Climatic signals in tree rings of Burkea africana and Pterocarpus angolensis from semiarid forests in Namibia

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ORIGINAL ARTICLE

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Climatic signals in tree rings of *Burkea africana* and *Pterocarpus angolensis* from semiarid forests in Namibia

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Abstract Tree-ring studies contribute worldwide to the understanding of climate and its relation to tree growth. Long tree-ring chronologies serve as climate *proxies* for the reconstruction of past, pre-instrument climate and its recent change. In tropical regions, the availability of exactly dated tree-ring chronologies is limited. The dendroclimatic potential of two dominant species from dry forests in northern Namibia was examined in the study presented in this paper. Both species (*Burkea africana* Hook and *Pterocarpus angolensis* DC) were sampled at two sites (ca. 900 km apart), and the response to several climatic variables, including ENSO indices, is studied. All specimens showed distinct growth rings and crossdating between radii was successful for all trees. Species-specific mean curves were built for both sites. The mean curves of different species of the same site synchronised significantly, allowing the construction of a site-specific chronology. Synchronisation between sites was not possible, but spectral analysis of the chronologies implied that both show similar long-term (6.7 year) oscillation patterns. *B. africana* is more sensitive to rainfall variation than *P. angolensis* at both sites. Growth response to rainfall was positive, but a time-lag in the reaction occurred between the sites, corresponding to the time-lag of the beginning of the rainy season. Air temperature showed a negative correlation with stem increment at both sites. The response at the westernmost site to two ENSO indices indicates a tree growth decrease during El Niño years, which are generally dry in southern Africa.

Keywords Tree rings · Semiarid Africa · El Niño Southern Oscillation · *Burkea africana* · *Pterocarpus angolensis*

Introduction

To understand natural climate variability and the magnitude of possible human impact on it, high resolution, long-term climate data are needed (Bradley et al. 1996). The availability of such data becomes more urgent in critical regions, where the environment is closely linked with its climate (Yadav and Singh 2002). Because the major part of southern Africa suffers from poor infrastructure and low socio-economic development, the consequences of extreme weather or climate anomalies are often devastating to both people and property (Fauchereau et al. 2003). High vulnerability to weather and climate hazards, associated with the growing population, make southern Africa one of the regions where potential changes in the hydrological cycle due to global warming could lead to extreme negative impacts on societies (Shulze et al. 2001).

Climatic time-series, as provided by instrument-acquired records, are very limited in Africa, in time as well as in space (Anyamba and Eastman 1996). Proxy data offer a potential solution to this problem. Tree-ring data in particular often have a fixed annual resolution and can produce absolute time-series (Cook 1992). If trees show annual rings, dendrochronology is doubtless the safest and most reproducible way of age dating (Worbes 2002). Long-term ring chronologies are a potentially powerful tool for analysing demographic trends and ecological factors influencing growth in tropical trees (Vetter and Botosso 1989). Previous tree-ring studies have shown the dendroclimatic potential of several tree species in southern Africa (February 2000; Gourlay 1995; Stahle et al. 1996, 1999; Trouet et al. 2001, 2004). Basic knowledge of

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the relationship between environmental variables and tree growth is crucial for the prediction of future growth responses to climatic variation (Pumijumnong 1999) and to such long-term phenomena as El Niño Southern Oscillation (ENSO) (Cook 1992).

Recent climatic change may bring about rapid environmental changes that may have extreme impacts on tree growth (Jalilvand et al. 2001), as tropical tree growth is sensitive to the timing and variation in local climatic regimes (Enquist and Leffler 2001). Global warming could also partly be related to the enhanced influence of ENSO on southern African rainfall (Fauchereau et al. 2003). The reconstruction of the regional influence of ENSO on climate, can only be derived from information acquired in the centre of the relevant region and therefore proxy data need to be acquired locally (D'Arrigo and Jacoby 1992).

This study examines the potential of tree rings of two indigenous species in Namibia for dendrochronological studies and the connection between tree growth and climate for these species. Up to now no chronologies are available for *Burkea africana* Hook or *Pterocarpus angolensis* DC from Namibian stands, although for the latter a short chronology from Zimbabwe exists (Stahle et al. 1999). Special emphasis is placed on the connection between tree growth and the ENSO phenomenon.

Material and methods

Study sites

At two sites in northern Namibia, Ondangwa (56°17′S, 59°15′E) and Katima Mulilo (30°17′S, 17°24′E), 32 individual trees of two species (*Burkea africana* Hook, Caesalpiniaceae; *Pterocarpus angolensis* DC, Papilionaceae, both Leguminosae) were sampled during the dry season of 1998 (Katima Mulilo) and 2000 (Ondangwa). Total annual rainfall is lower in Ondangwa (454 mm) as compared to Katima Mulilo (672 mm). The climate of both sites is characterised by an annual dry season of 5–7 months with less than 50 mm precipitation (Fig. 1), which lasts in general from May to October.

