proxy capable of delivering relevant information about climate in recent years (Hughes and Ammann 2009; Tomazello Filho et al. 2009). This study presents a perspective on the climate–tree growth relationship for an area with scarce dendroclimatic studies, in São Paulo state, Brazil. Results show a significant positive correlation between two tropical trees and drought indices during different seasons of the year since the climatic response of teak trees is stronger than that of Caribbean pine.

A positive correlation between current summer (DJFc) and fall (MAMc) drought indices and teak tree growth could be observed. This positive association is explained by its dependence on the rainfall period, supporting previous studies which reported maximum cambial activity occurring during the rainy season, e.g., natural vegetation (Rao and Rajput 1999), plantations in Africa (Die et al. 2012) and Brazil (Tomazello Filho and Cardoso 1999). Many studies of teak trees in tropical Asia connect ring widths with the monsoon, which is a seasonal shift in the prevailing wind direction accompanied by rain in hot summers (Pumijumnong et al. 1995; Shah et al. 2007; Borgaonkar et al. 2010; D'Arrigo et al. 2011b). In South America, Worbes (1999) performed a dendrochronological analysis of teak trees, finding a significant positive correlation between tree rings and total precipitation during the rainy and the dry–rainy transition seasons. Therefore, the SPI index attended the relationship between rainfall and tree ring width in teak trees better than the other two indices. These indices have been used as a trend analysis of extreme climatic events of the twentieth century and also could be used for future climate projections for the twenty-first century in Brazil (Sansigolo 2004; Li et al. 2008).

With respect to the MAMc–growth relationship in teak trees, we observed that when there is enough soil water availability in the current fall, a positive effect on ring widths, and thereby extended tree growth, is observed for the current season, PDSI being the best growth regressor index. This result could be related to the fact that the wet intensity of the current month depends on the weather characteristics of this month

