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Hydroclimatic variation in Far North Queensland since 1860 inferred from tree rings

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Abstract

In tropical Australia, palaeoclimatic proxies derived from tree-rings are sought after sources for reconstructing climate variations. However, dendroclimatology has not been widely applied in tropical forests and even less so in the Australian tropics due to the extreme rarity of species producing anatomically distinct annual growth rings. Furthermore, most Australian tree species exhibit rather strong opportunistic growth with non-annual growth zones that are less suitable for dendrochronology. Recent studies on the Australian Red Cedar (*Toona ciliata*) in the Upper Kangaroo Valley near Sydney revealed that tree-ring based climate reconstructions are feasible with this species. This study moved 2500 km further north and concentrated on the tropical stands of *T. ciliata* because it is one of the few deciduous tree species in tropical Australia likely characterised by a dormant period of the cambium and thus annual tree rings. Although dendroclimatological studies indicate that some Australian tree species are suitable for reconstructing climate patterns, a well replicated tree-ring record from Far North Queensland has not been developed until now. Tree cores of *T. ciliata* were developed into a 140-year tree-ring widths index chronology. The analyses showed that the ring-widths indices correlate with March-June precipitation as recorded at Kairi research station. March-June precipitation was reconstructed using the tree-ring data with 35% of the variance explained. The reconstructed series contains both high- and low-frequency climate signals. This suggests that growth of *T. ciliata* is influenced by climate phenomena of different wave lengths which can be associated with El Niño Southern Oscillation (ENSO) and Interdecadal Pacific Oscillation (IPO).

Keywords: Australia; Toona ciliata; Tropics; Rainforest; Dendroclimatology; Precipitation

1. Introduction

Eastern Australia is prone to droughts and floods often associated with the extremes of the El Niño Southern Oscillation (ENSO) and modulated by the Interdecadal Pacific Oscillation (IPO) (Nicholls, 1992; Power et al., 1999). A better knowledge of past climate helps to understand the present climate, to better predict its future variability thus assisting societies affected by weather extremes to better prepare for the effects of climate change. This requires sufficient temporal and spatial resolution of climate data. However, the network of weather stations in Australia is mainly concentrated in the coastal areas. The coastal highlands and adjacent hinterland contain fewer meteorological stations because of the complex topography and because large areas are sparsely populated. For that reason, most of the stations with long-term records are located near the coast where most of the early European settlements were established. Only in the last few decades have additional stations been opened in remote places to increase the spatial resolution of the network (Australian Bureau of Meteorology, 2002). Several studies have used interpolation techniques taking into account the complex topography of the Eastern Australian landscape (Hutchinson, 1998; Turton et al., 1999; Hancock et al., 2001) to improve the spatial coverage of climate data for remote areas but only for a limited number of years. Generally, a lack of long-term climate data, especially in the tropics, remains a critical issue for climate research in Australia.

One potential source of long-term proxy climate data is the analysis of tree rings but dendrochronology has been little applied in tropical forests of Australia probably due to the lack of easily datable growth rings in many species. Dendrochronology faces several problems in mainland Australia: the highly variable climate with extreme rainfall events and prolonged drought periods resulting in unpredictable precipitation, in large areas of Australia very dry environments, poor soils, wild fires and wood-destroying insects such as termites. Large parts of the formerly forested areas in Australia have been reduced by intense deforestation (Wells et al., 1984). Over the past millennia the unpredictability of rain has produced a well-adapted phanerophytic evergreen vegetation generally dominated by Eucalypts and Acacias and exhibiting mostly opportunistic growth whenever conditions are suitable. This opportunism often results in non-annual growth increments, which complicate or prevent reliable tree-ring chronology building. Furthermore, fires and termites often destroy old forest stands and dead wood that would potentially be useful for tree-ring research (Bowman and Cook, 2002).

Nevertheless, in Australia tree rings have been used for dating (Francis, 1928; Helms, 1945), to reconstruct past fire regimes (Banks, 1982; Bowman and Panton, 1993; Burrows et al., 1995) and temperatures in mountain regions (Brookhouse et al., 2006) or to examine processes of special interest, such as effects of sand mining on the chemical compositions of tree rings (Banks, 1992). In tropical Australia, the few dendroclimatological studies that have been conducted have only been preliminary and exploratory in character (Amos and Dadswell, 1950; Johnston, 1975; Mucha, 1979; Hammer, 1981; Ash, 1981, 1983a, 1983b).

In countries to the north of Australia, relevant studies have been carried out by Chowdhury (1964) in India, and Coster (1927, 1928) and Berlage (1931) in Indonesia. The first two studies successfully proved the annuality of tree rings in several tropical trees while Berlage (1931) produced the first long tropical tree-ring chronology with teak (*Tectona grandis* L.f.). More recently, successful work in the region was conducted by Jacoby and D`Arrigo (1990), Murphy (1994) and Stahle et al. (1998) in Indonesia and Buckley et al. (1995, 2007) in Thailand. The latest achievement is a 448 proxy drought record for northwestern Thailand derived from tree rings (Buckley et al., 2007). Tree rings of several species of the *Meliaceae* family, to which *Toona ciliata* belongs, have been studied successfully in Africa (Détienne and Mariaux, 1977) and in the Central Amazon (Dünisch et al., 2003). Bhattacharyya et al. (1992) analysed the dendroclimatological potential of *T. ciliata* in India and, even though the authors reported the presence of false rings, they were still able to crossdate the samples. The authors detected and deleted the false rings by applying crossdating techniques and developed a master skeleton plot extending back to the year 1800. The comparison of the tree-ring data with precipitation data revealed that the eight trees they analysed formed narrow rings during both high and extremely deficient rainfall years, *i.e.*, a nonlinear response to rainfall. The ecological explanations for the narrow rings were that low photosynthetic activity caused by soil-water deficit during the dry periods or excessive soil moisture due to insufficient drainage that resulted in a reduction of soil oxygen and inhibition of root growth (Bhattacharyya et al., 1992).

In a recent study, Heinrich and Banks (2005) examined the dendroclimatological potential of *T. ciliata* by analysing tree rings of specimens growing near Sydney, NSW, the southern limit of the species´ distribution, and also monitored their stem-diameter growth with dendrometer bands. The species was found to be deciduous for several weeks per year and exhibited distinct annual tree rings. It was demonstrated that *T. ciliata* can be crossdated and that near Sydney the species can be used to reconstruct early season temperatures and late-season rainfall. In a preliminary study, increment core samples of *T. ciliata* taken at several places in the Australian tropics were examined further to estimate the crossdating capacity of *T. ciliata* in northeast Australia (Heinrich and Banks, 2006a). Although false rings were discovered, preliminary crossdating was feasible and for selected years a positive relationship between ring width and precipitation data was found. The suitability of *T. ciliata* for tropical tree-ring research was further confirmed by analysing the phenological behaviour and the influence of environmental conditions on intraseasonal growth and wood anatomical properties (Heinrich and Banks, 2006b).

Heinrich (2004) showed that only total defoliation, in contrast to partial defoliation, leads to false rings in *T. ciliata*, and that false rings occur mainly in the inner younger part of the trees. Heinrich and Banks (2006a) concluded that false rings can occur in young trees but in adult specimens only under very extreme conditions, such as total defoliation during a direct tropical cyclone hit or a very extreme drought in combination with a fire entering the rainforest, as suggested by Herwitz et al. (1998). One explanation for false rings mainly in young trees is the cedar tip moth *Hypsipyla robusta* Moore (Lepidoptera: Pyralidae) which sometimes attacks *T. ciliata*. In young plants the caterpillars of *H. robusta* often destroy the apical shoots, leading to the formation of side branching, and ultimately, a deformed trunk (Volk, 1968; Campbell, 1998). Similar results have been reported by Dünisch et al. (2002) from Central Amazonia where insect attacks of *Hypsipyla grandella* Zeller induced locally restricted formation of parenchyma bands and bands of resin canals in *Cedrela odorata* L..

