Clim Dyn (2009) 33:63–73
DOI 10.1007/s00382-009-0544-5

Interdecadal modulation of the relationship between ENSO, IPO and precipitation: insights from tree rings in Australia

Ingo Heinrich · Kathrin Weidner · Gerhard Helle · Heinz Vos · Janette Lindesay · John C. G. Banks

Received: 30 January 2008 / Accepted: 16 February 2009 / Published online: 6 March 2009

Abstract Australian climate-proxy reconstructions based on tree rings from tropical and subtropical forests have not been achieved so far due to the rarity of species producing anatomically distinct annual growth rings. Our study identifies the Australian Red Cedar (*Toona ciliata*) as one of the most promising tree species for tree-ring research in Australasia because this species exhibits distinct annual tree rings, a prerequisite for high quality tropical dendroclimatology. Based on these preliminary studies, we were able, for the first time in subtropical and tropical Australia, to develop a statistically robust, precisely dated and annually resolved chronology back to AD1854. We show that the variability in ring widths of *T. ciliata* is mainly dependent on annual precipitation. The developed proxy data series contains both high- and low-frequency climate signals which can be associated with the El Niño Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO). A comparison of different data sets (Brisbane precipitation, tree rings, coral luminescence record from the Great Barrier Reef, ENSO and IPO) revealed non-stationary correlation patterns throughout the twentieth century but little instability between the new tree-ring chronology and Brisbane precipitation.

Keywords Dendroclimatology · Australia · Toona ciliata · Rainforest · Precipitation · ENSO

I. Heinrich · J. Lindesay · J. C. G. Banks
School of Resources, Environment and Society,
Australian National University, Canberra, ACT 0200, Australia

I. Heinrich (✉) · K. Weidner · G. Helle
Helmholtz Centre Potsdam, GFZ German Research Centre
for Geosciences, Climate Dynamics and Landscape Evolution,
Telegrafenberg, 14473 Potsdam, Germany
e-mail: heinrich@gfz-potsdam.de

H. Vos
Forschungszentrum Jülich GmbH, Institute for Chemistry
and Dynamics of the Geosphere, Wilhelm-Johnen-Str.,
52425 Jülich, Germany

1 Introduction

Australia's status as the driest inhabited continent has always been a critical issue for its population. Drought and flooding events of catastrophic dimensions have harmed the Australian society many times. These events have been related mainly to the El Niño Southern Oscillation (ENSO) (Nicholls 1992). However, the relationship between Queensland rainfall and ENSO has been shown to be non-stationary through time. In particular, a weakening during the 1920–1950s has been noted (Lough 1991; Allan et al. 1996).

Corals from the Great Barrier Reef have been used as marine-based proxies to reconstruct, e.g., river runoff, summer rainfall and Pacific sea surface salinity (Hendy et al. 2002, 2003). Hendy et al. (2003) noted that the strength of the relationships between the coral luminescence record from the Great Barrier Reef (GBR) and Queensland summer rainfall, the instrumental Burdekin River flow and the instrumental Southern Oscillation Index (SOI), respectively, varied in time. Hendy et al. (2003) also compared their coral luminescence master series with a long-term reconstruction of ENSO. Cross-correlations using a 30-year sliding window revealed that the relationship between the luminescence master series and the ENSO reconstruction varied in time, was highly significant from the 1870s to 1920s and collapsed completely from the 1920s to 1950s. Over the whole period of the record the correlation was only weak, likely as a consequence of this non-stationary correlation. Therefore, Hendy et al. (2003) state that the luminescence master series will not be a particularly strong measure of ENSO but, in combination with other proxy climate series, can provide a record of long-term rainfall variability related to ENSO (Hendy et al. 2003).

It has been discovered that the ENSO effects are statistically linked to changes in the Interdecadal Pacific Oscillation (IPO) of the surface temperature over the Pacific Ocean (Folland et al. 1999; Power et al. 1999). For rainfall in particular it has been shown that the influence of ENSO on Australia and accordingly the success of an ENSO-based statistical prediction scheme both vary in association with the IPO. When the IPO raises the temperatures in the tropical Pacific Ocean the correlation between All-Australian rainfall variations and ENSO index weakens substantially. When the IPO is in a positive phase, sea surface temperatures (SST) over a large area of the south-west Pacific are low, as are the SSTs over the extra-tropical north-west Pacific. At the same time SSTs over the tropical Pacific are high, unlike the situation occurring during an ENSO event (Cai and Whetton 2001). Three phases of the IPO have been identified during the twentieth century: a positive phase (1922–1944), a negative phase (1946–1977) and another positive phase (1978–1998). Due to the IPO a 30% increase of annual precipitation might occur in some parts of the West Pacific region (Power et al. 1999; Salinger et al. 2001). In the light of the unstable relationships between instrumental and proxy data, it is of particular interest to evaluate whether the relationship between our tree-ring chronology and precipitation is stable in time and if the relationship is also affected by the status of the IPO.

There are few long meteorological records in Australia. Most long-running weather stations are concentrated in the coastal plains but the coastal highlands and the adjacent hinterland contain fewer meteorological stations (Australian Bureau of Meteorology 2002). High-resolution proxy data such as coral records and tree rings can be used to reconstruct climate and can reveal oscillation patterns in different frequency domains. Such results can improve climate models which will support decision makers in their choices of agricultural productions to adjust the long-term plans according to drier or wetter periods (Meinke and Stone 2005; Lo et al. 2007).

In contrast to the advanced research on marine-based climate proxy archives, not many dendroclimatological studies have been conducted in mainland Australia so far, as reviewed e.g., in Brookhouse (2006) and Ogden (1978). Until now, the few existing tree-ring records were mainly restricted to reconstruct the regional climate patterns of southern Australia (Brookhouse and Brack 2006) but they have little significance for climate reconstructions in subtropical to tropical Australia. Furthermore, most of the Australian mainland tree species examined have shown little dendrochronological potential, although, for some tropical Australian tree species the annual character of the tree rings has been verified and preliminary dendroclimatological studies have been conducted (Mucha 1979; Hammer 1981; Ash 1983a, b; Heinrich and Banks 2006a, b).

Only recently has the rainforest species *Toona ciliata* M. Roem. been identified to be potentially useful for dendroclimatology in tropical eastern Australia (Heinrich and Banks 2006a, b). Except for the efforts in Australia, only one tree-ring study with *T. ciliata* has been conducted elsewhere. In India, Bhattacharyya et al. (1992) analysed the dendroclimatological potential of the species and although the authors reported the presence of false rings they were still able to crossdate the samples.

In this paper, we present a 146-year tree-ring width record from Australian Red Cedar trees from subtropical eastern Australia (Fig. 1). This is the first and best replicated tree-ring chronology yet produced from subtropical and tropical Australia. We illustrate that the new tree-ring chronology is statistically robust and precisely dated. Secondly, the climate significance of the new tree-ring record is evaluated by comparison with precipitation, temperature, relative humidity and radiation data from Brisbane. Based on this evaluation precipitation was reconstructed for the Brisbane area reaching back to AD1854. Finally, temporal correlation patterns between the new tree-ring chronology, the coral luminescence master series from the GBR (Hendy et al. 2003), the Brisbane precipitation, the SOI and the IPO were examined in order to assess the stability, i.e., quality of this first tree-ring based climate reconstruction in subtropical Australia.