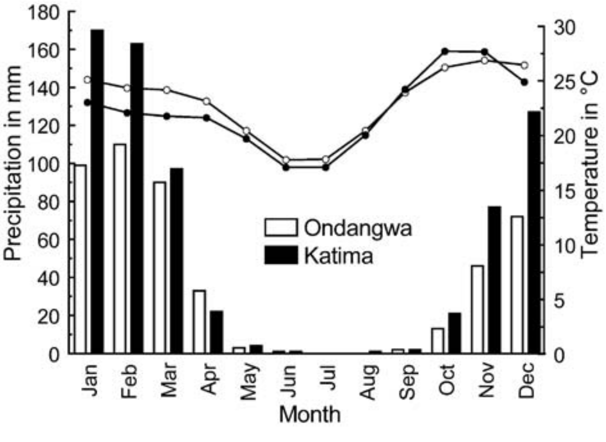

Fig. 1 Annual distribution of rainfall (*bars*) and temperature (*lines*) at Ondangwa (*white*) and Katima Mulilo (*black*)

Tree species

Both tree species are common in southern African woodlands. *Burkea africana* (Red Syringa) is a medium sized tree usually 8–10 m tall, with a maximum height of 20 m (Coates Palgrave 1997; Storrs 1995). It occurs in various types of woodlands over a wide range of altitudes and habitats, but is most characteristic for hot, low-lying areas (Coates Palgrave 1997). Leaf fall takes place from May to September and new leaves flush from August to December. Flowers appear from August to November whereas fruits ripen from February to October but can remain on the tree for a very long time (Coates Palgrave 1997; Storrs 1995). The wood is hard, heavy (865 kg/m^3 at 12% moisture content, Goldsmith and Carter 1981) and tough. Because of its small tree stature the wood is limited in use.

Pterocarpus angolensis (African Blood wood) is a medium sized to large tree up to 16 m high, but reaching 28 m under ideal conditions (Coates Palgrave 1997; Storrs 1995). It occurs in woodland and wooded grasslands. Leaves fall from May to June and new ones emerge from September to October. Flowering takes place in the months August–December while fruiting occurs from January to June (Coates Palgrave 1997; Storrs 1995). *P. angolensis* is very resistant to fire. It is one of the best-known, most generally used and most valuable timber crops in southern tropical Africa (Coates Palgrave 1997) with a density of 640 kg/m^3 at 12% moisture content (Goldsmith and Carter 1981).

Tree-ring analysis

All samples consisted of full stem discs. The discs were dried in open air and polished progressively with sanding paper bands up to grit 600. Then the samples were cleaned from dust with compressed air.

Tree-ring structure was analysed under a stereo-microscope with low magnification. Ring boundaries were marked starting from the wane edge to the centre, with special attention paid to the determination and registration of wedging rings.

Ring widths were measured to the nearest 0.01 mm using LINTAB equipment (Rinn and Jäkel 1997). To avoid any inaccuracy the discs were readjusted during the procedure to measure perpendicularly to the rings.

Cross-dating and indexation

Growth curves are compared visually and statistically to bring ring-width series in a synchronous position (Pilcher 1990; Worbes 1995). Successful cross-dating indicates the influence of an external growth factor on tree growth in a region (Eckstein et al. 1981). To gain reliable results the overlap of cross-dated time-series should reach a minimum of 40 years (Pilcher 1990). The Student's t-value expresses the degree of affinity of two time-series (Baillie and Pilcher 1973):

$$\text{Student's } T = r\frac{\sqrt{n-2}}{\sqrt{1-r}}$$

where n is the number of values and r is the correlation coefficient.

In addition to this the "Gleichläufigkeitskoeffizient" (GLK) is used in dendrochronology to investigate the success of cross-dating. The Gleichläufigkeit is a measure of the year-to-year agreement between the interval trends of two chronologies based upon the sign of agreement, expressed by the following equations (Schweingruber 1988):

$$G_{(x,y)} = \frac{1}{n-1}\sum_{i=1}^{n-1}\left[G_{ix} + G_{iy}\right]$$

where G, Gleichläufigkeit; n, number of values; and x, y, series.

The indexation and calculation of the GLK as well as the Student's t-value were performed with time-series analysis and presentation (TSAP) software (Rinn and Jäkel 1997). In addition mean sensitivity values were calculated for all chronologies to provide a measure of between-ring variability (Schweingruber 1988):

$$\overline{S} = \frac{\sum_{i=1}^{n-1}[S_i+1]}{n-1} \text{ with } S_i = \frac{(x_i - x_{i-1}) \times 2}{(x_i + x_{i-1})}$$

where S is the sensitivity and n is the number of values.

In order to obtain a correlation coefficient that can be interpreted correctly, a transformation of the time-series into indexed curves is necessary (Cook and Briffa 1990). Long-term growth trends are thus removed from the individual curves by division of a one-sided running mean of 5 years (Baillie and Pilcher 1973; Schweingruber 1988).

In the present study 3–4 radii of a tree were visually and statistically cross-dated to produce a mean curve for every individual tree. Successfully cross-dated ring-width series of different individuals were averaged to build species-specific mean and site-specific mean chronologies. In case of successful correlation of the specific chronologies, master chronologies for species and/or stands were obtained in the same way. Correlation analysis with climatic data sets was performed using Pearson's correlation calculation with a 5% significance level.

Climate data

The climatic data set used for the correlation analysis, contained precipitation, relative humidity and temperature data. Nicholson (2001) defined regions of the African continent, which have been shown to be climatically homogenous with respect to intra-annual variability of rainfall. Mean monthly precipitation data for two corresponding regions were calculated in order to investigate (a) long time-series and (b) the impact of large-scale precipitation events. Data from region 61 (including Ondangwa), were available for 1901 up to 2000 (Nicholson, personal communication), and data from region 57 (Katima Mulilo) for 1901 to 1984 (National Centre for Atmospheric Research, http://ncardata.ucar.edu/datasets).