Although *T. ciliata* has been the subject of preliminary dendroclimatological studies in the subtropics of India (Bhattacharyya et al., 1992) and Australia (Heinrich and Banks, 2005), it has never been used for dendroclimatology in the tropics. Therefore, the fundamental goal of this study is to demonstrate that the species can be used for tree-ring analysis in tropical Australia, and that the resulting chronology is sensitive to climate and hence valuable for palaeoclimate reconstructions.

2. Materials and Methods

Study site

The study site Curtain Fig Tree is located 1600 km north of Brisbane on the Atherton Tableland (720 m asl) in Far North Queensland (Fig. 1). The forest is an old-growth submontane tropical rainforest in the Yungaburra National Park (Herwitz and Slye, 1996) with no signs of having been logged or silviculturally treated (Stocker et al., 1995). The forest is a mature structurally complex notophyll vine forest of the cooler uplands (Webb, 1959). The trunk sizes are uneven and plank buttresses are common. The canopy averages 20 to 40 m and deciduous trees (e.g., *Toona ciliata*) are present. Dense ground ferns, tree ferns and walking stick palms are characteristic of this type of rainforest (Tracey, 1982). The nutrient-rich krasnozem soils are derived from moderately weathered young basalts and the topography is gently rolling (Brasell et al., 1980).

The climate on the tropical Atherton Tablelands is determined by the latitudinal movement of the monsoonal trough. During the austral summer, typically October to April, the monsoon moves south over northern Australia. The summer period starts with rising temperatures and the wet season commences with convective tropical storms bringing torrential rain mainly in October to December. Between January and March the study site is under the influence of the tropical monsoonal weather with moist and warm air. Moist northwesterly winds bring humid conditions with showers and thunderstorms. Rainfall amounts may vary markedly from year to year, and occasional tropical cyclones can bring abundant rainfall to tropical coastal regions and possibly further inland. Once the monsoon has retreated back to 10-15º north of the equator, winter brings blue skies and mild, dry conditions. During the cool dry season, usually July to September, the Atherton Tablelands irregularly receive rain through the incoming easterly trade winds and anticyclonic winds after the air masses have been lifted orographically by the tablelands (Sturman and Tapper, 1996). At the end of the dry season

(September-October), cold fronts of extra-tropical origin can bring frosty nights to the highlands. These fronts usually bring clear weather with unusually cold nights and temperatures dropping below 0 ºC for several nights (Duff and Stocker, 1989). The mean annual rainfall and mean annual temperature at the site are 1388.4 mm and 20.5 ºC, respectively (Australian Bureau of Meteorology, 2002). The phenology of *Toona ciliata* at the Curtain Fig Tree site follows the seasons. The leaves are shed in July to August, leaf flush occurs in September and flowering in late October, *i.e*. the trees have an approximate growing period of ten months between September and June (Tracey, 1982). Since, at the Curtain Fig Tree site, September is the beginning of the growth period, the dating of the tree rings 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).

Chronology building

The methods of dendrochronology applied in the current study follow those described in Stokes and Smiley (1968), Fritts (1976), Schweingruber (1983) and Cook and Kairiukstis (1990). Worbes (1990) advises to sample trees in the tropics growing at their climatic distribution limits. Since the present day distribution of *Toona ciliata* is very patchy due to past logging activities, such a strategy of sampling at the most limiting sites was restricted. But Schweingruber et al. (1990) suggest that dendroclimatological studies can be conducted successfully with trees growing under more favourable conditions. At the study site Curtain Fig Tree, located in the Yungaburra National Park on the Atherton Tablelands, 53 cores from 37 dominant to subdominant trees were collected in September 2002. Although steep slopes at the site were missing, trees were selected for sampling only if they grew on the small ridges or slopes in order to stay away from waterlogged zones. In the presence of plank buttresses, core samples were taken outside of their range. In addition, an old tree stem disc of *Toona ciliata*, felled in 1923 and exhibited in the Powerhouse Museum in Sydney, was also included in the analysis. The surfaces of the core samples were smoothed with a belt-sander using paper grit size of 240 according to routine sample preparations (Bowers, 1964) followed by an orbital sander treatment with paper of increasingly fine grit size up to 1200 (Pilcher, 1990). Individual samples were checked in advance under low magnification for problematic zones such as narrow or false rings and some were removed before continuing with digital image analysis. The smooth surface of the cores allowed them to be scanned in high resolution mode and imported to the image analysis program WinDENDRO for measurements of the ring widths with an accuracy of 0.02 mm (WinDENDRO, 2003). Prior to the digital analysis, visual crossdating was achieved by comparing samples from one tree and different trees under low magnification. Ring boundaries and distinct wood anatomical structures, that is, potential false rings, density fluctuations and other distinct wood anatomical features visible in both samples were marked on the samples (Heinrich and Banks 2006a). This short-cut form of the skeleton plot technique (Schweingruber et al., 1990) helped to find common features in each pair of core samples and thus iteratively increased the quality of the initial crossdating. Digital images of the samples passing this first quality check were imported to WinDENDRO and were visually and graphically crossdated. The results were verified by means of the computer program 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. Statistical parameters evaluating the quality of the series were the mean, minimum and maximum values, the standard deviation, mean sensitivity, autocorrelation and Pearson’s coefficient of correlation. 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 (Fritts, 1976).

After the quality of the crossdating of the raw data series was verified, they were standardised and filtered in the computer program Turbo ARSTAN using a multi-step process (Cook, 2002). One source of systematic mistakes is the positive relationship between the raw ring width and the year to year spread in variance. The juvenile period of a tree is usually characterised by large increments and large local variance which decrease with increasing age to a level typical for each species. This growth tendency in each tree-ring series, if not treated, would import unwanted trends into dendroclimatological studies. Therefore, standardisation techniques are usually applied to remove, as much as possible, the deleterious effects of the age trend and environmental noise to which the climatic signal in the tree has been subjected. This is done by processing the ring-width measurements with digital filters that remove unwanted frequencies, sharpen diffuse signals, and subdue the noise in the record until the desired but attenuated signal can be seen more clearly (Fritts 1976). First, we stabilised the variance using a power transformation which uses the positive relationship between level of raw values and spread of variance in an adaptive way (Druckenbrod and Shugart, 2004). Second, a detrending procedure translated the power-transformed ring-width data into new series of normalised dimensionless tree-ring indices. For this detrending, the cubic smoothing spline was favoured against deterministic methods such as the exponential curve fitting because the series exhibited pulse-like disturbances and other growth irregularities not related to climate and therefore demanded a more flexible detrending treatment (Cook and Peters, 1997). Hence, the individual series were detrended applying a 66-year cubic smoothing spline function with a 50 % cutoff in conjunction with the residuals method, *i.e.*, 50 % of the variance in each series at the period of 66 years was removed. The bi-weight robust mean was preferred over the arithmetic mean to finally compute the mean site chronologies because the bi-weight robust mean discounts the influence of outliers, which can be sources of unwanted bias (Cook et al., 1990).

The increasing negative correlation between sample depth and variance in that part of the series with a smaller sample size is a consequence of the noise in the remaining series ensemble that is not properly reduced by averaging. The resulting mean values are less robust than those derived from larger sample sizes (Briffa and Jones, 1990). Therefore, the sample size over time was illustrated to ensure better control over the quality of the chronology with decreasing sample size. A commonly used guide to assess the likely loss of reconstruction accuracy is the expressed population signal EPS (Wigley et al., 1984). It measures how well the finite-sample chronology compares with the theoretical population chronology based on an infinite number of trees. Theoretically, the EPS ranges from 0.0 to 1.0, *i.e.* from no agreement to perfect agreement with the population chronology, but Wigley et al. (1984) give an EPS = 0.85 as a reasonable limit for the chronology to still be reliable. The mean site chronology used for calibration and climate reconstruction purposes was then cut off at a critical EPS of 0.85.

The mean tree-ring index was also analysed for possible autocorrelations of varying time lags before and after detrending. The presence of autocorrelations would indicate the existence of lagged physiological effects that persist for longer than the current year (Cook and Kairiukstis 1990). In the current study the comparison of the plots before and after standardisation indicated that the autocorrelation in the mean tree-ring index was reduced below the limit of significance and therefore statistical assumptions for further dendroclimatological examinations were not unduly influenced by autocorrelation in the data (Fig. 3). Consequently, no additional autoregressive modelling was necessary, and thus the Turbo ARSTAN standard chronology (STNDRD) was used for the comparison with the climate data (Cook and Holmes, 1984).