2 Materials and methods

2.1 Study site

The study site Lamington National Park (LNP) is located on the tablelands 30 km inland off the coast near Brisbane in southeast Queensland, Australia (28° 15′ S, 153° 08′ E) (Fig. 1). The forest is an old-growth submontane subtropical rainforest and is found in altitudes ranging from 600 to 900 m above sea level (asl). At the LNP site, 38 samples from 20 dominant to sub-dominant trees of *Toona ciliata* were collected and averaged into one chronology.

During the cool dry season (July–September) the LNP irregularly receives rain through the incoming trade winds and anticyclonic winds. The site profits from the orographically lifted air masses generating enough rain to support subtropical rainforest. Additional rain is delivered

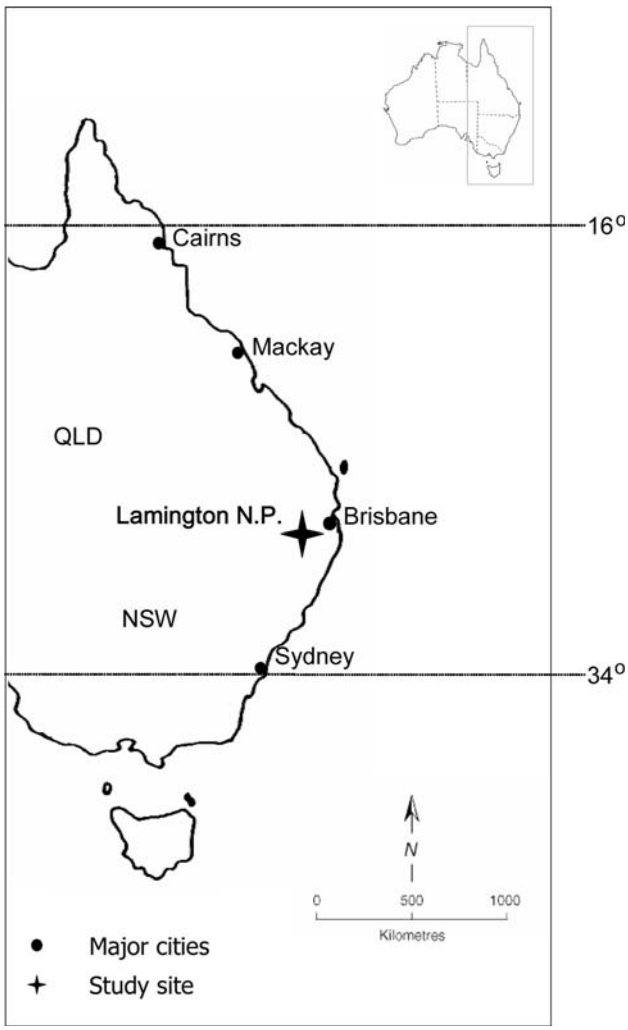


Fig. 1 Location of the study site Lamington National Park indicated by the asterisk; the old-growth montane subtropical rainforest is located in southeast Queensland 600–900 m asl (28° 15′ S, 153° 08′ E)

by outliers of frontal cyclones moving through further south. During the dry season (July–August) cold fronts from the south can bring frosty nights to the highlands. In spring the temperatures rise and the rainy season starts with convective storms bringing torrential rain mainly in October to December. Between January and March the LNP site is under the influence of the tropical monsoon with moist and warm air. From April to June temperatures decrease and allow the gradual return of the trade winds and outliers of frontal cyclones (Sturmann and Tapper 1996). The long-term mean annual values for precipitation and temperature are 1091.2 mm and 20.8°C, respectively (Fig. 2). The site conditions are reflected by the phenological behaviour of *T. ciliata* which usually flushes and sheds its leaves in September and May, respectively, leading to a dormant period from June to August. Since September is the beginning of the growth period, the dating of the tree rings

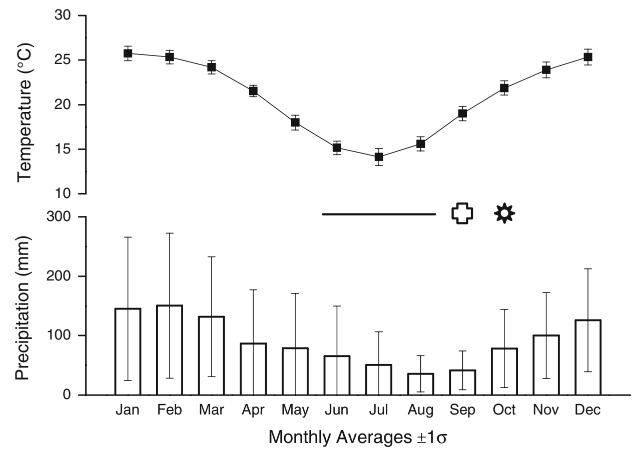


Fig. 2 Climate diagram derived from long-term averages for Brisbane meteorological station, (*Source*: Australian Bureau of Meteorology, Canberra 2002); the phenology of *Toona ciliata* is marked by a line (leafless period, June to August), cross (leaf flushing, September) and asterisk (flowering, October)

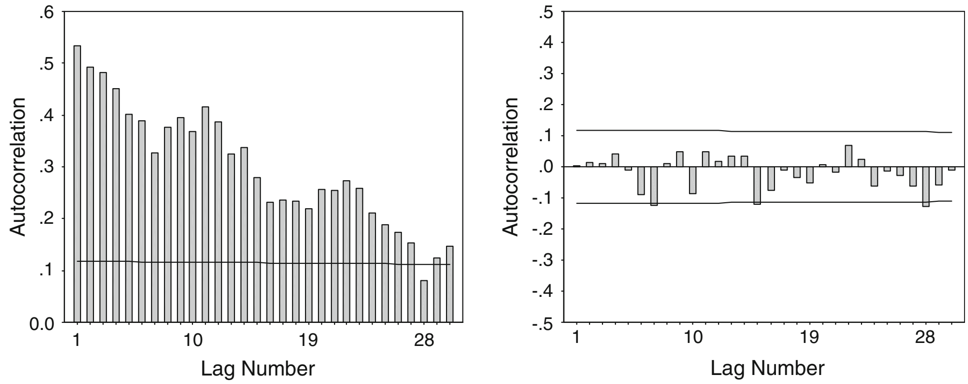
and the grouping of climate data do not follow the calendar year but the growing period of the trees, that is, September of the current year to August of the following year (Fig. 2).