Mean monthly relative humidity and temperature data for both sites were derived from the IPSL ClimServ data set (Centre National de la Recherche Scientifique, Laboratoire de Météorologie Dynamique, http://climserv.lmd.polytechnique.fr/las/main.pl) and were available for a time period covering 1948–2000.

For the correlation analysis, precipitation data for single months as well as the sum of all months [corresponding to the "growth year" August (n–1)–July (n)] were used. Further precipitation variables such as the sum of precipitation from August to December (SAD) and January to June (SJJ) were calculated. In addition to this the sum of rainfall in the transition months between dry and rainy season [September–October (SSO)] and between rainy and dry season [April–May (SAM)] were built (cf. Worbes 1999). Depending on the results of the correlation between single months and chronologies, the variables sum of precipitation in October and November (SON) and January and February (SJF) were added to the data set.

In the same way mean monthly and mean annual relative humidity and temperature data were used in the correlation analysis. Additional time-series of mean values of August–December (MAD), January–June (MJJ), September–October (MSO), April–May (MAM), November–May (MNM) and finally June–August (MJUNAUG) were constructed.

In addition to correlation with climate data, response of growth ring widths to the ENSO signal, as defined by the southern oscillation index (SOI; Ropelewski and Jones 1987) and the Sea Surface Temperature Index for the Niño 3.4 region (5°N–5°S; 120°–170°W; Niño 3.4; Trenberth and Stepaniak 2001) was investigated. Therefore monthly deviation and mean annual deviation of these indices were used. In the same way as with temperature and relative humidity mean values of the monthly data were created as the mean from October to August (MOA), May to December (MMD), MAD and MJJ. The time-series of these indices were obtained from the NOAA Climate Prediction Centre (http://www.cpc.ncep.noaa.gov/data/indices/index.html). Additionally, correlation was calculated with time-series of sea surface temperature anomalies (SSTa) from the southern Atlantic Ocean and from the southwestern Indian Ocean. Time-series of these indices were obtained from the NOAA Climate Prediction Centre (http://www.cpc.ncep.noaa.gov/data/indices/index.html).

Statistical analysis

Statistical analysis was performed using TSAP and *Statistica* software.

In addition to cross-dating and correlation analysis, spectral analysis was executed, which can be used to describe cycles in time-series (Jenkins and Watts 1968). The spectra of the chronologies of both stands were analysed to examine the distribution (over frequency) of the strength of their periodic signal, using Autosignal software (Systat Software). The significance of the signal's peaks was tested based on Monte Carlo permutation tests (Barnard 1963). Time-series were also filtered using eigendecomposition (Elsner and Tsonis 1996) in order to reveal significant peaks. Furthermore a cross-spectral analysis was performed between the chronologies.

Results

Tree-ring analysis

Tree-ring structure

Both species show distinct growth rings (Figs. 2, 3). The sites are affected by an annual drought and both species are deciduous, shedding their leaves during the dry period. As cambial activity in tropical trees is generally induced by flushing and terminates some time before leaf shedding (Borchert 1999), the growth patterns found can be considered as consisting of annual rings.

The wood structure of *B. africana* is characterized by a marginal parenchyma band at the limit of a ring often combined with a tissue band containing very few pores (Fig. 2a). In some rings the wood rays become broader on the ring boundary (Fig. 2b). In *B. africana* wedging rings occur but can be determined by analysing various radii (Trouet et al. 2001).

The tree-ring structure of *P. angolensis* (Fig. 3a,b) is characterized by a weak ring porous vessel distribution where many larger, mainly solitary, vessels aggregate at the beginning of the ring (Fig. 3a). Apart from that, the rings are delimited by a thin marginal parenchyma band and a slight difference in fibre cell wall thickness, between earlywood and latewood (Fig. 3b). *P. angolensis* rarely shows wedging rings, and these can also be determined following the same procedure as in *B. africana*.

Cross-dating

Cross-dating between radii of the same disc was successful for all trees for both species at both sites. According to Worbes (2002) tree rings of the juvenile wood cannot be used, as very young trees (4–5 years) respond

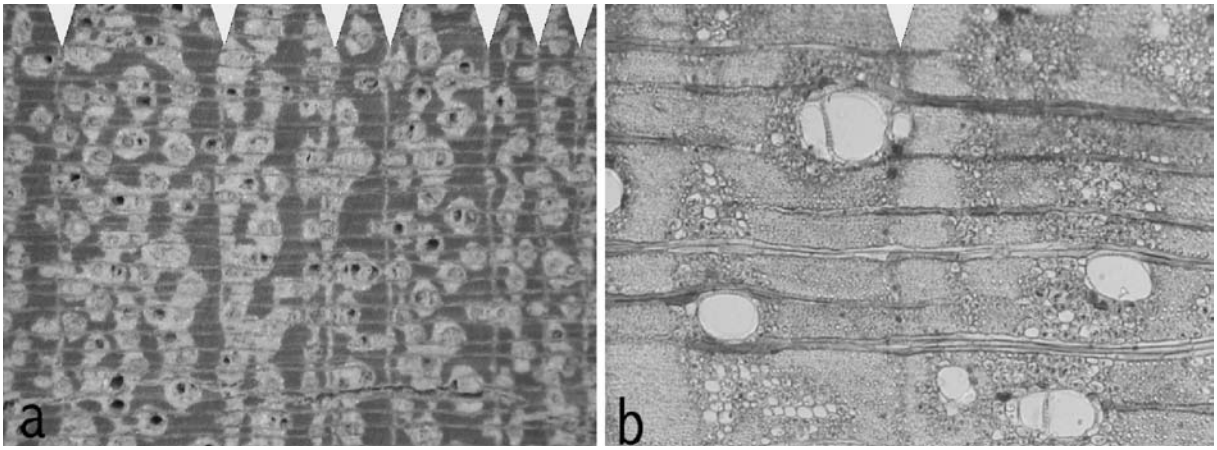

Fig. 2 *Burkea africana* macroscopical (**a** ×16) and microscopical (**b** ×25); *white triangles* indicate ring boundaries