Extreme year analysis of tree growth

During the continuous time series analysis it is not possible to explain all parts of the tree-ring variance. Tree growth is always explained by several climate variables and there is always a certain amount of signal noise that remains unexplained (Schweingruber et al., 1991). In reality, only in years with very limiting or encouraging climate conditions do most trees form narrow or wide rings, respectively. For a reliable proxy record it is important that these rings can be found in a large part of the sample trees, thus the wide or narrow rings should occur simultaneously. In this regard, the continuous time series analysis between tree-ring chronologies and climate data series contains a systematic error. The linear correlation between tree-rings and climate data is upset if contradicting tree-ring width measurements are averaged. The tree-ring widths of such years were most likely not determined climatologically but by different possibly non-climatic factors, and thus such years reduce the meaningfulness of continuous time series analysis. Apart from the temporarily occurring heterogeneity of the tree-ring series, a second reason can be responsible for the reduced power of the continuous time series analysis, that is, the long-term meteorological record is reflecting the climate conditions of the sampled forest stand only to some extent. The two reasons are responsible for the fact that the tree-ring series contain sequences with reduced climatic information (Schweingruber et al., 1991). One way to address this problem is the extreme year analysis which only examines the conspicuously wide and narrow tree-rings exhibited by as many sampled trees as possible. In doing so the extreme year analysis ensures that the climate growth relationship concentrates only on those years in which tree growth of the majority of the individuals has been limited by the same climatic factor. The results of the extreme year analysis help during the continuous times series analysis of tree rings and climate data.

The identification, presentation and interpretation of extreme years as a basis for the skeleton plot technique usually aid during the initial task of crossdating the samples (Schweingruber et al., 1990). The idea of such extreme events was also employed here as an *a posteriori* examination in order to identify extreme years of the tree-ring chronology. They were then used for a dendroclimatological investigation of individual extreme years. The aim of this section is to isolate individual extreme years which are replicated by as many trees per site as possible. Those years are then climatologically investigated to separate characteristic features that might be repeated in all extreme years. Such an examination promises to enhance the comprehension of the relationship between tree growth and climate. Numerous methods exist to identify extreme years (*cf*. Gumbel, 1958; Coles, 2001; Reiss et al., 2001). For the current study the standard deviation technique (Allen, 2002) was applied. The standard deviations for each year were computed and the years with values one standard deviation below and above the mean identified. The list of such years is then analysed for the numbers of trees showing this particular year as an extreme year. In this study, the ten most extreme years are characterised by the largest number of trees showing extreme values above and below the mean (Esper, 2000). However, the total sample size never reaches the maximum number of 53 core samples because the individual segment lengths are different and some samples cover different and not overlapping periods.

Climate response

In contrast to the extreme year analysis which only concentrates on individual years, the continuous time series analysis techniques are used to identify important climate factors correlating with tree growth. 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 most complete meteorological record closest to the Curtain Fig Tree site is derived from the Kairi research station. The homogeneity test of the Kairi research station data was conducted with records from Cairns, Walkamin and Atherton. The tests showed highly homogeneous data sets and no obvious bends or other irregularities were discernable. Since the Kairi research station record is highly homogeneous and only 8 km away from the study site, simple Pearson's coefficients of correlation were computed for monthly climate data from Kairi research station and the mean tree-ring index (Esper et al., 2001). The available monthly climate data comprised precipitation, maximum, minimum and mean temperatures, relative humidity and sunshine duration (the hours of bright sunshine per day). At Kairi research station, precipitation data were available from 2000 to 1920 and those for temperature, relative humidity and sunshine duration from 2000 to 1966. 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 to August of the current growth period and averages for the seasons September to November, December to February, March to May and June to August.

Calibration, verification and reconstruction

The dominant climatic forcing factor controlling tree growth on the Atherton Tablelands was calibrated against the site tree-ring chronology. The climate record was split into two periods. The first period, 2000-1960, is used for calibration and the second one, 1959-1920, for the independent verification of the data. The ordinary least square method was applied to find the best regression model which was then used as the transfer function (Fritts, 1976). The Pearson's correlation coefficient between instrumental and reconstructed values was computed to estimate the ability of the tree-ring data to predict the selected climate factors. The verified simple linear regression model was then used to reconstruct climate for the site.

Spectral analysis

Finally, the climate reconstruction was subjected to a spectral analysis to decompose the original series into different frequencies and analyse the variance in each frequency band to uncover possible trends and periodicities in the series (Jenkins and Watts, 1968). The software package Autosignal (Systat) determines those spectral density values that appear particularly strong and enables an easy graphical estimation of possible trends within the chronology (Davis, 1986).

3. Results and discussion

The total length of the mean tree-ring width chronology, which consists of 53 crossdated cores from 37 trees, covers the period from 1591 to 2000 but between 1591 and 1859 the series consists of less than five trees and the EPS drops below the critical value 0.85 (Fig. 4C). Therefore, the series was terminated in 1860 due to the small sample size in the older section and low EPS values. The mean curve of the individual raw tree-ring width series displays a long-term trend starting with slow growth in the 1860s, increasing until the mid 1950s to 1960s to then decrease again to 2001 (Fig. 4 A). This trend might be explained by aging and competition and has been removed by the standardisation procedure (Fig. 4 B). Extreme outliers, for example, 1884 and 1973 have been smoothed by the bi-weight robust mean. The standardised site chronology exhibits a high mean sensitivity (0.597) with sharp changes between lows and peaks. Only rarely does the growth remain stable on a low or high level for longer than two years, for example, in the early 1940s, the late 1960s to early 1970s and the early 1990s. This indicates a remarkable variability of the reconstructed precipitation record which is only interrupted by prolonged dry or wet periods such as the drought of the 1990s. This variability is also illustrated in rainfall variability index maps released by the Australian Bureau of Meteorology. The rainfall variability indices are based on 104 years (1900 to 2003) of monthly and annual rainfall data (Australian Bureau of Meteorology, 2008). Rainfall variability was calculated with the formula “Rainfall variability = (90th percentile –

10th percentile) / 50th percentile". The maps show that the Atherton Tableland has a low to moderate annual rainfall variability but a high to very high variability during the months March to June.

In average for all 53 core samples, *T. ciliata* exhibits tree-ring widths of 3.58 mm and the minimum and maximum values have a wide range extending from 0.01 mm to more than 20 mm with a standard deviation of 2.89 mm (Table 1). The mean segment length is 90 years, most of the samples have a segment length of 50 to 100 years and only a few segments are shorter or longer. The standard error of the mean, as a measure of precision and uncertainty of how the sampled trees represent the underlying population, increases through time and is related to the decreasing sample depth. It indicates that the early part of the mean tree-ring width index curve is a less precise estimate of the mean than the later part. The mean sensitivity of nearly 0.6 and the mean series intercorrelation of 0.52 as a measure of the strength of the common signal in the chronology indicate that the Atherton Tablelands chronology is a robust estimate of annual growth changes and that it is suitable for dendroclimatic research in the tropics (Worbes, 2002).

Extreme years

The four most extreme positive and negative years replicated by the largest number of trees (printed in bold letters in Table 2) were compared to temperature and precipitation data to determine if climatic anomalies were associated with extreme growth anomalies. The long-term monthly mean is subtracted from the extracted climate data for the extreme years and the resulting residuals have been plotted as monthly values starting in January of the previous growing season to the end of the current period in August (Fig. 5). The available temperature data at Kairi research station only reach back to 1966 and thus the extreme years listed for the period before 1966 could not be analysed. Therefore, the analysis had to jump to those extreme years in the table with available temperature data, that is, 1990, 1997, 1967 and 1966.