2.2 Tree-ring data

The methods of dendrochronology applied in the current study follow the general methodology described in Stokes and Smiley (1968), Fritts (1976), Schweingruber (1983) and Cook and Kairiukstis (1990). Additionally, a prototype corer capable of collecting cores up to 150 cm was developed to sample large trees with diameters of 300 cm. The surfaces of the core samples were smoothed according to routine sample preparations (Bowers 1964) followed by semi-automatic measurements of the tree-ring width in WinDENDRO software and crossdating of the individual series in COFECHA (Holmes 1994). For dating purposes, we followed Schulman's (1956) convention for the southern hemisphere, which assigns to each tree ring the date in which radial growth started.

After the quality of the crossdating of the raw data series was verified, they were power transformed to stabilise the variance in the computer program ARSTAN using a multi-step process (Cook and Peters 1997). Then the series were detrended (Cook 2002) applying a 66-year cubic smoothing spline function with a 50% cutoff in conjunction with the residual method, i.e., 50% of the variance in each series at the period of 66 years were removed (Cook and Peters 1981). The spline sufficiently removes the early age trend and some growth releases. The mean tree-ring index was also analysed for possible autocorrelations of varying time lags before and after detrending. Since standardisation has reduced the autocorrelation below the limit of significance

Fig. 3 Autocorrelation (lags 1–30) for the raw (*left*) and detrended (*right*) tree-ring values from the Lamington National Park site



(Fig. 3), no additional autoregressive modelling was necessary, and thus the Turbo ARSTAN standard chronology (STNDRD) was used for the comparison with the climate data (Cook 2002). The bi-weight robust mean was preferred over the arithmetic mean (Cook et al. 1990) because it discounts the influence of outliers. The standard error was computed to characterise the fluctuation of the data around the mean value. Further statistical parameters evaluating the quality of the series were the mean, minimum and maximum values, the standard deviation, mean sensitivity and mean series intercorrelation. The mean sensitivity as a measure of relative difference in ring width from one ring to the next measures the high-frequency variance whereas the standard deviation is a good quantifier of the variance in all frequency domains. Higher values of the mean sensitivity and the standard deviation are indicative of more climatically responsive chronologies. The mean series intercorrelation is a measure of the strength of the common signal in the chronology (Fritts 1976). The sample size and the expressed population signal (EPS, Wigley et al. 1984) over time was included in the series plots to ensure better control over the quality of the chronology with decreasing sample size. The EPS is a commonly used guide to assess the likely loss of reconstruction accuracy. It measures how well the finite-sample chronology compares with the theoretical population chronology based on an infinite number of trees. Wigley et al. (1984) give an EPS = 0.85 as a reasonable limit for the chronology to still be reliable. Thus, the mean site chronology used for calibration and climate reconstruction purposes was cut off at a critical EPS of 0.85.

2.3 Climate response

For the climate response analysis between monthly climate data and the tree rings the available data comprised precipitation, maximum, minimum and mean temperatures, relative humidity, sunshine duration and number of clear and cloudy days (the hours of bright sunshine per day). We first checked the meteorological data for inhomogeneities that might interfere with the tree-ring calibration procedure using the techniques recommended by Mitchell et al. (1966). For the comparison between stations, monthly precipitation data were summed cumulatively. The totals for one station were then plotted as a function of the totals for the other station resulting in so-called double mass plots. Monthly temperature data of two stations were differenced and the result summed cumulatively. Only homogeneous meteorological data were then used for further analysis. The tests showed homogeneous data for the Brisbane station between 1900 and 2000. Although the precipitation record goes back to 1840, the period before 1900 contained some data gaps and inhomogeneities and therefore only the data from 1900 to 2000 were selected for further climate response analysis.

Simple Pearson's coefficients of correlation were computed for monthly climate data from Brisbane and the mean tree-ring index (Esper et al. 2002). The correlation coefficients computed between monthly climate data and the mean tree-ring index were plotted in histograms starting with January to August before the current growth period, followed by September–August of the current growth period and averages for the seasons September–November, December–February, March–May and June–August. Subsequently, the dominant climatic forcing factor controlling tree growth was calibrated against the site index. The climate record was split into two equal periods (50 years), the first period for calibration and the second one for the independent verification of the data. The verified regression model was used to reconstruct precipitation of the Brisbane area back to 1854.

The Systat software Autosignal was used for the spectral analysis of the proxy record. It determines those spectral density values that appear particularly strong or important and enables an easy graphical estimation of possible trends (Jenkins and Watts 1968). The temporal relationships between the new proxy record, the Brisbane precipitation data, the coral luminescence master series (Hendy et al. 2003), the ENSO and IPO records was analysed by applying a 13-year window of moving correlation.

3 Results and discussion

The LNP series exhibit tree-ring widths of 3.05 mm in average. The minimum and maximum values have a wide range extending from 0.01 mm to more than 20 mm with a standard deviation of 2.64 mm. The mean sensitivity of 0.59 (a measure of variability) and the mean series intercorrelation (a measure of agreement) of 0.54 indicate that the LNP chronology is a robust estimate of annual growth changes and that it is suitable for dendroclimatic research (Table 1). The LNP index series covers the period from 1854 to 2000 and contains some conspicuous growth periods such as the growth peak in the late 1980s followed by considerable low values in the early 1990s (Fig. 4).

Table 1 Summary statistics for the Lamington National Park site chronology

Site name	Lamington National Park
Latitude/Longitude/Elevation (m asl)	28° 15′ S/153° 08′ E/600–900
Chronology length	2000–1854
Length (years)	146
No. of trees	20
No. of samples	38
Mean (min./max.) annual increment (mm)	3.05 (0.1/21.49)
Standard deviation (mm)	2.64
Mean sensitivity	0.588
Series intercorrelation	0.539

The correlation for precipitation is significantly positive from January to the end of the season with declines below the 95% significance level in May and July, but the highest correlation with the annual precipitation ($r = 0.59$) (Fig. 5). Tree growth is positively correlated with the temperature of the previous and the beginning of the current season up to November. From December to the end of the growing season maximum temperatures correlate negatively above the 95% significance level most of the months. The minimum temperatures show the reverse displaying significant positive correlations in April and May. This seems to suggest that *T. ciliata* might be sensitive to temperature variations; high maximum temperatures exert a negative effect while high minimum temperatures point in the positive direction. The relative humidity and cloudiness data show positive correlations and sunshine duration exhibits a negative correlation during the middle of the season when the maximum temperatures and precipitation values are correlated negatively and positively, respectively. In summary the three diagrams indicate that the trees are only indirectly sensitive to temperature but directly to changing humidity levels which in turn are strongly influenced by high maximum temperatures. Therefore, for calibration against the LNP series only the precipitation data will be used.

