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A tree-ring width based drought reconstruction for southeastern China: links to Pacific Ocean climate variability.

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Abstract

We present a drought reconstruction for southeastern China based on a tree-ring width chronology of *Cryptomeria fortunei* developed from the two sampling sites in central Fujian. A reconstruction of July-February drought variability, spanning AD 1855–2011, was developed by calibrating tree-ring width data (total ring or latewood? Specify here) with the Palmer drought severity index (PDSI). The reconstruction was verified against an independent data set, and accounts for 36% of the actual PDSI variance during their common period (1955–2011). Dry intervals are reconstructed between AD 1859–1880, 1899–1911, 1927–1933, 1946–1959, 1964–1970 and 1987–1997. Wet conditions prevailed during 1855–1858, 1881–1898, 1912–1926, 1934–1945, 1960–1963, 1971–1986

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and 1998–2011. Comparisons between our PDSI reconstruction and a moisture-sensitive tree-ring width record from Vietnam reveal consistencies with the Southeast Asia drought record, suggesting similar drought regimes. Spectral peaks of 2.8–6.4 years may be indicative of El Niño-Southern Oscillation (ENSO) activity, as also suggested by the significant correlations with Sea Surface Temperatures (SST) in the eastern equatorial and southeastern Pacific Ocean and an extreme event analysis. The analysis of links between our PDSI reconstruction and the large-scale regional climatic variation shows that there is a relationship of regional drought variation with the East Asian Summer Monsoon (EASM) intensity.

Keywords: Tree-rings, Southeastern China, Drought reconstruction, Sea surface temperature, El Niño-Southern Oscillation, East Asian summer monsoon

Introduction

The Asian summer monsoon is one of the most energetic components of the Asian climate system. Its spatiotemporal variability can result in drought or floods, crop failure and famine, and changes in the hydrologic regimes of monsoonal China, and has the potential to impact the lives of most of the population of China. The city of Shanghai, and other coastal cities, have meteorological records which be traced back to the late 19th century, however, most of the climate records for monsoonal China begin in the 1950s and provide poor temporal and spatial coverage. Thus, due in part to the lack of long-term climatic records, the historical characteristics and variability of the Asian summer monsoon circulation, at various timescales, is not sufficiently understood for modelling studies to be used predictively (Zhou et al. 2009; Cook *et al*. 2010). Indirect evidence for past variability, such as tree-rings, historical climate documents, lake sediment records and stalagmite-based reconstructions have successfully served as proxy records of Asian summer monsoon intensity (Wang *et al*. 2001; Yancheva *et al*. 2007; Cook *et al*. 2010)..

Existing dendroclimatological reconstructions exist for the subtropical and tropical regions of monsoonal Asia, giving an insight into the history of the regional monsoon climate. The most southerly studies in Asia were carried out in Java, Indonesia, where the signals of monsoon drought and streamflow are recorded in the ring variability of *Tectona grandis* (D'Arrigo *et al*. 2006, 2011a). Buckley *et al*. (2007) develop a 448-year teak chronology for northwestern Thailand revealing significant correlations with the regional ENSO signal. Elsewhere in Indochina and Myanmar, dendroclimatical studies have been used to evaluate various drought patterns and climate trends (Sano *et al*. 2009; D'Arrigo *et al*. 2011b). Buckley *et al*. (2010), based-on tree-ring width records from Vietnam, explore drought fluctuations over the past 759 years discussing the significant contribution of drought to the demise of the Temple at Angkor Wat. Such has been the success of tree-ring based climate reconstructions in Asia , Cook *et al*. (2010) developed the Monsoon Asia Drought Atlas (MADA), a seasonally resolved gridded spatial reconstruction of Asian monsoon drought and pluvials over the last millennium, derived from a 327-series tree-ring chronology network. Despite the significant sample depth of this network southern China is not represented (Cook *et al*. 2010), and, to the best of our knowledge, no drought reconstructions based on tree-rings have been developed to date in southern China.