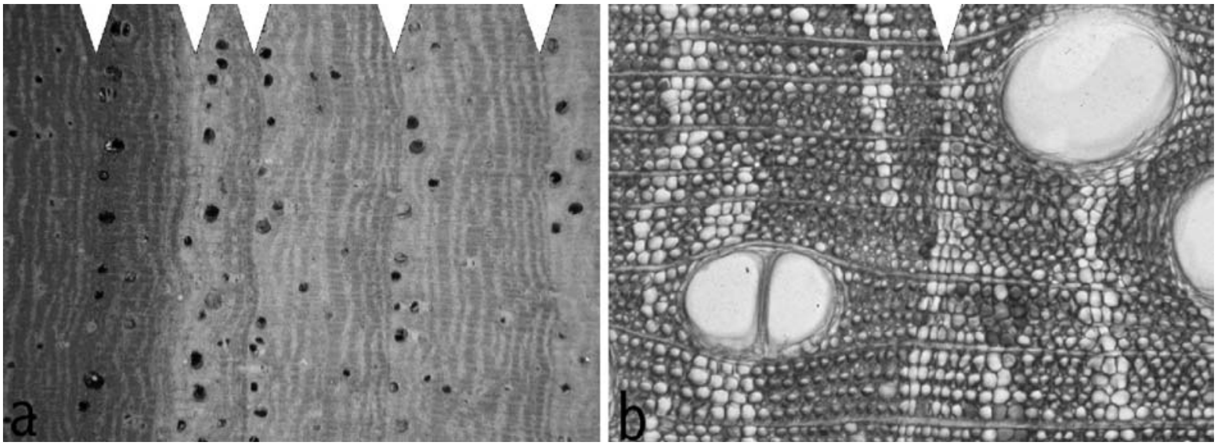

Fig. 3 *Pterocarpus angolensis* macroscopical (**a** ×10) and microscopical (**b** ×25); *white triangles* indicate ring boundaries

Table 1 Sampling and chronology characteristics for Ondangwa and Katima Mulilo

Study site	Species	No. of samples available	No. trees/ chrono	Age chronology (years $\geq$ four trees)	Mean sensitivity
Ondangwa	*B. africana*	15	12	110	0.27
	P. angolensis	8	5	79	0.31
Katima Mulilo	*B. africana*	5	5	65	0.29
	P. angolensis	4	4	60	0.41

differently physiologically to climatic factors compared to mature trees.

Cross-dating of *B. africana* trees at Ondangwa was successful for 12 out of 15 trees (Table 1),varying in length between 25 and 187 years. A chronology was constructed for this site with a length of 110 years (based on four contributing trees) and a mean sensitivity value of 0.27. All five sampled trees of *B. africana* at Katima Mulilo, contributed to the chronology, which had a length of 65 years (based on four contributing trees) and a mean sensitivity value of 0.29. The master chronology of *P. angolensis* at Ondangwa consisted of five out of eight sampled trees. It had a length of 79 years (based on four contributing trees) and a mean sensitivity value of 0.31. Finally the chronology of *P. angolensis* at Katima Mulilo consisted of all four studied individuals with an age between 15 and 152 and had a length of 60 years (based on four contributing trees) with a mean sensitivity value of 0.41. The species-specific chronologies built for both sites are shown in Fig. 4.

Cross-dating among different species from the same sites was possible with significant T-values (with $p<0.05$) and GLK values (Table 2), but the chronologies of the same species at the two different sites did not correlate strongly. The master chronology for Ondangwa thus consists of 17 series, while the master chronology for Katima Mulilo consists of nine.