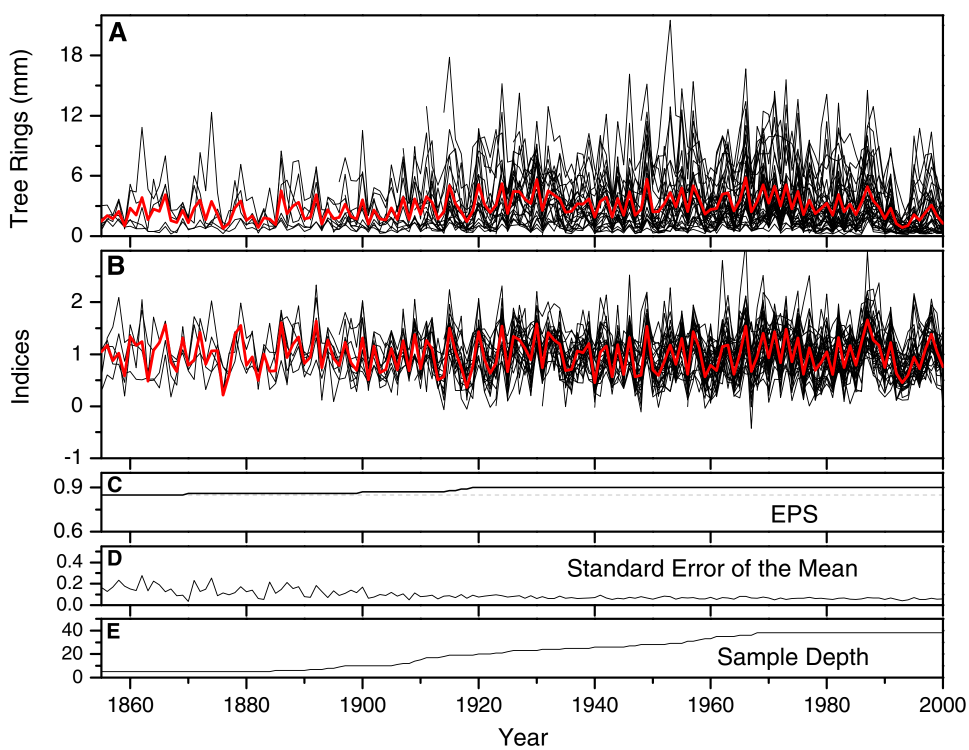


Fig. 4 Plots of the Lamington National Park raw tree-ring width series (A), tree-ring indices (B), expressed population signal (EPS) (C), standard error of the mean (D) and sample depth (E) through time. The red graphs represent the means of the raw values and the index series

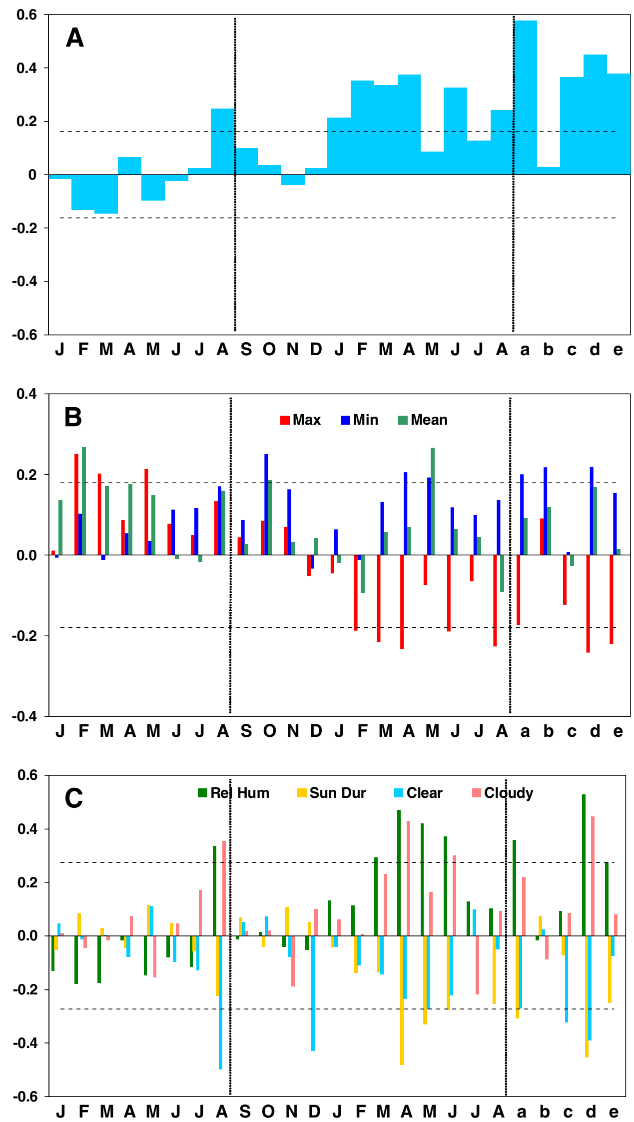


Fig. 5 Climate response plots for the Lamington National Park site with Brisbane meteorological data: Monthly coefficients of correlation for precipitation (A), maximum, minimum and mean temperatures (B) and relative humidity, sunshine duration and number of clear and cloudy days (C). The climate response plots are subdivided into three parts by vertical hatched lines. The left half of the diagram covers the period January to August before the current season, the middle part stands for this season (September–August) and the small letters a to e stand for the annual value and the averages for the periods for September–November, December–February, March–May and June–August of the current season, respectively. In each diagram the 95% confidence intervals are indicated by the horizontal hatched lines with different levels due to available time series lengths (*Source*: Australian Bureau of Meteorology Canberra 2002)

The regression analysis between the LNP series and the annual precipitation for the calibration period 1950–2000 determined the linear relationship $y = (689.49 \pm 133.01)\ x + 472.22 \pm 136.40$ explaining 35% of the tree-ring variations through annual precipitation data (Fig. 6).

The reconstructed precipitation record indicates that longer drought periods were common in the early 1880s, between 1900 and 1920, for most of the 1940s and 1990s and to a lesser extent in the early 1980s (Fig. 7). Episodes of wetter years are suggested for the 1860s, 1890s, 1930s and 1970s. Extremely dry years are suggested by the model for 1876, 1918, 1940, 1993 and extremely wet years for 1880, 1866, 1886, 1892, 1930 and 1987. The start of the twentieth century is modelled as the longest period of below average precipitation, which is well known as the socalled “Federation drought” in Australia (Nicholls 1997). Prolonged drought periods occurred three times approximately every 45 years, that is, the federation drought between 1895 and 1902, the World War II drought and the severe drought from 1991 to 1994. The precipitation proxy reconstruction mostly reflects the historical drought and flooding records for eastern Australia presented in Whetton (1997) (Fig. 7).