Fujian Province has widespread forests and, indeed is the Chinese province with the highest forest coverage on the mainland. The region, as it contains significant areas where tree growth is moisture sensitive, has great potential for contributing drought-deconstructions .. Here we address this research gap with the aim to : (i) develop tree-ring width chronologies from Chinese cedar (*Cryptomeria fortunei*) in the region of Fujian Province, southeastern China; (ii) explore the relationships between tree growth and climate; (iii) develop a drought reconstruction and investigate the effects of El Niño-Southern Oscillation (ENSO), East Asian summer monsoon (EASM), and other forcing factors on the regional climate as revealed by the time-series.

Materials and methods

Site description and tree-ring data

Tree-ring width data were collected from two sites known as TDS (located at 25°56′N, 117°30′E, and at an altitude of 998 m a.s.l.) and TMC (located at 27°48′N, 117°42′E, and at an altitude of 950 m a.s.l.) in Fujian Province (Fig. 1). Existing climate records from the study area (located at Nanping, 26°39′N, 118°10′E, 127.8 m a.s.l.) reveal a 1955–2011 mean annual precipitation of 1632 mm and mean annual temperature of 19.5 °C. January (mean temperature of 9.4 °C) and July (28.8 °C) are the coldest and the warmest month, respectively (Fig. 2). The regional precipitation regime is, as previously stated, powerfully influenced by the East Asian summer monsoon rainfall belt (Song and Cai 2007), with 58.5% of the total annual precipitation falling during the rainy season from March to June (approximately). There is a dry season (July to February), influenced by the west pacific subtropical high and Asian winter monsoon (Chen *et al.* 2012a). The regional landscape consists of low hills with extensive forested areas of cedar and yew and patches of dense bamboo forest. There is no evidence of a significant fire history or of human disturbance. The largest tree sampled was over 1 m in diameter, however, it was later found to be hollow when cored. The ring-width chronology of Chinese cedar is comprised of data derived from 69 series sampled from 39 living trees.

A standard sampling protocol was followed. Samples were air-dried and mounted on wooden holders, before being sanded with progressively finer grit sand paper. Annual tree-ring widths were measured to a precision of 0.001 mm using a Velmex measuring system (Velmex, Bloomfield, USA). Measurement errors and cross-dating were further checked with the use of the computer program COFECHA (Holmes *et al.* 1986). A 60-year cubic smoothing spline was used to remove non-climatic trends in each series due to age, stand dynamics and increasing trunk diameter (Cook & Kairiukstis 1990). The variance in the mean chronology was stabilized during the chronology compilation process using the Briffa RBAR-weighted method, which uses the average correlations between series in combination with the sample size each year to make adjustments in the variance (Osborn *et al*. 1997). Finally, the detrended ring-width series were standardized and developed into the standard (STD) tree-ring width chronology using a bi-weight robust mean function with the program ARSTAN (Cook & Kairiukstis 1990).

We calculated signal to noise ratio (SNR), expressed population signal (EPS) and the variance in first eigenvector (VFE) for the common time interval 1950–2011. The SNR and VFE are the expressions of the strength of the common signals among the trees. The EPS quantifies how well a chronology based on a finite number of trees represents the hypothetical true chronology (Wigley *et al*. 1984). At the same time, the running EPS statistic, based on a 50-year window lagged by 25-years at each step, was used to evaluate the time-varying signal strength over the length of the chronology (see Figure 3?).