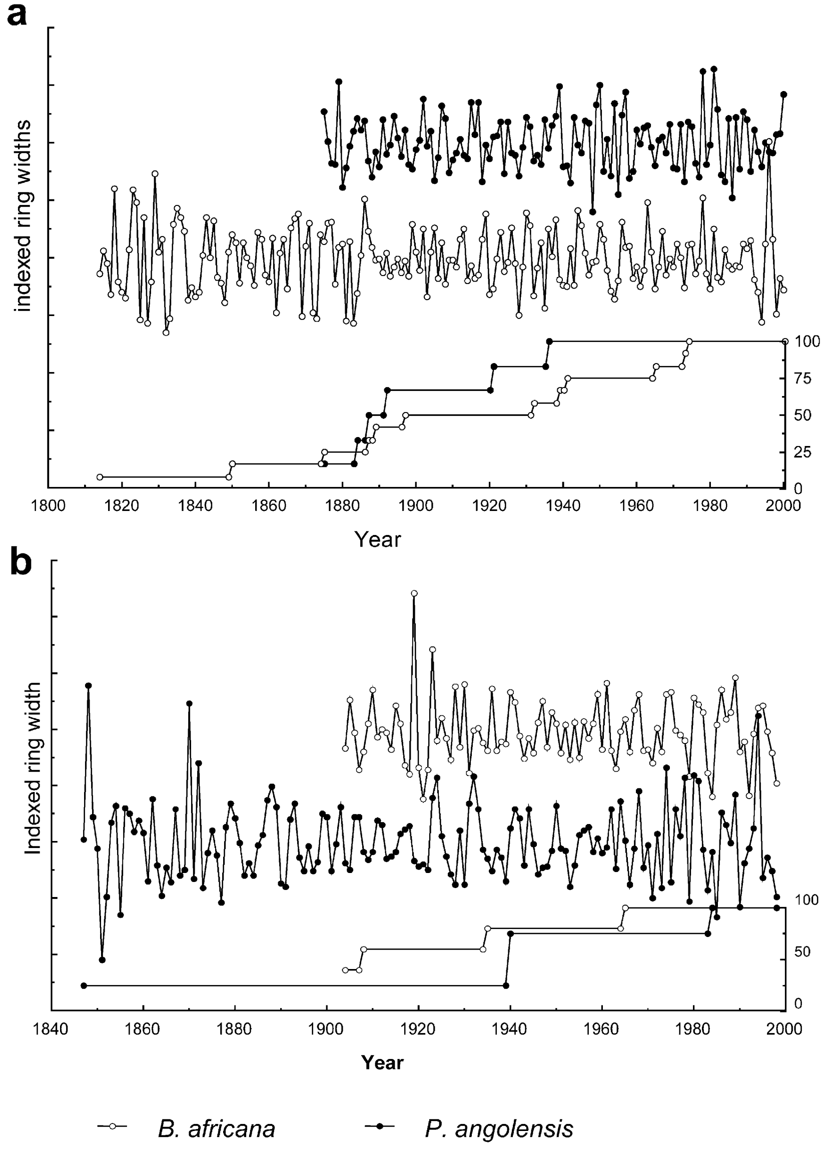

Fig. 4 Chronologies and sampling depth for *B. africana* and *P. angolensis* at Ondangwa (**a**) and Katima Mulilo (**b**). Sampling depth 100% in Ondangwa for *B. africana* (12 trees), and for *P. angolensis* (5 trees); in Katima Mulilo for *B. africana* (5 trees), for *P. angolensis* (4 trees)

Table 2 Gleichläufigkeitskoeffizient (*GLK*), *T*-value, *r*-value and overlap period (*OVL*) for the cross-dating of *B. africana* and *P. angolensis* at the two sites

Site	species	GLK	*T*-value	*r*-value ($P<0.05$)	OVL
Ondangwa	*Burkea* vs *Pterocarpus*	63	2.8	0.264	81
Katima Mulilo	*Burkea* vs *Pterocarpus*	68	3.9	0.472	59

Spectral analysis

The spectral analysis reveals for both chronologies significant (>95%) peaks in the frequency domain of 0.145–0.155 (Fig. 5), corresponding to periods of 6.4–6.9 years. Cross-spectral analysis shows a coherency of 0.86 between the chronologies at a frequency of 0.155. The Ondangwa chronology shows a second peak at a frequency of 0.277 (3.6 years), which is significant (>99%) when the first four signal components of the time-series are filtered.

Response to climate

A correlation analysis was conducted using the species-specific chronologies and the master chronologies for both sites. Response to all climatic variables was tested separately.

Response to precipitation

B. africana shows for both sites higher correlations to rainfall variables than *P. angolensis*, which is only highly

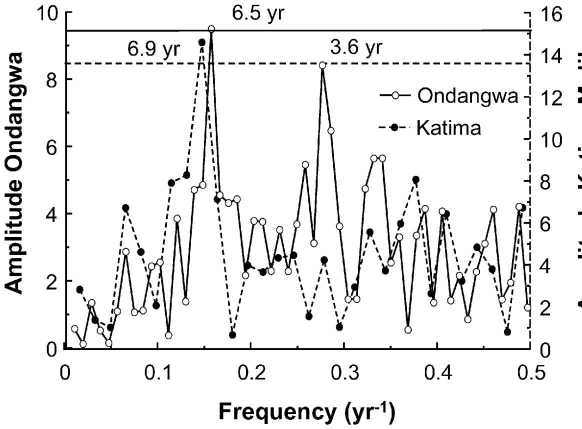

Fig. 5 Results of the spectral analysis of the master chronologies from Ondangwa (1890-2000) and Katima Mulilo (1938-1998). 95% significance levels are shown as *solid lines* (Ondangwa) and *dashed lines* (Katima Mulilo)

correlated to rainfall in April and to the summed rainfall of April and May in Katima Mulilo (Fig. 6). In Ondangwa, *B. africana* responds strongly to rainfall in January and February. In addition, the chronology correlates to the total rainfall over the vegetation period. In Katima Mulilo, strong correlations between the *B. africana* chronology and the rainfall data are found for the months of August, September and November, as well as for the sum of the months October and November.