The reconstructed LNP precipitation indicates the presence of low-frequency variances. Since any growth trends longer than 66 years due to aging and competition have been removed in the process of standardisation, the remaining low-frequency oscillations might be explained by other forcing factors such as the inter-decadal oscillation of the Pacific Ocean temperatures. The spectral analysis plot shows peaks at about 2.8, 4.2, 32 and 42 years (Fig. 8). The peaks near the 2-year frequency might be associated with the quasi-biennial oscillation (Landsberg 1962). The peak at about 4 years seems to be related to the ENSO bandwidth. The ENSO is associated with several weather phenomena worldwide and hence its fingerprint can be found in numerous meteorological and proxy records at wavelength between 3 and 20 years (Allan et al. 1996; Allan 2000). The long-term cycles at 32 and 42 years are likely linked to the IPO which recently was also revealed in a teak tree-ring series in Thailand (Buckley et al. 2007). The 13-year running mean of the LNP precipitation-proxy seems to run parallel to the courses of both ENSO and IPO only periodically (top of Fig. 7) and the relatively low correlation values with ENSO and IPO do not indicate a strong coherence overall (Table 2), which suggests that the association between the LNP proxy, ENSO and IPO might not be stable over time, comparable to the results in Hendy et al. (2003). They compared the coral luminescence record with the multi-proxy NINO3 SST record of Mann et al. (2000) and found that the coral record from the Great Barrier Reef exhibits temporally varying linkages with ENSO, resulting in an overall weak, although significant, correlation between the coral record and an ENSO proxy record.

The comparison of the LNP tree-ring chronology with the coral luminescence record (Hendy et al. 2003) suggests good correspondence at times (Fig. 9) but the correlation

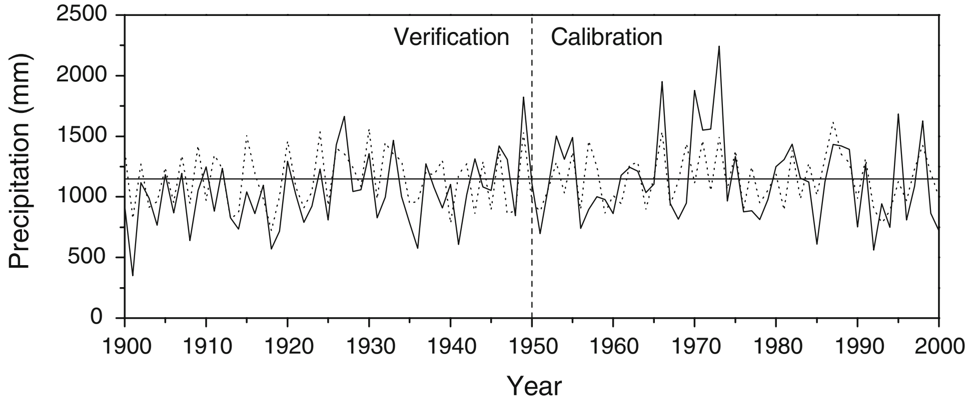


Fig. 6 Observed (*solid line*) and reconstructed March to June precipitation (*dashed line*) for calibration period 1950–2000 and verification period 1900–1949 for the Lamington National Park site

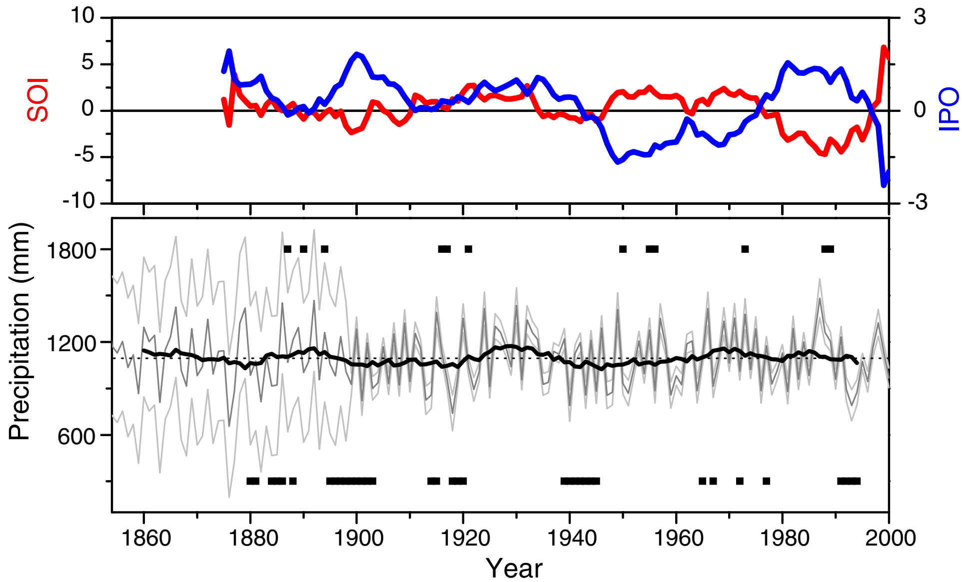


Fig. 7 Reconstructed annual precipitation for Lamington National Park (*dark grey line*) with 13-year running mean (*black line*) and 95% confidence intervals (*light grey lines*) in comparison to major drought (*lower markings*) and flooding events (*upper markings*) (Whetton, 1997) and 13-year running means of SOI (Australian Bureau of Meteorology Canberra 2002) (*red*) and IPO (Folland et al. 1999; Power et al. 1999, kindly provided by the UK Met Office) (*blue*)

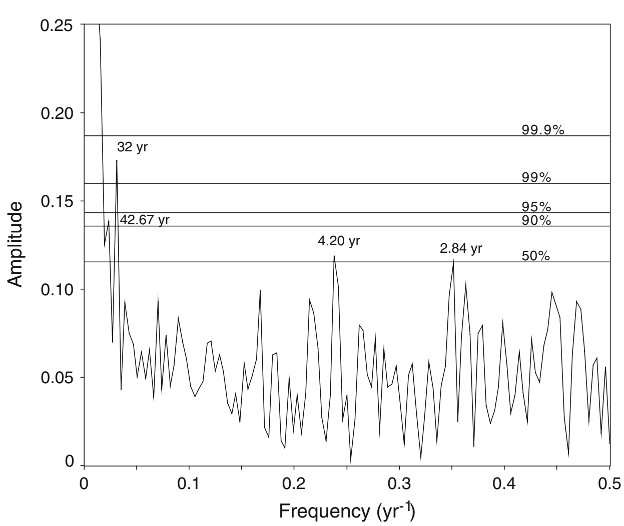


Fig. 8 Spectral analysis of the Lamington National Park tree-ring width index for the period 1854–2000 shows significant peaks at approximately 42 and 32 years. 50, 90, 95, 99 and 99.9% confidence levels are indicated

Table 2 Correlation between LNP tree rings, Brisbane annual precipitation, SOI and IPO (all significant at the 99% level)

	Tree-ring index	Annual Precip	IPO
Annual Precip	0.59		
IPO	−0.31	−0.42	
SOI	0.33	0.43	−0.71

between the two series is only 0.263, though, highly significant at the 99% confidence level. The temporal correlation, calculated in a moving window of 13 years, illustrates varying linkages between the tree rings and the corals. The correlation breaks down completely in the 1870s to 1880s, the 1920s to 1930s and the 1950s to 1960s but is high during the rest of the time. This is comparable to the correlation between the coral data and the NINO3 SST record presented in Hendy et al. (2003) which was weak most of the period from the 1800s to 1870s and between the 1920s and 1950s. Both our tree-ring data and the coral