The comparison of the temperature and precipitation data shows that all positive extreme growth years identified in table 2 exhibit monthly values for March rainfall which are above the x-axis, i.e., the long-term mean rainfall, and all negative extreme growth years experienced March rainfall that was below the long-term mean. In addition, February and April seem to exert some influence as well, however, to a lesser extent. Reoccurring temperature and precipitation anomalies seem to have influenced many trees to grow much faster or slower than normal. In three out of four years the March rainfall of the previous year also lies below the long-term mean. In the fourth negative growth year, namely 1967, the March rainfall recorded during the previous growth period 1966 to 1967 was far above the average as a result of tropical cyclone Elaine which delivered a lot of rain to the region between the 13th and 19th of March 1967 (Australian Bureau of Meteorology, 2002). In contrast, the previous year 1966 is listed as a positive extreme year. The sequence of the years 1966 and 1967 illustrates that the timing of extreme precipitation events can have different effects on tree growth. The additional precipitation delivered by tropical cyclone Elaine in March 1967, i.e. in the previous growing period 1966 to 1967, did not help to compensate for the below-average precipitation of March to April 1968 in the growing period 1967 to 1968. However, the above-average precipitation due to Elaine resulted in a positive extreme year in the growing period 1966 to 1967 which implies that the soil at the study site has poor water storage qualities and tree growth mainly uses precipitation received during the current growth period.

Climate response

In general, the tree-ring width chronology correlates positively with precipitation data (Fig. 6 A). Tree rings are correlated positively with March to May precipitation of the previous vegetation period but only the April-value rises above the 95% confidence limit. The correlation increases towards the second part of the current vegetation period until it reaches a peak in March followed by lower but still significant values for May and June. The correlation between annual precipitation (September to August) and tree growth is significantly positive. The data indicate that the precipitation of the months March to June of the current season is most important for tree growth which corroborates similar results for *Toona ciliata* in the Upper Kangaroo Valley located near Sydney (Heinrich and Banks, 2005). The authors studied the dendroclimatological potential of the species at the southern limit of its distribution and found significant climate-growth correlations between late-season rainfall and tree growth (Heinrich and Banks, 2005). Correlation patterns between the tree-ring width chronology and the monthly precipitation data are generally low during the months December to February. One possible explanation is that tropical cyclones interfere with the climate-growth correlations. Tropical cyclones mainly occur during these months and bring torrential rains and destructive winds unfavourable to tree growth to the region, although the Atherton Tableland is usually affected by heavy subsequent rainfall depressions (Australian Bureau of Meteorology, 2002).

Support for this hypothesis comes from a dendrometer analysis of *T. ciliata* in the Upper Kangaroo Valley (Heinrich and Banks, 2005). It also showed a general positive relationship between rainfall and tree growth until torrential rains in February 2002 hit the site which resulted in a sharp decrease of diameter tree-growth. Subsequently, the coefficient of correlation turned negative during this short period. Once the heavy rainfall stopped, tree growth increased again and remained high until the end of the growing season then likely profiting from the humidity stored in the soil. A similar process might be responsible for the negative correlation between precipitation and tree growth in December on the Atherton Tableland. In contrast, the extreme year analysis showed that the heavy cyclonic precipitation in March 1967 positively supported growth, hence, resulting in a positive extreme year (Fig. 5), whereas potentially harmful winds and low light levels due to heavy cloudiness seem not have affected tree growth negatively.

Dünisch et al. (2003) investigated with dendroecological methods the two tropical Meliaceae species *Swietenia macrophylla* King and *Cedrela odorata* L. in Mato Grosso, Brazil. Correlation analyses revealed a significant relationship between tree rings of *S. macrophylla* and precipitation at the beginning and at the end of the growing season. In contrast, tree rings of *C. odorata* were significantly correlated with the precipitation in March and May of the previous growth period (Dünisch et al. 2003). Although the two species showed different correlation patterns, both have in common that they correlate mainly with precipitation. Comparably, growth of *Toona ciliata* at the Curtain Fig Tree site seems also to be mainly controlled by precipitation of the second half of the growing season.

The temperature data of the previous growing season correlate mainly positively with tree growth (Fig. 6 B), however, the maximum temperatures correlate significantly only in May, the minimum temperatures only in March and April and the mean temperatures only in January and February. The only significant correlation for the current growing season is shown for minimum temperature in October. The correlation patterns suggest that tree growth of *T. ciliata* at the Curtain Fig Tree site seems to be influenced positively by high temperatures during the previous year. In contrast, high maximum temperatures during the current growing season seem are negatively correlated with tree growth. In general, the correlation patterns between temperature and tree growth are not very meaningful and thus the tree-ring chronology at the Curtain Fig Tree site holds little potential for further temperature reconstructions, unlike the tree-ring chronology from the Upper Kangaroo Valley (Heinrich and Banks, 2005) which showed potential to reconstruct early season temperatures.

The monthly correlations between tree rings and both relative humidity and sunshine duration frequently point in opposite directions (Fig. 6 C) most likely due to the fact that relative humidity is negatively correlated with air temperatures which again is related to sunshine duration. Relative humidity and tree rings correlate well between July and August of the previous growing season and September and October of the current season. In comparison, the main period of positive influence of relative humidity in Upper Kangaroo Valley (Heinrich and Banks, 2005) is between December and March, a bit later during the year than on the Atherton Tableland. The correlations for duration of sunshine mainly correlate negatively but less significant except for March of the previous and the current season. The values indicate that during March of both the previous and current growing season *T. ciliata* grows best when humid conditions with high minimum but low maximum temperatures and short durations of sunshine prevail. The significant values for relative humidity in September and October suggest that trees grow best under more humid conditions at the beginning of the growing season when soil moisture is at its annual low following the dry season. Although the study site and the Upper Kangaroo Valley site are located far apart, the similar climate responses of the tree rings at both places are surprising as the climate at the northern site is determined by tropical air masses while the Upper Kangaroo Valley site in the south is mainly influenced by temperate climate systems. Since a comparison of the climate and tree-ring data did not reveal any significant correlations between the sites (Heinrich, 2004), tree growth in *T. ciliata* seems to be consistent despite differences in the climate regimes of the two sites.

Nevertheless, the results from the extreme year analysis are confirmed. Both extreme year analysis and response plots identified March precipitation as the most important month influencing tree growth on the Atherton Tableland. Moreover, the response plots also reveal a good correlation with May and June precipitation. Generally, the climate sensitivity of *T. ciliata* tree-rings from the Atherton Tableland seems to differ from *T. ciliata* tree-rings presented by Bhattacharyya et al. (1992) in India. The authors suggested an ambivalent interpretation of narrow growth rings formed during both high and extremely deficient rainfall years. At the Curtain Fig Tree site, only a positive relationship with precipitation, in particular March rainfall, is apparent. Since the precipitation data correlated best with tree growth, the sum for March to June precipitation was calibrated against tree rings.

The regression analysis between the mean tree-ring index and the March to June precipitation for the calibration period 1960 to 2000 determined the linear relationship y = 517.61x - 30.283. The correlation r = 0.59 is highly significant for the calibration period and also for the verification period 1920 to 1959 (r = 0.45), and 35 % of the tree-ring variation is explained by the March to June rainfall data. The reduction of error (RE) and coefficient of efficiency (CE) were calculated and are included in table 1 to provide an indication of the robustness of the relationship between the mean tree-ring index and the March to June precipitation. Although the values are not very high (RE = 0.09 / CE = 0.1) both values are positive. The theoretical limits for the RE and CE statistics range from 1 which indicates perfect agreement to minus infinity. A minus value indicates no agreement but any positive value can be considered as encouraging (Fritts 1976). Observed and modelled precipitation values show only a few differences during the calibration and verification periods. In the verification period more differences are apparent but generally the model follows the course of the observed data (Fig. 7).