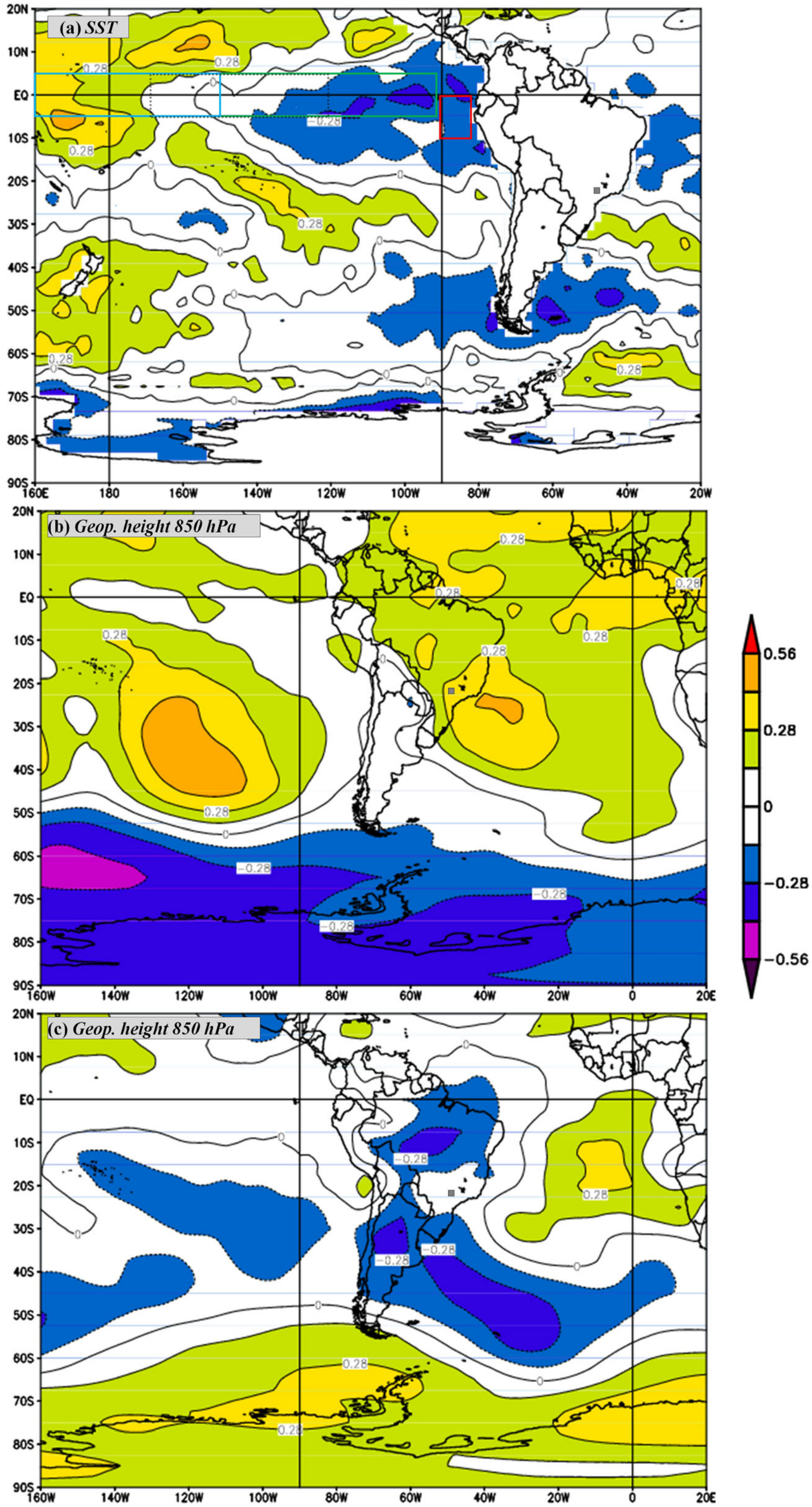


Fig. 7 Spatial correlation fields of tree ring chronology and 2.5°× 2.5° gridded monthly average: **a** teak vs SST (previous March–May), **b** teak vs 850-hPa geopotential height (previous December–February) and **c** Caribbean pine vs 850-hPa geopotential height (current March–May). Correlation values are shown in the *color scale*. Data were obtained from the National Oceanic and Atmospheric Administration website (www.esrl.noaa.gov/psd/data/correlation). Study area is indicated by *gray square*. Niño 1+2, Niño 3, Niño 4 and Niño 3.4 regions are indicated by *red*, *green*, *blue* and *black dashed rectangle*, respectively. Significant correlation at 90 % confidence level is $r=0.28$

more than of the previous months (D'Arrigo et al. 2008). However, this favorable water condition in the fall negatively influences tree growth in the next season, as demonstrated by MAMp (Fig. 4a, c), although it was significant to 90 % confidence level (results not shown). This phenomenon can be explained by this species' semi-deciduous characteristic, so it would avoid or delay leaf drop and trigger physiological imbalance in the teak trees in the next growing season.