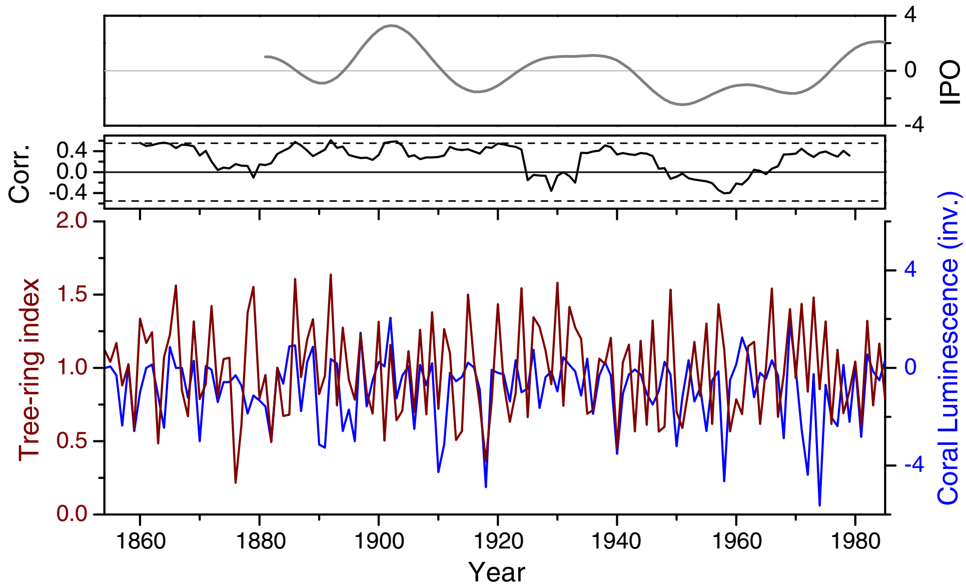


Fig. 9 Lamington National Park tree-ring site chronology (*brown*) in comparison to the coral luminescence master chronology (Hendy et al. 2003) (*blue*); Pearson's correlation (Corr.) calculated in moving windows of 13 years (95% confidence levels are indicated); for comparison printed on top, the Interdecadal Pacific Oscillation Index (Folland et al. 1999; Power et al. 1999, kindly provided by the UK Met Office) (*grey*)

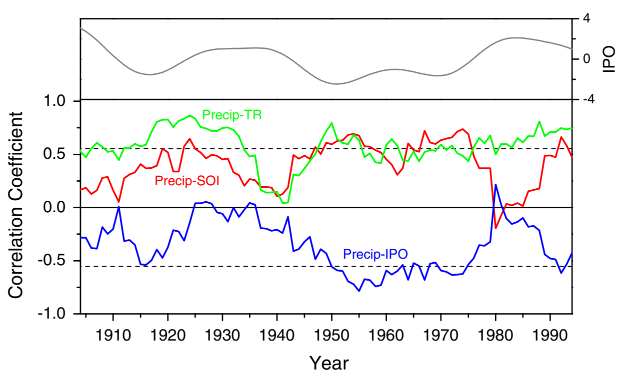


Fig. 10 Coefficients of correlation between Brisbane precipitation and Lamington National Park tree-ring chronology (*green*), Southern Oscillation Index (*red*) and Interdecadal Pacific Oscillation (*blue*) in moving windows of 13 years (95% confidence levels are indicated); for comparison printed on top, the Interdecadal Pacific Oscillation Index (Folland et al. 1999; Power et al. 1999, kindly provided by the UK Met Office) (grey)

record exhibit temporal instabilities which might hinder long-term climate reconstructions, however, a combination of marine and terrestrial proxy records can result in a more reliable record.

The climate response plots (Fig. 5) have illustrated that the LNP series is mainly controlled by precipitation which in turn, however, is to a large extent correlated to the status of the SOI and the IPO. Recently, it has also been found that the predicting power of SOI towards precipitation in Australia is not stable over time and that this is statistically linked to the status of the IPO (Cai and Whetton 2001; Power et al. 1999). We might therefore expect to see links to this low-frequency oscillation in the tree rings as well. Our results for the Brisbane meteorological precipitation record, SOI and IPO confirm the results of Power et al. (1999) (Fig. 10). We found varying correlations in time between Brisbane precipitation and the LNP tree-ring series, the SOI and the IPO. The courses of correlations between precipitation and SOI and IPO, respectively, are mirrored near the zero-correlation line, with precipitation-SOI staying positive and precipitation-IPO remaining mostly negative. The correlations vary in time and are related to the status of the IPO. The correlations collapse three times during the analysis period, in 1912, in the late 1930s to early 1940s and in 1980–1981. Times of low correlations are related to a high status of the IPO. In contrast, the correlation between tree rings and precipitation collapses only in the early 1940s and is relatively stable afterwards. Moreover the correlation between tree rings and precipitation has been increasing since the mid-1970s. There are several reasons for this more stable relationship between tree rings and precipitation: tree growth and thus tree rings are mainly controlled by variations in climate parameters such as precipitation and temperature which, however, are not only controlled by one atmospheric or oceanic circulation pattern such as ENSO or IPO but are an integration of several other potential factors such as the quasi-biennial oscillation (Landsberg 1962). El Niño events are often followed by a La Niña, and the relative regular occurrence of these events incorporates a quasi-biennial oscillation signal into most Australian precipitation records resulting in an extreme year-to-year variation (Nicholls 1992) which was also found in the LNP series. Other possible internal oceanic modes responsible for teleconnected rainfall variability are the Indian Ocean dipole mode (Saji et al. 1999) and the Southern Hemisphere annular mode (Cai et al. 2003; Cai and Cowan 2006; Hendon et al. 2007). Possible extraterrestrial factors potentially influencing the variability of the Brisbane precipitation include the sunspot cycle (Douglass 1917; Stuiver 1961), changes of the solar cycle linked to the sun's irregular oscillation (Landscheidt 1984) and the lunar tidal force (Treloar 2002). However, the influences are not visible as significant peaks in the spectral analysis of the LNP reconstruction and it can be assumed that they explain only small parts of the variability of the reconstructed Brisbane precipitation record.

Several authors have provided a plausible physical basis for the view that forecasting the strength of El Niño might not be enough to predict rainfall variations in Australia during El Niño events (e.g., Allan et al. 1996). They have shown that the centres of ENSO (maximum anomalies of the SOI measured) have shifted and were not at the same location during various El Niño events. Wang and Hendon (2007) compared the El Niño events of 1997 and 2002 and found that Australian rainfall is sensitive to the zonal distribution of SST anomalies during El Niño. However, positive SST anomalies maximised near the date line in 2002, but in 1997 maximum anomalies were shifted well into the eastern Pacific, where their influence on Australian rainfall appeared to be less. Similar results are reported by Murphy and Ribbe (2004) which discovered several instabilities in the correlation between ENSO and precipitation.