The reconstructed March to June precipitation is plotted for the time period 1860 to 2000 (Fig. 8). Extremely dry conditions are indicated for the years 1882, 1936, and 1991 to 1992 and very wet years are apparent in 1885 and 1958 (Table 3). The data illustrate the strong year-to-year variation of both observed and reconstructed precipitation. In several instances, extremely negative and positive years are separated by only a few years, for example, negative from 1914 to 1919 and extremely positive in 1920. Historical droughts and flooding data for eastern Australia also report incidences of such extremes (Whetton, 1997), *e.g.*, a prolonged drought directly followed by heavy flooding events in 1920. Although the reconstructed March to June precipitation represents only the later part of the growing period, it is remarkable that it exhibits much variability. However, this high variability in autumn precipitation has also been shown by the Bureau of Meteorology (2008). Their variability analysis of precipitation data (104 years) throughout Australia revealed that the variability of rain is higher in autumn than it is in summer or for the entire year. The highest variability was found for the early season period (September to December) when precipitation is received mainly from thunderstorms and thus highly variable (Bureau of Meteorology, 2008).

To emphasise the low-frequency signals in the reconstructed records, a 15-year moving average was calculated for the data sets and plotted on top of the yearly values (bolt line in Fig. 8). It indicates periods of above-average precipitation during the 1880s to early 1890s, early mid-1920s to mid-1930s and to a lesser extent in the 1950s and 1970s. Periods of below-average precipitation values occurred during the 1870s, around 1900, during the 1940s and the late 1980s. Some of the drought events have had such devastating consequences for Australia that names were given to them. The best known droughts are the "centennial drought" and the "Federation drought" which had the country in its grip between 1895 and 1902 (Nicholls, 1997). Other well-known droughts are the World War II drought between 1937 and 1945. Apart from the 1888 drought, all droughts are reflected in the tree-ring reconstruction from the Atherton Tablelands.

Spectral analysis

The 15-year moving average of the reconstructed precipitation indicates the presence of some low-frequency variability. For further analysis of such possible non-random variations the data were subjected to a spectral analysis. The resulting spectral plot investigates possible reoccurring cycles (Fig. 9). Peaks at about 5, 10, 21 and 51 years can be identified. The peaks near the 2-year frequency are probably associated with the quasi-biennial oscillation (Landsberg, 1962). The peak at 5 years falls in the ENSO bandwidth (Diaz and Markgraf, 1992). The peaks between 10 and 21 years seem to be related to the 11-year and 22-year periodicity in sunspots (Douglass, 1917; Stuiver, 1961). The multidecadal peak of 51 years corresponds to the Pacific decadal to inter-decadal climate variability (D'Arrigo et al., 2001; Mantua et al., 1997) which recently was also revealed in a teak tree-ring series in Thailand

(Buckley et al., 2007). The authors identified a strong peak around 48.5 years reflecting the decadal scale variance retained in the teak tree-rings. The *T. ciliata* record also supports the concept of long-term multidecadal variations in the Pacific (Power et al., 1999) and that such variations have been present in the tropical West-Pacific at least since 1860. Apart from the strongest signal at 51 years, it is of interest to note that the peak at 5 years is not significant. Previously, it has been demonstrated that the modern ENSO frequency lies between 3 and 8.5 years (Rodbell et al. 1999). Since the tree-ring record has been shown to be most sensitive to variations in precipitation, it is surprising that the peak at 5 years is not significant. The correlation between the reconstructed March to June precipitation and the Southern Oscillation Index (SOI) (Table 4) gives a clue why this might be. The correlation throughout the entire period 2000 to 1900 is rather low (r = 0.21). However, interestingly in the first half of the 20th century it is significantly higher (r = 0.37) than in the second half (r = 0.15), hence the correlation is not stable in time. Several studies have demonstrated that the pattern of correlation between rainfall and the SOI has changed between 1932-1953 and 1954-1973 and that 1921-1950 were years with a weak SOI (McBride and Nicholls, 1983; Pittock, 1984; Nicholls, 1985). Lough (1991) analysed rainfall variations in Queensland aiming to identify the major temporal variations of rainfall from 1891 to 1986. She found that during the period of weak SOI variations (1921-1950) rainfall in Queensland was less variable (Lough, 1991). Further dendroclimatic studies in the Australian tropics should focus on this temporary unstable relation between proxy data such as March to June precipitation and the SOI.

4. Conclusion

It has been established that *T. ciliata* can be used for tree-ring analysis in Far North Queensland. The presented mean tree-ring index is the first chronology of its kind in tropical Australia. It is sensitive to precipitation records especially of the months March to June. However, during the months December to February the correlation between tree growth and precipitation weakens. Although the negative effects of tropical cyclones are possible reasons for this weakening, the extreme year analysis of the years 1966 to 1968 indicates that the additional cyclonic rains had positive effects on tree growth. Therefore, to clarify the different results from the climate response and extreme year analysis and also from the dendrometer studies conducted in the Upper Kangaroo Valley (Heinrich and Banks, 2005) growth monitoring using dendrometers and cambium wounding techniques are needed in tropical Australia. Such studies will help to better comprehend the varying growth responses to extreme weather conditions, in particular drought and very wet conditions which may induce nonlinear growth responses in *T. ciliata* on the Atherton Tablelands, comparable to *T. ciliata* in India (Bhattacharyya et al., 1992). Nonetheless, the positive relationship was used to reconstruct March to June precipitation back to 1861. The record reflects both the high year-to-year variation and the long-term changes of Australian rainfall. In several instances extremely positive years are followed by extremely negative years and vice versa. The spectral analysis revealed peaks at four recognisable band widths of 5, 10, 21 and 51 years. As the frequencies with band widths of 5 and 51 years can be associated with the two climate phenomena ENSO and IPO, proxy data derived from *T. ciliata* from tropical Australia have a promising potential to reconstruct climate in the high- and low-frequency domain. Further sampling of old trees and of wood used for old buildings such as farmhouses on the Atherton Tablelands are needed to confirm the results and to expand the existing chronology, however, a preliminary search for older material has not been successful yet (Heinrich, 2004). Nevertheless, further studies should aim for a network of *Toona ciliata* sites in Australasia because the species has a large latitudinal range between China and Southeast Australia (30° N and 30° S). Such a multi-latitudinal network promises to offer further insights into the ecology of the species and a better understanding of the spatial and temporal distribution of the climate in the region. In most countries of its distribution substantial forest stands of *Toona ciliata* and related *Toona* species 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. Nevertheless, the new record already helps broaden the climatic information resource to the western region of the tropical Pacific where heretofore there was little long-term tree-ring data available.

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Figures and Tables

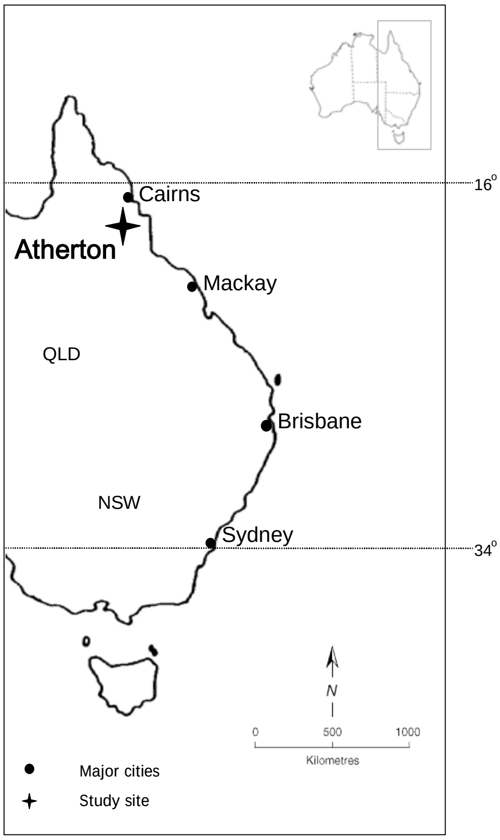

Fig. 1. Location of the study site Curtain Fig Tree on the Atherton Tablelands indicated by the asterisk; the old-growth submontane tropical rainforest is located in Far North Queensland 720m asl (17º 30’ S, 145º 58’ E)