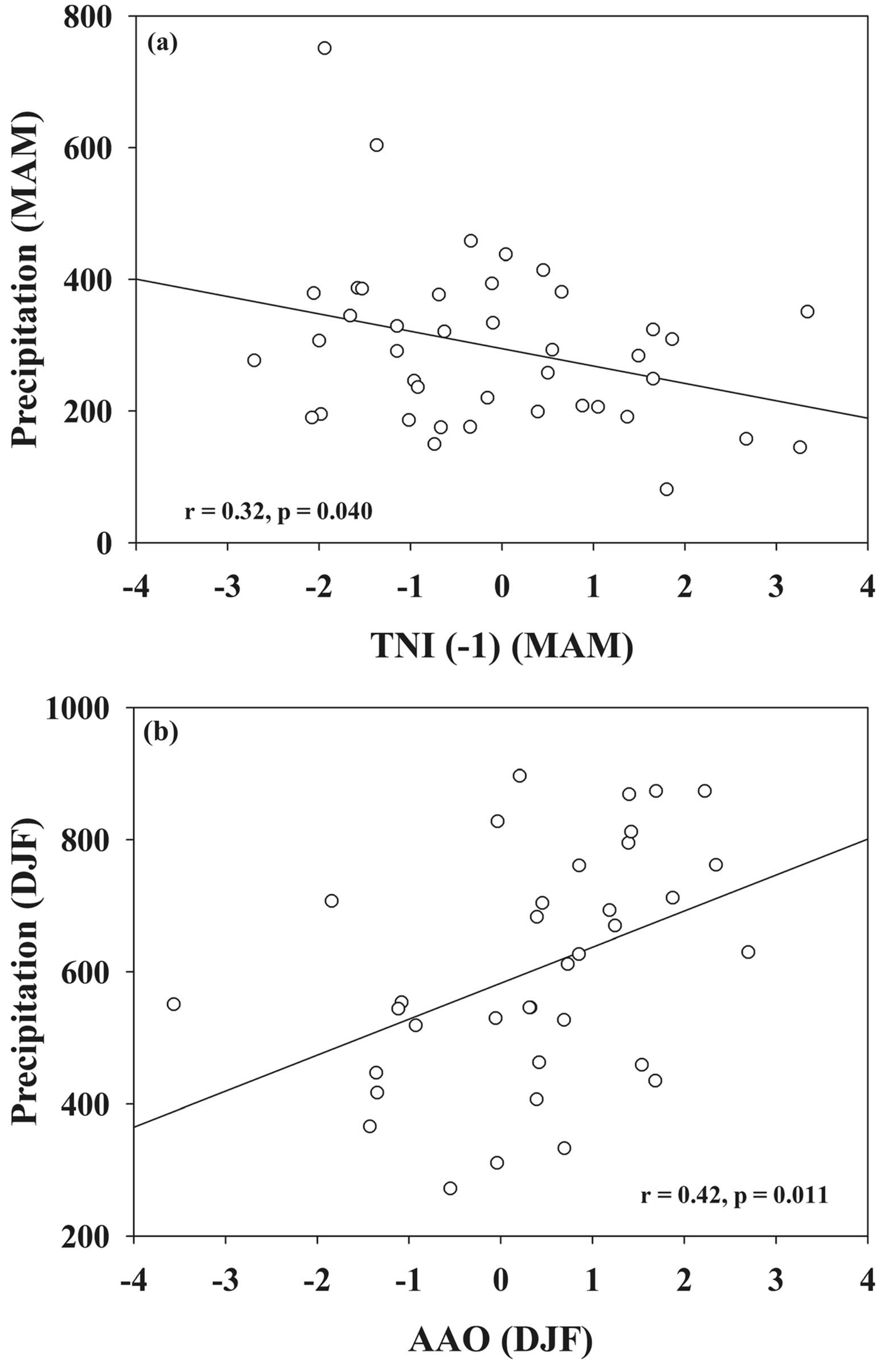


Fig. 8 Better correlations between large-scale climate and precipitation in Piracicaba region during the period 1971–2011. **a** Trans-Niño Index (lag −1 year) vs. precipitation in March–May, **b** Antarctic oscillation vs. precipitation in December–February

On the other hand, for Caribbean pine trees, the WRSI index showed a significant correlation during the prior dry season (June to August; SPI also showed a positive relationship with tree ring growth, although not significant). We inferred that Caribbean pine growth may react to rainfall in the months before the growing season (dry period), and in this context, previous studies of cambial activity for tropical pine showed that the first rainfalls are relevant to start the xylem formation (Pumijumnong and Wanyaphet 2006; Singh and

Venugopal 2011). Similar results were found by Worbes (1999) in Venezuela, where rainfall during the dry season (November to April) positively correlates with tree growth. In this species, the wet season positively influenced the formation of type E intra-annual density fluctuations (formation of narrower, thicker-walled earlywood) due to water saturation in the soil (Venegas-González et al. 2015), with a less growth consequence.

In summary, in this study there was a significant positive correlation between tree growth and moisture indices (Fig. 4). However, tree response is different according to each index in a given season. In teak trees, it was observed that there is a strong positive relationship with PDSI in the fall, while the relationship between teak trees and SPI is higher in the rainy and hot seasons. In turn, for Caribbean pine, WRSI is the index that best explains climate influence on tree rings in the dry season, before the growth period begins. In addition, there was a great difference between the results for different species, so working with more than one species in dendroclimatic studies would be critical for more accurate results since different species tend to have different climatic responses, even if they grow in the same environment (García-Suárez et al. 2009), especially if they are exotic species (Bouriaud and Popa 2007). Therefore, we suggest dendroclimatological studies that use only one drought index and one species.

As expected from the results above, only teak trees have a significant association with both large-scale climate variables (ENSO and AAO). This verifies the species' dendroclimatological potential, already in use for global change studies by International Tree-Ring Data (ITRD) (Cook et al. 2010; Ahmed et al. 2013). In Brazil, it may have potential for climate–tree relationships aiming to interpret the environmental variations in the South America subtropical regions, besides presenting an opportunity to investigate the interaction between planted and native species.