Another reason why tree rings in some years do not correlate well with the SOI but remain correlated with precipitation might be the phase-locking of the SOI to the annual calendar year cycle, i.e., the average length and onset dates of the El Niño and La Niña events are of interest. Several studies (e.g., Rasmusson and Carpenter 1982; Ropelewski and Halpert 1989) demonstrated that El Niño and La Niña events usually tend to last about 12 months and start early in the calendar year and end early in the following year. The El Niño event 1982–1983, for example, started in April 1982 and ended in April 1983 (Fig. 11), but the LNP tree-ring index value for 1982 is above-average and 1983 only little below the average, indicating that the trees were not as limited by dry conditions as the strong negative SOI might have predicted. The growing period of the trees from LNP lasts from about September of the current year to May of the next year. Before the El Niño event (April 1982), the trees had grown under normal conditions for almost 7 months. After the onset of the El Niño event in April the trees became dormant in June, i.e., they had to cope with dry conditions for only 3 months. The new growing season started in September. Having avoided about 3 months of the El Niño episode due to their dormancy the trees then were restricted during the second half of the El Niño which finally ended in April 1983. However, tree growth at the LNP site continued until the end of May 1983 which gave the trees enough time to compensate for the dry and hot conditions during the previous months.

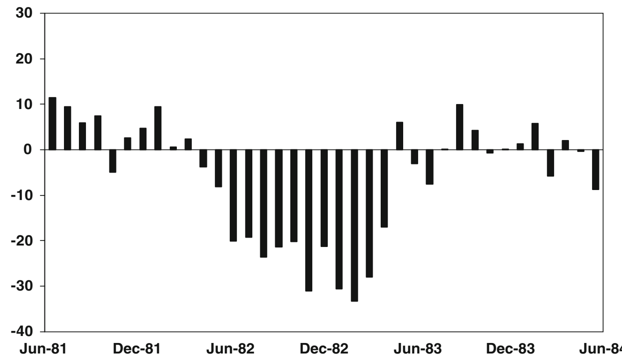


Fig. 11 Monthly status of the Southern Oscillation Index for the period June 1981 to June 1984 (*Source*: Australian Bureau of Meteorology Canberra 2002)

4 Conclusions

We have presented the first precisely dated and climatically sensitive tree-ring chronology for subtropical Australia where heretofore there was little tree-ring proxy data available. The LNP site index shows a multi-decadal oscillation of around 30–40 years with the last peak of the oscillation recorded for the 1970s which suggests that tree growth has always been influenced by the IPO. Further tree-ring studies on the genus *Toona* from Australia and in neighbouring countries to the north need to clarify this important issue. The addition of older trees and of wood used for old buildings such as farmhouses will expand the existing chronology in Australia. Moreover, *Toona ciliata* occurs not only in Australia but has a large natural range between China and Southeast Australia (30° N and 30° S). In most countries of its distribution substantial forest stands are still present in national state forests, nature reserves and national parks. Moreover, the genus has durable wood and as a result dead wood does not decay easily increasing the chances to find valuable dead sample material. Consequently, a network of sites with *Toona* tree-ring series in combination with other proxy data such as coral records from the Great Barrier Reef will offer a better understanding of the Australasian climate. The temporal correlation patterns between precipitation, tree rings, coral luminescence records, ENSO and IPO have been shown to be unstable. A multi-proxy approach seems indispensable to increase the quality of reconstructing precipitation in Australia.

Acknowledgements Ingo Heinrich would like to thank the late Dr. John Banks, School of Resources, Environment and Society (SRES), Australian National University (ANU), for his excellent guidance and advice as PhD supervisor and friend. IH also thanks all other members of the SRES-ANU staff, in particular Peter Kanowski, Sue Holzknecht, Ann Gibson and Jürgen Bauhus, for their important support during his PhD. IH is grateful to the rangers of the Lamington National Park for their advice and logistic support during the field work. IH received PhD scholarships from the Australian National University, the Cooperative Research Centre for Greenhouse Accounting, and the German Academic Exchange Service (DAAD).

References

Allan RJ (2000) ENSO and climatic variability in the past 150 years. In: Diaz HF, Markgraf V (eds) El Niño and the Southern Oscillation: multiscale variability and global and regional impacts. Cambridge University Press, Cambridge, pp 3–55

Allan R, Lindesay J, Parker D (1996) El Niño southern oscillation and climatic variability. CSIRO Publishing, Collingwood, Australia

Ash J (1983a) Growth rings in *Agathis robusta* and *Araucaria cunninghamii* from Tropical Australia. Aust J Bot 31:269–275. doi:10.1071/BT9830269

Ash J (1983b) Tree-rings in tropical *Callitris macleayana* F. Muell. Aust J Bot 33:277–281. doi:10.1071/BT9830277

Australian Bureau of Meteorology (2002) Annual report 2001–02. Canberra

Bhattacharyya A, Yadav RR, Borgaonkar HP, Pant GB (1992) Growth-ring analysis of Indian tropical trees: dendroclimatic potential. Curr Sci 62:736–741

Bowers NA (1964) New method of surfacing wood specimens for study. Tree-Ring Bull 26:2–5

Brookhouse MT (2006) Eucalypt dendrochronology: past, present and potential. Aust J Bot 54:435–449. doi:10.1071/BT05039

Brookhouse MT, Brack C (2006) Crossdating and analysis of eucalypt tree rings exhibiting terminal and reverse latewood. Trees-Structure Funct 20:767–781

Buckley BM, Palakit K, Duangsathaporn K, Sanguantham P, Prasomsin P (2007) Decadal scale droughts over northwestern Thailand over the past 448 years: links to the tropical Pacific and Indian Ocean sectors. Clim Dyn 29:63–71. doi:10.1007/s00382-007-0225-1

Cai W, Cowan T (2006) SAM and regional rainfall in IPCC AR4 models: can anthropogenic forcing account for southwest Western Australian winter rainfall reduction? Geophys Res Lett 33:L24708. doi:10.1029/2006GL028037

Cai W, Whetton PH (2001) Modes of SST variability and the fluctuation of global mean temperature. Clim Dyn 17:889–901. doi:10.1007/s003820100152

Cai W, Whetton PH, Karoly DJ (2003) The response of the Antarctic Oscillation to increasing and stabilized atmospheric CO_2. J Clim 16:1525–1538

Cook ER (2002) Turbo Arstan software: version 36. Tree-ring laboratory. Lamont-Doherty Earth Observatory, Palisades, NY

Cook ER, Kairiukstis LA (1990) Methods of dendrochronology. Kluwer, Dordrecht, Netherlands

Cook ER, Peters K (1981) The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. Tree-Ring Bull 41:45–53

Cook ER, Peters K (1997) Calculating unbiased tree-ring indices for the study of climatic and environmental change. Holocene 7:361–370. doi:10.1177/095968369700700314

Cook ER, Shiyatov S, Mazepa V (1990) Estimation of the mean chronology. In: Cook ER, Kairiukstis LA (eds) Methods in dendrochronology. International Institute for Applied System Analysis, Dordrecht, Netherlands, pp 123–132