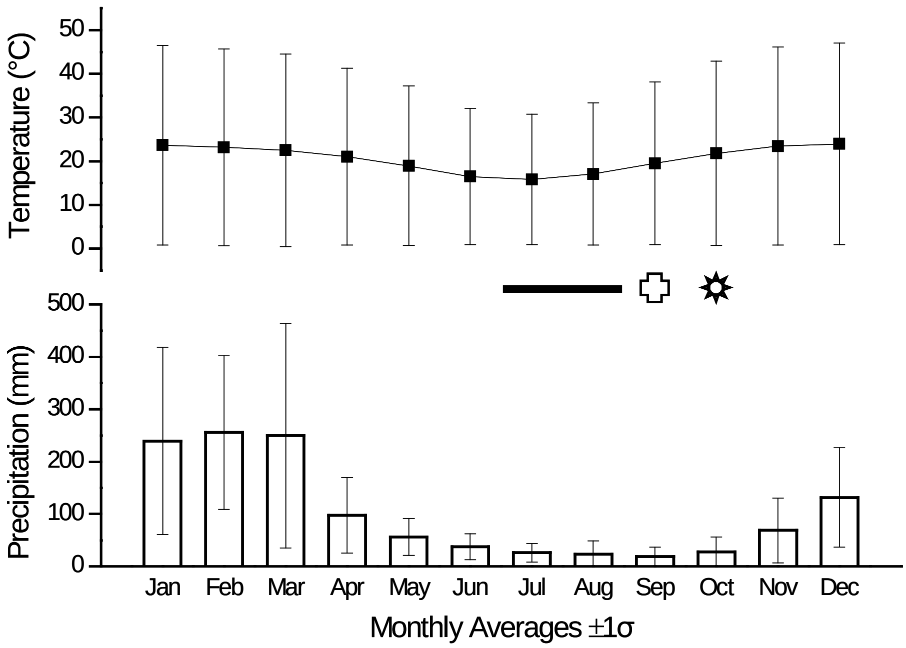

Fig. 2. Climate diagram derived from long-term averages for Kairi meteorological station, located 8 km north of the sample site Curtain Fig Tree (Source: Australian Bureau of Meteorology, Canberra 2002); the phenology of *Toona ciliata* is marked by a line, cross and asterisk, indicating the leafless period (July to August), leaf flushing (September) and flowering (October)

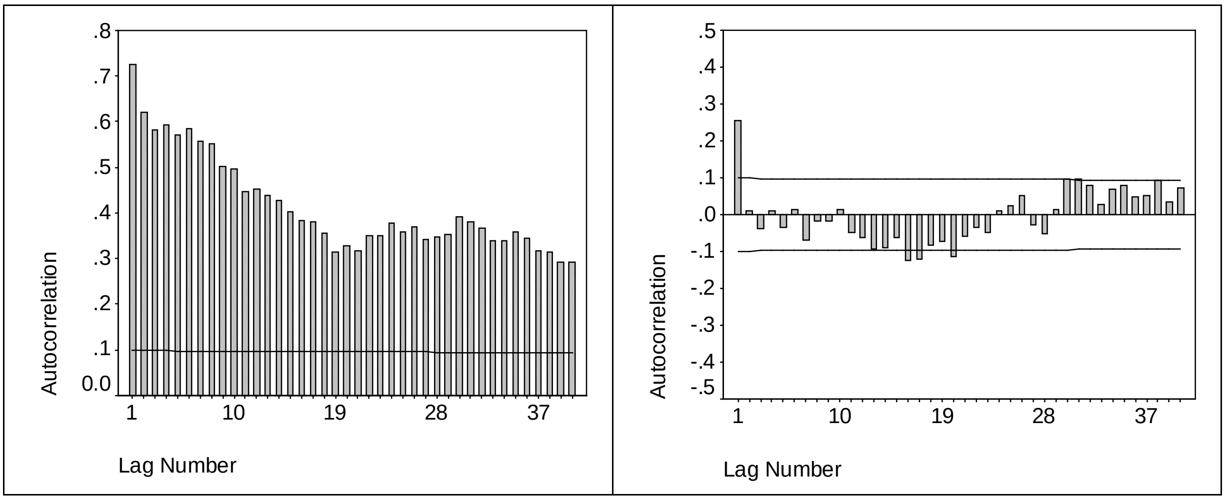

Fig. 3. Autocorrelation (lags 1 to 40) for the raw (left) and detrended (right) tree-ring values from the Curtain Fig Tree site

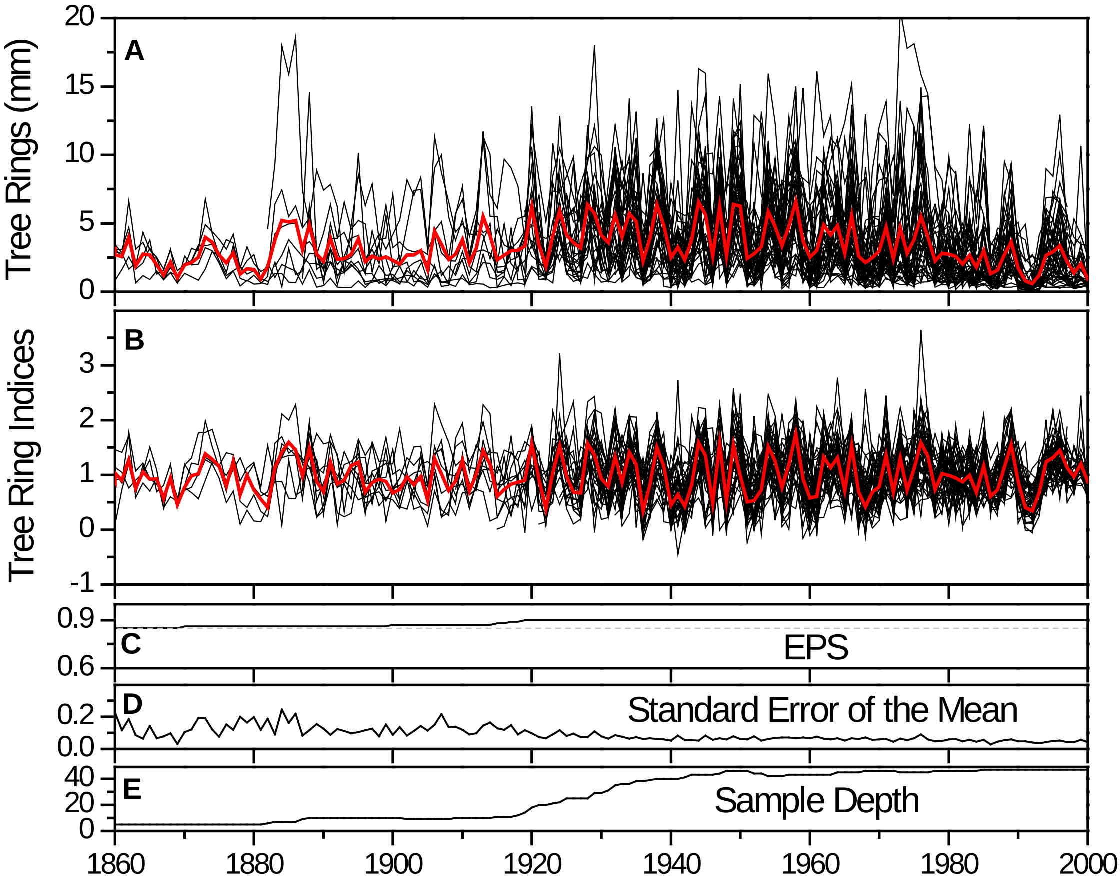

Fig. 4. Plots of the Atherton Tablelands raw tree-ring width series (A), tree-ring indices (B), expressed population signal (C), standard error of the mean (D) and sample depth (E) through time. The red graphs represent the means of the raw values and the index series, respectively.