Meteorological data and statistical analysis

The tree-ring width climate relationships were initially investigated by exploring the simple correlations with several local climate indices. The climate data included the monthly records of mean temperature and total precipitation (1955–2011) from the Nanping meteorological station. The gridded monthly PDSI data was obtained from the Climatic Research Unit (CRU), East Anglia, UK (http://www.cru.uea.ac.uk; 0.5° × 0.5°; van der Schrier *et al*. 2011) for our study area for the time period 1955–2011 (averaged over 25.50–27.50° N, 116.50–117.50° E). All statistical procedures were evaluated at $P < 0.05$ level of significance using DENDROCLIM2002 (Biondi & Waikul 2004). In the correlation analysis, monthly climate data for the period from the previous January to the current September were investigated to account for potential lagged growth-climate correlations. To investigate the relationships between tree-ring indices and the climatic data in more detail, we also screened the tree-ring chronology during the correlation analysis with seasonal combinations of temperature, precipitation and PDSI from previous January to current September (Figure 4)Based on the results of climate response analysis, a linear regression equation between the predictors (tree-ring indices) and the predictand (PDSI) was computed for the calibration period using the program SPSS. The 'leave-one-out' method was employed to test the potential and reliability of the PDSI reconstruction (Cook & Kairiukstis 1990). Statistics used to test the reliability of the reconstruction models included the reduction of error (RE) and coefficient of efficiency (CE), the sign test, the first-order sign test and the Pearson's correlation coefficient.

To demonstrate that our tree-ring record is representative of regional-scale PDSI variability, we correlated the tree-ring series and instrumental PDSI series with the gridded PDSI dataset set after removing the linear trends of data during the period 1955–2011 , using the detrending options containing within the KNMI Climate Explorer (http://climexp.knmi.nl). In addition, we also used the KNMI Climate Explorer to generate correlation fields with synoptic scale climate parameters, including sea surface temperature (SST) (Rayner *et al*. 2003). We applied Multi-taper (MTM) spectral analysis (Mann & Lees 1996) to examine the characteristics the tree-ring record's variability in the frequency domain. Spectral analysis was performed over the full temporal range of our reconstruction, using 5×3π tapers and a red noise background. Furthermore, wavelet coherence analysis (Torrence & Compo 1998) was used to analyze the relationships between the PDSI reconstruction and an index of ENSO activity (http://jisao.washington.edu/data_sets/globalsstenso/#analysis). Finally, we also compared our tree-ring series with moisture-sensitive tree-ring width series from the surrounding regions to find the large-scale climate signals.

In order to establish whether our tree-ring width series exhibited links with the Asian summer monsoon, we analyzed correlations with the June–August EASM index (Li & Zeng 2002). Composites of July–February SST anomalies from the 1981–2010 mean were created using National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis data (Kalnay *et al*. 1996) for the highest and lowest deciles of reconstructed PDSI (n=10) in the period 1981–2011. Composites of July–February 500 hPa vector wind were also created for the highest and lowest deciles of reconstructed PDSI (n=10) in the period 1948–2011.

Results

Tree-ring chronology of Chinese cedar

Figure 3 presents the tree-ring chronology of Chinese cedar (1822–2011) developed from the merged tree-ring width data from Fujian. The most reliable period of the tree-ring chronology is from 1855 to 2011, based on an EPS value greater than 0.85. The mean sensitivity (MS: 0.14) and standard deviations (SD: 0.18) of the chronology are small, indicating rather moderate interannual variations in the ring-width series, characteristic for trees growing in humid and warm environments. In addition, the common interval analysis reveals that the EPS (agreement with population chronology: 0.85) and VFE (the variance in first eigenvector: 31.7%) are high, both indicative of strong common signals in the time-series. The first-order autocorrelation is 0.59. This implies that conditions that cause a ring to be narrow (or wide) in one year tend to carry over and impact the growth of the following year's ring.

Climate response analysis and PDSI reconstruction

Significant positive correlations (all at $P<0.05$) between the mean chronology and regional precipitation occur in the previous November, whereas significant positive correlations occur just for precipitation for the concurrent June (Fig. 4a). Significant positive correlations are found with temperature of the previous October and concurrent February and September (Fig. 4b). Continuous correlations between the tree-ring index and the PDSI index are found in both prior and concurrent growing seasons, with greater strength from previous July to concurrent February (see Figure…). Various multi-month seasons of climate data were also explored in the correlation analysis (Figure…). Finally, the average the PDSI Index from previous July through concurrent February was found to correlate most strongly with the tree-ring index of the current year (r=0.60, n=57, p<0.001).