Many authors claim a weak ENSO signal in Southeastern Brazil due to its transition characteristics between opposite signs of rainfall anomalies in North/Northeast and South Brazil (Ropelewski and Halpert 1987; Coelho et al. 2002; Grimm 2003, 2004, 2011). This explains why only strong events are detected, such as the anomalies of the 1924/25 La Niña (severe drought) and the 1982/83 El Niño (heavy rain) (Sansigolo 2012). However, a negative relationship between the teak radial growth and the trans-Niño index (TNI) during months before the period of growth was observed (Fig. 6a). For example, when the SST in Niño 1+2 region decreases (increases) and SST in Niño 4 region increases (decreases), probably the tree rings will be wider (narrower) (Fig. 7a). Trans-Niño index is a measure of the zonal Pacific east–west SST gradient (Li et al 2013). Our results showed that tree growth is better correlated with TNI than with the Niño-3.4 index (which represents the SST anomalies of east-central Pacific; Fig. 6b), suggesting that the teak tree ring chronology is more sensitive to TNI. In addition, there is a negative association between average TNI values in fall and the cumulative precipitation of next year's fall for Piracicaba (Fig. 8b). This verifies the relationship between ENSO and precipitation in this period for this region since TNI represents the evolution of tropical Pacific SST during the onset or decay phases of the ENSO, frequently occurring in austral fall (Lee et al 2013). Consequently, TNI probably may better express the ENSO influence on the study region (Sansigolo, personal communication).

Positive associations between AAO and tree growth in the previous summer season occurs for teak (rainfall period); however, there was a negative correlation between AAO and Caribbean pine during the current fall (Fig. 6c). This demonstrates the different responses among the species to seasonal climate variability of the Antarctic Oscillation. For Patagonian trees, a negative effect on growth is observed in the positive AAO phase (e.g., Lara et al. 2008; Mundo et al. 2012). In this context, the annual mean temperature increases in recent decades have been associated with positive AAO values at the Southern Hemisphere high latitudes (Garreaud et al. 2009) mainly because of the decreased precipitation for these positive values (Aravena and Luckman 2009), but it is necessary to emphasize that in Patagonia, the precipitation regime is very different (maximum rainfall in winter) and that the length of the day and the colder winter there also have an influence, besides water availability.

However, in Southeastern Brazil, the rainiest summers are linked with positive AAO phases, while the driest are associated with its negative phase (Vasconcellos and Cavalcanti 2010). Dry summers occur when the high latitude westerlies (west winds) are reduced, and the jet stream is displaced to the middle latitudes during AAO negative phases. Carvalho et al. (2005) highlights a weakening of the high-level subtropical jet stream and a strengthening of the polar jet stream in positive (negative) AAO phases, and vice versa. In addition, Rao et al. (2003) examined how the AAO is related to the interannual variability of the storm tracks in the tropics during the austral summer (DJF), finding an increase of baroclinic eddy growth in the mid latitudes, during positive AAO phases, and a reduction in the negative phases. In this study, we observed that there is a significant association between the positive AAO phase and summer rainfall in Piracicaba (Fig. 8b). Although our results are focused on a city and do not represent the effect of AAO on precipitation in a larger region, Grimm and Saboia (2014) verified that the fifth rotated EOF mode of summer (DJF) precipitation decadal variability has strongest components exactly over the region studied in this manuscript, and it has been responsible for a decadal scale oscillation with around a 9-year period in the streamflow of the Paraná River [empirical orthogonal functions are tools used to explore and determine teleconnection patterns (Trenberth et al 2005)], besides this mode being negatively connected with AAO. Therefore, anomalous positive precipitation occurs in this region during the positive AAO phase (Vasconcellos and Cavalcanti 2010).

As the atmospheric pressure and geopotential height are positively related, an increased geopotential height means the same for pressure (Garreaud et al. 2009); thus, the lowest pressure in the Antarctic region means a decrease of geopotential height, thereby generating more positive AAO indices (Marshall and Connolley 2006). We were able to confirm this statement because there was a positive (negative) association between AAO and teak ring width chronology (Caribbean pine) and negative (positive) relationship between geopotential height 850 hPa and teak (Caribbean pine) (Figs. 6c and 7b, c) in the previous summer (current fall). The development of a new dendroclimatological study in São Paulo state, Brazil, sheds light on the local and large-scale climate influence on tree growth during recent decades and may thus be useful in future climate change studies. The exotic species *T. grandis* showed to be a good bioindicator of seasonal climate and weather variations on a temporal scale in Southeastern Brazil.

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