Douglass AE (1917) Climatic records in the trunks of trees. Am For 23:732–735

Esper J, Schweingruber FH, Winiger M (2002) 1,300 years of climate history for Western Central Asia inferred from tree-rings. Holocene 12:267–277. doi:10.1191/0959683602hl543rp

Folland CK, Parker DE, Colman AW, Washington R (1999) Large scale modes of ocean surface temperature since the late nineteenth century. In: Navarra A (ed) Beyond El Nino: decadal and interdecadal climate variability. Springer, Berlin, pp 73–102

Fritts HC (1976) Tree rings and climate. Blackburn Press, Caldwell, NJ

Hammer GL (1981) Site classification and tree diameter-height-age relationships for cypress pine in the Top End of the Northern Territory. Aust For 44:35–41

Heinrich I, Banks JCG (2006a) Tree-ring anomalies in *Toona ciliata*. IAWA J 27:213–231

Heinrich I, Banks JCG (2006b) Variation in phenology, growth, and wood anatomy of *Toona sinensis* and *Toona ciliata* in relation to different environmental conditions. Int J Plant Sci 167:831–841. doi:10.1086/503785

Hendon HH, Thompson DWJ, Wheeler MC (2007) Australian rainfall and surface temperature variations associated with the Southern Hemisphere annular mode. J Clim 20:2452–2467. doi:10.1175/JCLI4134.1

Hendy E, Gagan MK, Alibert CA, McCulloch M, Lough JM, Isdale PJ (2002) Abrupt decrease in tropical Pacific Sea surface salinity at end of little ice age. Science 295:1511–1514. doi:10.1126/science.1067693

Hendy E, Gagan MK, Lough JM (2003) Chronological control of coral records using luminescent lines and evidence for non-stationary ENSO teleconnections in northeast Australia. Holocene 13:187–199. doi:10.1191/0959683603hl606rp

Holmes RL (1994) Dendrochronolgy program manual. Laboratory of Tree-ring Research, Tucson, AZ

Jenkins GM, Watts DG (1968) Spectral analysis and its applications. Holden-Day, San Francisco

Mitchell JM Jr, Dzerdzeevskii B, Flohn H, Hofmeyr WL, Lamb HH, Rao KN, Wallen CC (1966) Climate change. Report of a working group of the Commission for Climatology, World Meteorological Organization Technical Note 79, Geneva

Landsberg HE (1962) Biennial pulses in the atmosphere. Beitr Phys Atmos 35:184–194

Landscheidt T (1984) Cycles of solar flares and weather. In: Moerner NA, Karlén W (eds) Climatic changes on a yearly to millenial basis. D. Reidel Publ. Comp, Dordrecht, pp 475–476

Lo F, Wheeler MC, Meinke H, Donald A (2007) Probabilistic forecasts of the onset of the North Australian wet season. Mon Weather Rev 135:3506–3520. doi:10.1175/MWR3473.1

Lough JM (1991) Rainfall variations in Queensland, Australia: 1891–1986. Int J Climatol 11:745–768

Mann ME, Gille E, Overpeck J, Gross W, Bradley RS, Keimig FT, Hughes MK (2000) Global temperature patterns in past centuries: an interactive presentation. Earth Interact 4:1–29. doi:10.1175/1087-3562(2000)004<0001:GTPIPC>2.3.CO;2

Meinke H, Stone RC (2005) Seasonal and inter-annual climate forecasting: the new tool for increasing preparedness to climate variability and change in agricultural planning and operations. Clim Change 70:221–253. doi:10.1007/s10584-005-5948-6

Mucha SB (1979) Estimation of tree ages from growth rings of eucalypts in northern Australia. Aust For 42:13–16

Murphy BF, Ribbe J (2004) Variability of southeastern Queensland rainfall and climate indices. Int J Climatol 24:703–721. doi:10.1002/joc.1018

Nicholls N (1992) Historical El Niño/Southern Oscillation variability in the Australasian region. In: Diaz HF, Markgraf V (eds) El Niño: historical and palaeoclimatic aspects of the southern oscillation. Cambridge University Press, Cambridge, UK, pp 151–174

Nicholls N (1997) The centennial drought. In: Webb EK (ed) Windows on meteorology: Australian perspective. CSIRO Publishing, Melbourne, pp 118–126

Ogden J (1978) On the dendrochronological potential of Australian trees. Aust J Ecol 3:339–356. doi:10.1111/j.1442-9993.1978.tb01184.x

Power S, Casey T, Folland C, Colman A, Mehta V (1999) Interdecadal modulation of the impact of ENSO on Australia. Clim Dyn 15:319–324. doi:10.1007/s003820050284

Rasmusson EM, Carpenter TH (1982) Variations in tropical sea surface temperature and surface wind fields associated with southern oscillation/El Nino. Mon Weather Rev 110:354–384. doi:10.1175/1520-0493(1982)110<0354:VITSST>2.0.CO;2

Ropelewski CF, Halpert MS (1989) Precipitation patterns associated with the high index phase of the Southern Oscillation. J Clim 2:268–284. doi:10.1175/1520-0442(1989)002<0268:PPAWTH>2.0.CO;2

Saji NH, Goswami BN, Vinayachandran PN, Yamagata T (1999) A dipole mode in the tropical Indian Ocean. Nature 401:360–363

Salinger MJ, Renwick JA, Mullan AB (2001) Interdecadal Pacific Oscillation and South Pacific climate. Int J Climatol 21:1705–1721. doi:10.1002/joc.691

Schulman E (1956) Dendroclimatic change in semiarid America. University of Arizona Press, Tucson, Arizona

Schweingruber FH (1983) Der Jahrring. Standort, Methodik, Zeit und Klima in der Dendrochronologie. Paul Haupt, Bern

Stokes MA, Smiley TL (1968) An introduction to tree ring dating. University of Chicago Press, Chicago

Stuiver M (1961) Variations in radiocarbon concentration and sunspot activity. J Geophys Res 66:273–276. doi:10.1029/JZ066i001p00273

Sturmann AP, Tapper NJ (1996) The weather and climate of Australia and New Zealand. Oxford University Press, Melbourne

Treloar NC (2002) Luni-Solar tidal influences on climate variability. Int J Climatol 22:1527–1542. doi:10.1002/joc.783

Wang G, Hendon HH (2007) Sensitivity of Australian rainfall to inter-El Nino variations. J Clim 20:4211–4226. doi:10.1175/JCLI4228.1

Whetton P (1997) Floods, droughts and the Southern Oscillation connection. In: Webb EK (ed) Windows on meteorology: Australian perspective. CSIRO Publishing, Melbourne, pp 180–199

Wigley TML, Briffa KR, Jones PD (1984) On the average of correlated time series, with applications in dendroclimatology and hydrometeorology. J Clim Appl Meteorol 23:201–213. doi:10.1175/1520-0450(1984)023<0201:OTAVOC>2.0.CO;2