Based on the above climate correlation analysis results, we concluded that mean July–February PDSI is the most appropriate seasonal predictand for developing a climate reconstruction from the tree-ring width time series. A linear regression model was employed to perform the reconstruction. During the common period (1955–2011), the reconstruction accounted for 36% of the actual PDSI variance. The results of a leave-one-out cross-validation are shown in Table 1. Both the RE and CE are strongly positive, indicating considerable validity in the reconstruction model. The results of the sign test and the first-order sign test, which describes how well the predicted value tracks the direction of actual data, exceed the 99% confidence level. These statistical tests demonstrate the veracity of the regression model and lend confidence to the resultant reconstruction (Fig. 5).

Drought signal.

Our July–February PDSI reconstruction reveals wet periods occuring in AD 1855–1858, 1881–1898, 1912–1926, 1934–1945, 1960–1963, 1971–1986 and 1998–2011, while episodes of below average PDSI value occurred in AD 1859–1880, 1899–1911, 1927–1933, 1946–1959, 1964–1970, 1987–1997 (Fig. 6A). The values of the first differences of tree-ring width series (±1SD) indicate dry and wet years. An extreme events analysis allowed the comparison of dry and wet years identified in the chronology with a historical archive for the region and the relevant climate data. The first differences of the tree-ring width series with the historical archive for Fujian (Song and Cai 2007) and climate data, reveals events of a severe magnitude in in 1856, 1857, 1858, 1864, 1869, 1876, 1881, 1891, 1894, 1895, 1904, 1908, 1924, 1927, 1933, 1944, 1956, 1962, 1965, 1966, 1978, 1988, 1998, 2004 and 2010 (Fig. 6B). These extreme eventsare revealed to have stronge effects on the local social and agricultural activities in Fujian (Table 2). In the most recent period, a a wetting trend can be observed (over the most recent 20 years)

Instrumental and reconstructed July–February PDSI correlate significantly with the regional gridded July–February PDSI and show very similar spatial correlation fields (Figure…). Significant positive correlations are found within Fujian, north Guangdong and Vietnam, with the highest correlations occurring in central Fujian. The results confirm that our tree-ring width series captures broad-scale regional drought variations (Fig. 7A, B). The instrumental and reconstructed July–February PDSI is significantly correlated with sea surface temperatures in the eastern equatorial and western Pacific Ocean (Fig. 7C). Correlations between reconstructed July–February PDSI and SSTs over the common period, 1900–2011, show similar patterns, albeit with somewhat lower signal strengths (Fig. 7D). The reconstructed PDSI correlates at r=-0.27 (p<0.01) with the ENSO index back to AD 1855. Significant high-frequency peaks are found at 9.1-year (99%), 6.4-year (99%), 2.6-year (95%) and 2.2-year (95%) (Figure 8A) and some significant common oscillations of 2-3 years, between the PDSI reconstruction and the ENSO index, were revealed by wavelet coherence analysis (Fig. 8B).

Several moisture-sensitive tree-ring records (D'Arrigo *et al*. 2006; Buckley *et a*l. 2007, 2010) from Southeast Asia provide a reference for comparisons with our record and validation of the climate dynamics revealed . Possibly due to site-specific factors, such as variations between tree species, regional climate and growing environments, correlations among the records describe a generally low level of agreement. However, significant positive correlations (r=0.22, p<0.01, n=154) are found between our PDSI reconstruction and a tree-ring width series from Vietnamese *Fokienia hodginsii* (Fig. 9, Buckley *et al*. 2010). We note also the presence ofcommon low value years in the periods (AD) 1864–1865, 1875–1877, 1889–1890 and 1956–1958 (Fig. 9). A significant positive correlation (r=0.35, n=63, p<0.01, Fig. 10) was also found between our PDSI reconstruction and the EASM index of Li & Zeng (2002). During the indicative dryer years, a positive SST anomaly, and weak wind vector at

500-hPa, are found in the tropical eastern Pacific indicating a warm ENSO phase, and vice versa (Fig. 11).