Response to temperature and relative humidity

In Ondangwa, strong responses to both relative humidity and temperature were found for the *B. africana* chronology, but not for *P. angolensis*. In contrast to Katima Mulilo where only *P. angolensis* was strongly influenced by these climate variables. For both sites, no additional significant results were obtained by using the master chronologies. Correlation for both sites is shown in Fig. 7. In general, influence of relative humidity was more explicit at Ondangwa as compared to Katima Mulilo. Tree growth of *B. africana* at Ondangwa was negatively correlated to relative humidity at the beginning of the growing season (August–December), but correlation tended to be positive towards the second half (January–June). No similar trend was found for Katima Mulilo. Response was negative for the months October, November and the mean of September and October at Ondangwa and for the month October only in Katima Mulilo.

Correlation with temperature data was stronger for *P. angolensis* in Katima Mulilo than for *B. africana* in Ondangwa. For both sites, correlation was negative in general and tended to become stronger towards the end of the growing season. Negative correlation was found with temperatures of the month of April for Ondangwa and the months of May to July for Katima Mulilo. Correlation was also strong for the mean of the corresponding months (April–May). In addition to this, the mean temperature of the first half of the growing season (August–December) as well as the second half (January–July), had a negative influence at both sites. At Katima Mulilo, tree growth of *P. angolensis* was negatively correlated to the mean annual temperature.

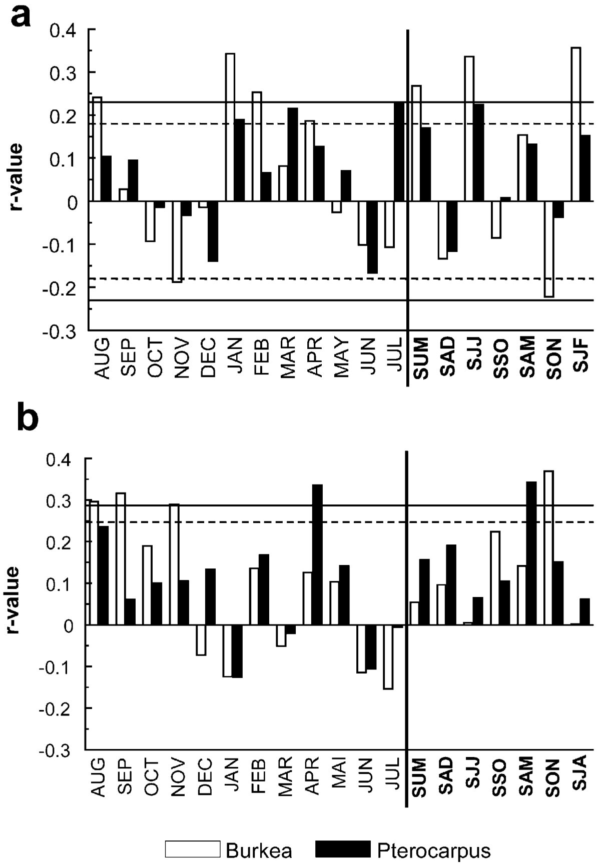

Fig. 6 Response of *B. africana* and *P. angolensis* chronologies from Ondangwa (**a**) and Katima Mulilo (**b**) to rainfall. Rainfall variables used are monthly rainfall data (*AUG* to *JUL*) and various sums over longer periods (cf. Material and methods). Significance levels are shown as *solid lines* (P=0.05) and *dashed lines* (P=0.1) lines

Response to ENSO

The individual chronologies of *B. africana* and *P. angolensis* showed a less strong correlation with ENSO than the master chronology at Ondangwa (Fig. 8). Correlation analysis of all chronologies at the Katima Mulilo site yielded no significant results.

The response of the Ondangwa chronology to both indices is overall positive to SOI and negative to Niño 3.4. Response to Niño 3.4 is negative for all individual months from May previous to the growth year up to March of the growth year. Response to Niño 3.4 of the end of the growing season (April–July) is weak. This trend is not visible in the response to SOI, where strong results are found throughout the growth year (August, October, January, April and May).

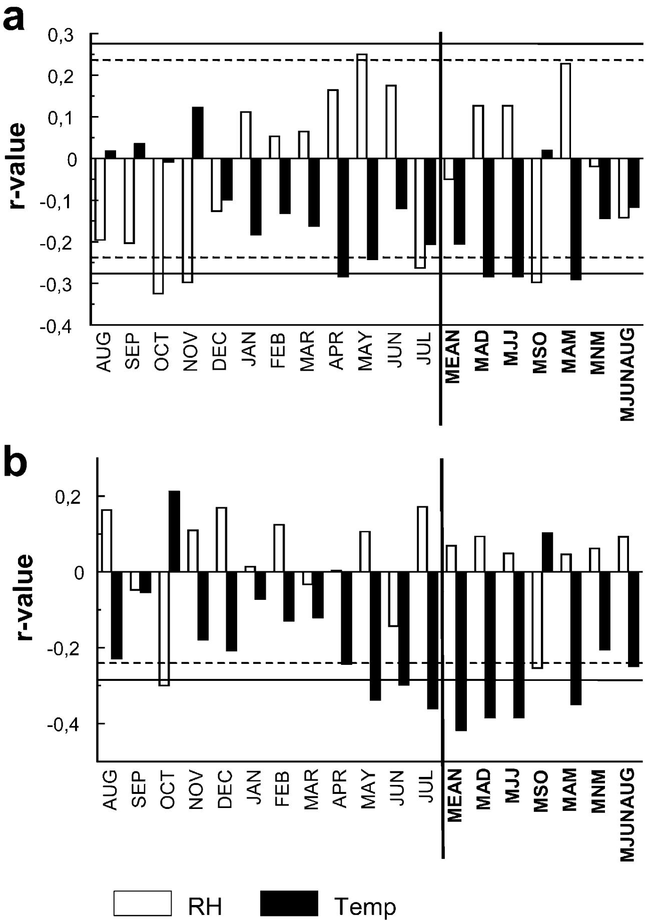

Fig. 7 Response to relative humidity (*RH*) and temperature (*temp*) of the *B. africana* chronology in Ondangwa (**a**) and the *P. angolensis* chronology in Katima Mulilo (**b**). Climatic variables used are monthly data (*AUG* to *JUL*) and various means over longer periods (cf. Materials and methods). Significance levels are shown as *solid lines* (P=0.05) and *dashed lines* (P=0.1)