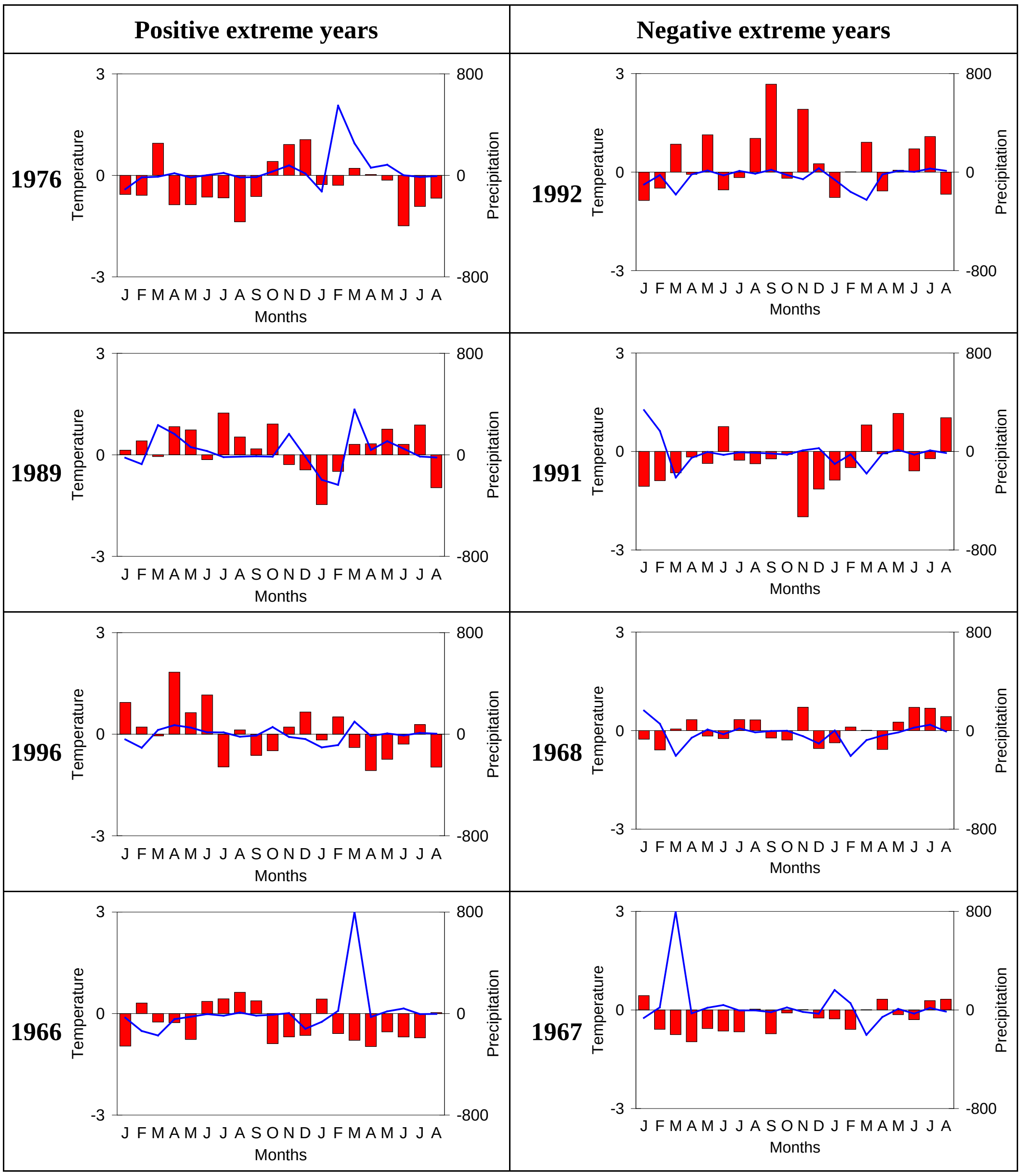

Fig. 5. Monthly precipitation and temperature variations in comparison to the long-term averages during extreme years (previous and current year) (Source: Australian Bureau of Meteorology, Canberra 2002)

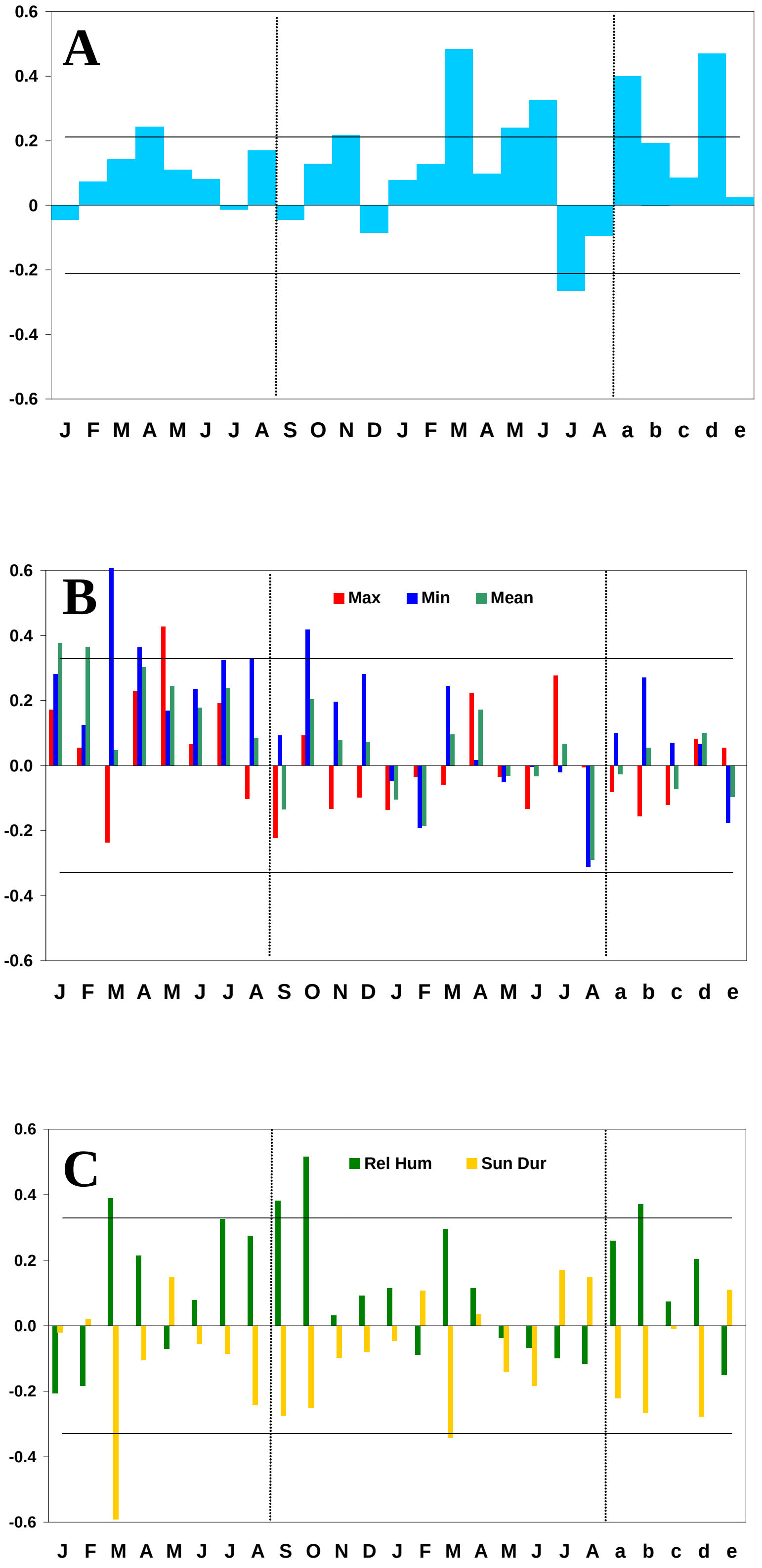

Fig. 6. Climate response plots for the Atherton Tableland site with Kairi research station meteorological data: Monthly coefficients of correlation for precipitation (top), maximum, minimum and mean temperatures (middle) and relative humidity and sunshine duration (the hours of bright sunshine per day) (bottom). The diagrams are separated into three parts by vertical lines. The left part of the diagram covers the period January to August

before the current season, the middle part stands for this season (September to August) and in the right part the small letters a to e stand for the annual value and the averages for the periods for September to November, December to February, March to May and June to 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).