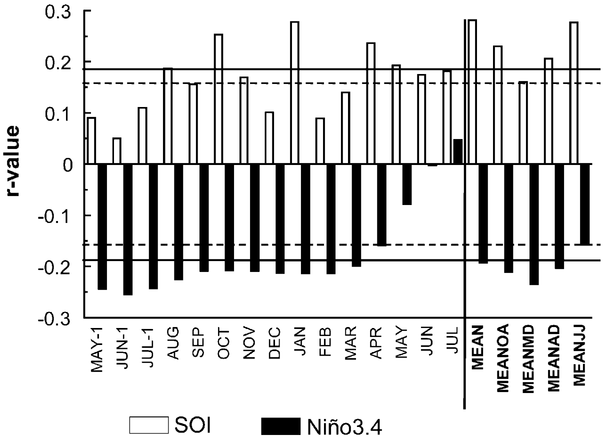

Fig. 8 Response to two ENSO-indices (SOI and Niño3.4) of the master chronology at Ondangwa (1890-2000). ENSO-indices used run from May of the previous year (*MAY-1*) to July of the growth year (*JUL*). In addition to this, mean indices over several months were used. Significance levels are shown as *solid lines* (P=0.05) and *dashed lines* (P=0.1)

No response was found to the Indian Ocean SSTa time-series, but the Ondangwa chronology responded strongly to southern Atlantic Ocean SSTa of the months of May (r=0.43, P<0.05) and June (r=0.37, P<0.05) previous to the growth year.

Discussion

The tree species investigated in the present study show distinct ring structures. A pronounced seasonality of rainfall appears at both sites, which provides an absolute annual rhythm in radial growth. This is obvious by the fact that the tree species are deciduous, shedding their leaves during the dry season, which makes the trees produce visible growth rings. As we investigated complete stem discs, no difficulties were caused by missing rings. Cross-dating of the ring widths over the entire life span of the individual trees was successful for both species at both stands. Successful cross-dating between individuals within the same stands expresses an external oscillation factor influencing tree growth (Worbes 1995). Thus, the growth of the studied tree species is periodical, tied to the annual calendar by seasonality of climate and synchronized among many trees in the same region by inter-annual variation in the shared regional climate (Stahle et al.1999). It can be concluded that tree rings in *B. africana* and *P. angolensis* are of annual nature.

Both species show a rather strong correlation between ring width and climate, suggesting that tree growth of *B. africana* and *P. angolensis* is sensitive to climate. The growth of *B. africana* seems to be more sensitive to precipitation at both sites, while *P. angolensis* shows stronger correlation with temperature and relative humidity at Katima Mulilo. The different sensitivity to rainfall could be a hint to different water-use strategies: for *B. africana* the rooting depth lies between 15 and 60 cm (Rutherford 1983) while for *P. angolensis* the range of the rooting depths lies between 30 and 200 cm (Vermeulen 1990). This indicates better access to groundwater in *P. angolensis* compared to *B. africana*, while the latter is more affected by different rainfall conditions.

In Katima Mulilo the strongest correlation between rainfall and tree growth is found in the period from September to November, in Ondangwa from January to April (cf. Fig. 6). In Katima Mulilo the rainy season starts up to a month earlier and is thereby more intensive with mean monthly precipitation above 50 mm already in November and a total of 3 months above 100 mm monthly rainfall (cf. Fig. 1). In Ondangwa the first month above 50 mm rainfall per month is December and amounts above 100 mm are only reached in 1 month, i.e. February. The crucial time of the vegetation period and thus the time of tree growth corresponds to the months with high precipitation rates (Worbes 1999). In Katima Mulilo these are the first months of the growing season compared to Ondangwa, where the highest rainfall occurs in the second half of the growing season. Interannual variation during and around the crucial months concerning rainfall could cause variation in growth and could thereby explain the time-lag of the strongest correlation of rainfall and tree growth at the two stands. As all significant responses to rainfall are positive, higher precipitation rates seem to have a positive influence on tree growth at both sites.

The overall negative correlation to temperature throughout the year can be explained by the fact that plant respiration increases exponentially with increasing temperature (Fitter and Hay 1981) and results in a higher loss of assimilated carbon as a source of energy. A similar trend was found by Clark et al. (2003), who observed highly significant negative correlation of tree growth deviations with current-year means for daily minimum temperature at a tropical rain forest in Costa Rica.

The overall positive effect of an increase in relative humidity on tree growth (except for the beginning of the growing season in Ondangwa), could be related to a direct physiological influence. Low relative humidity values can cause closure of the stomata and a reduction of the CO_2 uptake by the plant. However, the strong negative correlation between monthly temperature and relative humidity values, could also cause the observed continuous opposite effect of both variables on tree growth.

The annual nature of tree rings in *B. africana* and *P. angolensis* and the possibility of cross-dating implies high potential for dendrochronological studies in semi-arid forests in southern Africa. The correlation between rainfall, temperature, relative humidity and tree growth is obvious and is therefore useful for future investigations on tree growth and climate studies. The correlations found here lie in the range of other studies performed in the tropics (Jacoby and D'Arrigo 1990; Stahle et al. 1999; Worbes 1999).

The influence of the El Niño phase of the ENSO phenomenon on climate in southern Africa, is a decrease in precipitation (Nicholson and Entekhabi 1986; Ropelewski and Halpert 1996) and an increase in temperature (Trenberth and Caron 2000). Conversely, the La Niña phase brings an increase in precipitation. Tree growth in Ondangwa is correlated to the ENSO phenomenon (Fig. 8). Both the atmospheric (SOI) and the oceanic (Niño 3.4) aspect of the ENSO phenomenon (Kestin et al. 1998) are used in the correlation analysis applied in this study. The response of tree growth to both indices, which are strongly negatively correlated to one another, is consistently opposite over the entire growing season. As the Niño 3.4 index, which is based on sea surface temperatures in the Pacific Ocean, shows positive values during the El Niño phase of the ENSO-cycle (Trenberth and Stepaniak 2001), the observed negative correlations indicate a tree growth decrease during El Niño years and an increase in La Niña years. Tree growth decrease in dry El Niño years thus corresponds to the positive relation between tree-ring width and rainfall (Fig. 6). The effect of both phases is strongest during the mature phase of the phenomenon, which lasts from December until May in southern Africa (Anyamba et al. 2002). Cook (2000) found the strongest correlation between rainfall variance in southern Africa and SOI in the late rainy season, during the months January–March. Influence of ENSO on tree growth in western Zambia was also found to be strongest during these months (Trouet et al. 2004). The response of tree growth in Ondangwa to Niño 3.4 (Fig. 8) reflects this effect, as correlation coefficients drop rapidly after the month of March. This, however, could be due to a statistical bias, caused by the strong multicollinearity in the ENSO data set.

Despite statistical correlations found between rainfall and the ENSO phenomenon, not every El Niño year is dry over southern Africa. The strong El Niño event of 1997/1998 for instance, brought drought to Namibia, but did not influence precipitation patterns over other parts of southern Africa (Anyamba et al. 2002). Regional sea surface temperature conditions in the southwestern Indian Ocean and southern Atlantic Ocean may lie at the base of this spatial inconsistency, as they regionally can modify or dampen the precipitation anomaly patterns related to the ENSO phenomenon (Anyamba et al. 2002; Jury and Engert 1999). The correlations found between the Ondangwa chronology and both ENSO indices and the southern Atlantic Ocean SST anomalies (whereas no correlations were found with the Katima Mulilo chronology), confirm this statement.

The master chronologies built for Ondangwa and Katima Mulilo present a similar spectral character, both showing a power spectrum peak at a frequency of approximately 0.15. The explanation for this peak, which corresponds to a cycle of approximately 6.7 years, could be either climatological, physiological or external. All directly influencing climate variables (rainfall, temperature and relative humidity) were found to show no or only low-amplitude, high-frequency (0.35–0.4) spectral peaks and can thus not explain the spectral pattern in the chronologies. The peak corresponding to a period of 6.7 year does fall in the broad spectral peak corresponding to 2–8 years, which characterizes the variability of ENSO-related time-series (Rasmusson and Carpenter 1982; Schöngart et al. 2004) and could thus be attributed to the ENSO phenomenon. However, Wang and Wang (1996) found that this variability is not distributed evenly over time (1880–1990), but rather concentrated at different frequencies at different times. It is unlikely that the phenomenon, having a varying periodicity over the same time period as the length of the chronologies, would generate a singular and strong peak for both chronologies. The second spectral peak found in the Ondangwa chronology, corresponding to a period of 3.6 years, accurately reflects the power spectra of coral reefs in the Niño 3.4 region (Cole et al. 1993; Urban et al. 2000), which show a very similar periodicity. Remarkable is the appearance of this second peak in the Ondangwa chronology (which showed correlations to the Niño 3.4 time-series in the correlation analysis) but not in the Katima Mulilo chronology (which did not correlate to the Niño 3.4 time-series). However, as this peak occurs at a frequency approximately double of the major peak's frequency, it could also be a second harmonic of the same signal. A second possible, and maybe more plausible, explanation for the 6.7 year periodicity, could be a physiological one. As the chronologies at both sites are built based on the same tree species, the physiology of these species (e.g. the occurrence of mast years) could invoke a low frequency signal in the tree growth. Little is known, however, on the specific physiology of the two species studied and of dry tropical trees in general (Borchert 1994; Lawton 1978; Shackleton 2002). A third cause for the found periodicity could be an external one, as the vegetation at both sites is known to be regularly prone to insect outbreaks and fires. The periodicity of these external factors, however, is difficult to verify, as no archives are available. Fire (and insect) scars were visible on several samples taken for this study and could be investigated on this behalf.

Overall our results show that as cross-dating among different species was possible for both sites, a common influence on a regional scale can be considered. The significant response of tree growth to climate variables underlines this statement. Our results yield an additional indication for the notion that tropical trees are sensitive to variation in climate patterns. Both tree species are a source of reliable tree-ring data, which reflect sensitivity to climate.

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