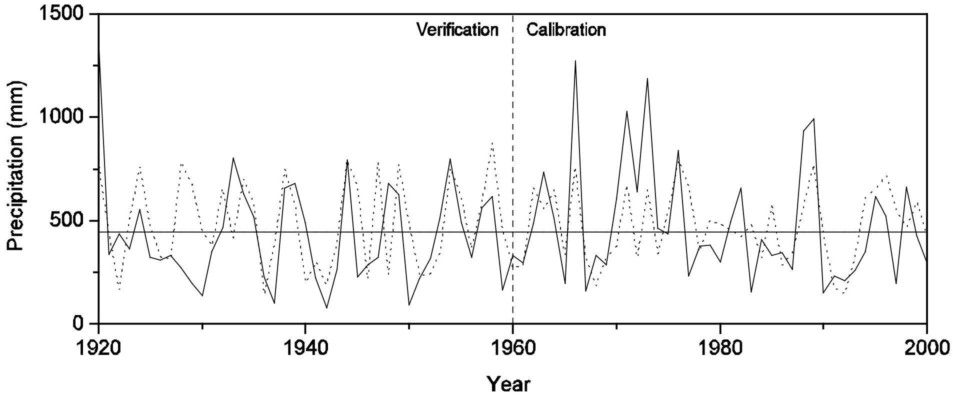

Fig. 7. Observed (solid line) and reconstructed March to June precipitation (dashed line) for calibration period 2000 to 1960 and verification period 1959 to 1920

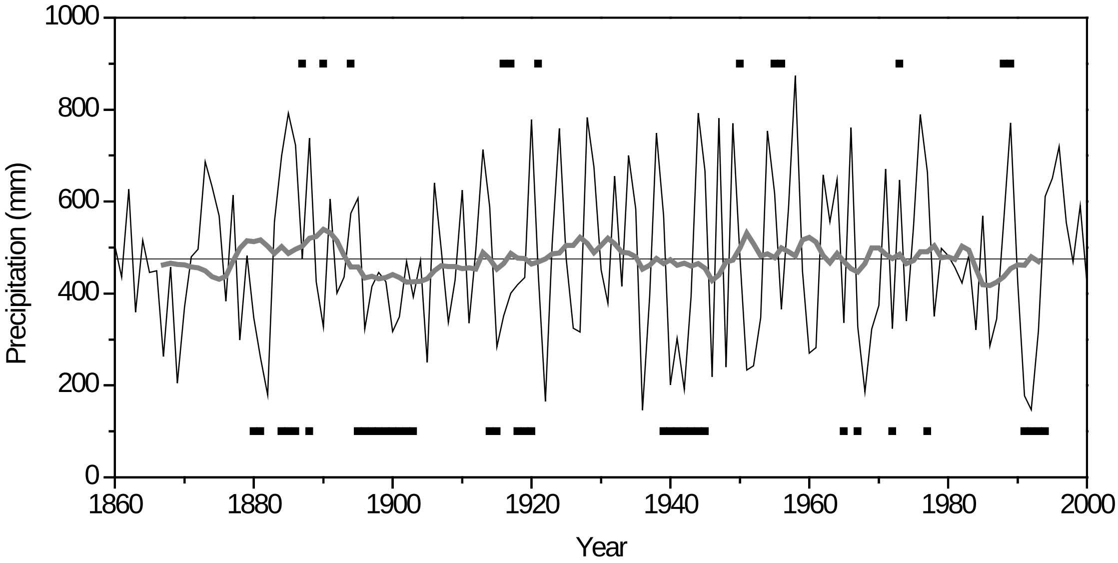

Fig. 8. Reconstruction of March to June precipitation for the Atherton Tablelands with 15-year moving average (grey line) in comparison to major drought (lower markings) and flooding events (upper markings) (Whetton, 1997)

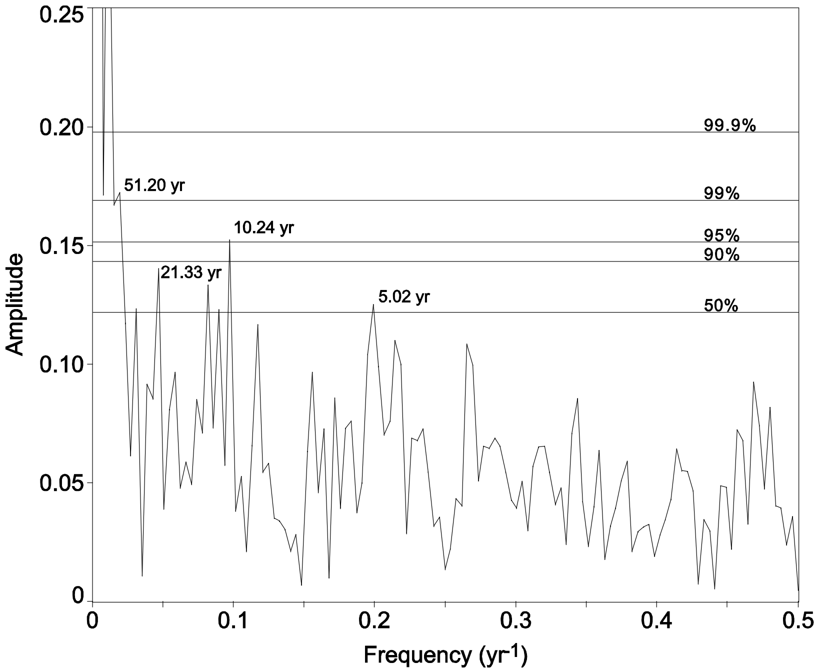

Fig. 9. Spectral analysis of the Atherton Tablelands tree-ring width index for the period 1860-2000 shows significant peaks at approximately 51, 21, 10 and 5 years. 50, 90, 95, 99 and 99.9 % confidence levels are indicated.

Table 1

Summary statistics for the Curtain Fig Tree site chronology

Site name	**Curtain Fig Tree**
Latitude/ Longitude / Elevation (m asl)	17˚ 30’ /145º 58’ / 720
Chronology length	2000-1860
Length (years)	140
No. of trees	37
No. of samples	53
Mean (min./max.) annual increment (mm)	3.58 (0.1/20.55)
Standard deviation (mm)	2.89
Mean sensitivity	0.597
Series intercorrelation	0.522
r (calibration / verification period)	0.59 / 0.45
Reduction of Error / Coef. of Efficiency	0.09 / 0.1

Table 2

The first 10 positive and negative extreme years of the tree-ring chronology; years printed in bold are used for further analysis. The columns "positive" and "negative" show the number of trees with extreme values in that particular year and the total sample size for that year, respectively.

	Positive	**Year**	**Negative**	**Year**
1.	23/45	**1976**	25/47	**1992**
2.	23/43	1958	25/47	**1991**
3.	21/46	1949	23/46	**1968**
4.	19/47	**1989**	21/38	1936
5.	18/47	**1996**	19/46	1951
6.	17/45	**1966**	18/43	1946
7.	17/42	1954	17/44	1952
8.	17/44	1947	17/41	1942
9.	15/43	1945	15/43	1960
10.	15/45	1973	14/45	**1967**

Table 3

The 5th, 10th, 90th and 95th percentiles of the reconstructed March to June precipitation for the period 2000 to 1860 at the Curtain Fig Tree site on the Atherton Tablelands, Queensland, Australia

Percentiles	Year	Rec. Mar-June precip.
5th	1936	145.7
	1992	147.3
	1922	165.9
	1991	177.8
	1882	178.8
	1968	186.1
	1942	190.7
	1940	201.1
10th	1869	205.2
	1946	218.7
	1951	233.2
	1948	239.9
	1952	243.0
	1905	249.7
	1881	260.1
90th	1886	722.3
	1888	737.9
	1938	748.7
	1954	753.4
	1924	759.6
	1966	760.6
	1949	770.5
95th	1989	771.5
	1920	778.7
	1947	781.3
	1928	782.9
	1976	789.1
	1944	792.2
	1885	792.7
	1958	874.5

Table 4

Coefficients of correlation between reconstructed March to June precipitation and Southern Oscillation Index

2000-1900	*2000-1951*	*1950-1900*
0.21*	0.37**	0.15

** = significant at the 99 % level, * = significant at the 95 % level