Discussion

The dendroclimatological potential of Chinese cedar

We found significant positive correlations between our tree-ring index and precipitation in the period from prior November through to concurrent June. The correlation analysis between the tree-ring width series and climate variables indicated that moisture availability was a major limiting factor for the growth of these trees. It is interesting to note that there is a marked dry season (July to February, Fig. 2), influenced by the west pacific subtropical high and Asian winter monsoon (Song and Cai 2007; Chen *et al*. 2012a). In central Fujian, dry and warm conditions before the onset of the summer monsoon season cause drought stress to the trees and are thus limiting to growth, which resembles other finding from Southeast Asian forests (D’Arrigo *et al*. 2006; Sano *et al*. 2009; Buckley *et al*. 2010). Tree growth thus benefits from the precipitation stored from the previous autumn and winter, which increases the soil moisture content during the critical early part of the growing season. Later on, after the onset of the rainy season, enough moisture is available to satisfy the water demand of the trees.

Linkages with the potential climate regimes

A wealth of low-latitude Asian tree-ring series now indicate significant palaeoclimatic potential in the trees of the region (D’Arrigo *et al*. 2006; Sano *et al*. 2009; Buckley *et al*. 2007, 2010). It is widely recognized that ENSO exerts an influence over the historical drought patterns in regions quite remote from the main centres of the tropical Pacific (D’Arrigo *et al*. 2006; Buckley *et al*. 2007, 2010). These regional teleconnections were also evident in our PDSI reconstruction (Fig. 7D). Of particular interest are correlations with the moisture-sensitive tree-ring width series from Vietnam, which is itself highly correlated with the Niño 3.4 index (Buckley *et al*. 2010). The significant positive correlation between our this series and our reconstruction is potentially the result of the strong common ENSO-derived climate signals in tree growth of the western Pacific region. The significant negative correlations, and the significant common oscillations of 2-3 years, between the PDSI reconstruction and the ENSO index also support the connections between the regional drought pattern revealed in our series and ENSO variability.

In comparison to the ENSO events occurring since AD 1840 (Gergis and Fowler 2009), our PDSI reconstruction reveals valuable information about extreme events related to ENSO variability over the last 166 years, with particular relevance to events in 1876–1879, 1926–1928, 1965–1966, 1997–1998 and 2004–2005 (Fig. 6). Detailed analysis reveals that drought events have occured in our study region during both the early and late phases of the El Niño events. The opposite is revealed in La Niña events with significant wet extremes occurring (Table 2). Significant drought events (1877, 1926, 1928 and 1998) follow some extreme events revealed within our study area (occurring in 1876, 1924, 1927 and 1998) as reported for northern China (Chen *et al*. 2012c, 2013). Investigations with regional instrumental records have revealed similar impacts of El Niño on the precipitation patterns in China over the recent past (Lu 2005). During the mature phase of El Niño events an intensified Western Pacific High allows more precipitation to reach the middle and lower reaches of the Yangtze and Huaihe Rivers, included in our study region, and less precipitation to reach northern China (Zhang *et al*. 1999; Lu 2005). This means that the ENSO-related climate events not only affect northern China, but also impact the precipitation regimes of southern China.

Composite maps of the wettest and driest years in the recent past also reveal patterns that are similar to those indicative of ENSO events, particularly with regards to ocean and atmospheric conditions in eastern Pacific (Fig. 11), revealing ENSO events as a causal mechanism for wet and dry conditions in southern China. Of particular interest are the shifts from the dry phases to the wet phases following primarily El Niño events (Fig. 6A). After warm phases of ENSO, the strength of East Asian summer monsoon (EASM) tends to be enhanced via the Walker circulation, and precipitation in southeast China increases (Zou and Ni 1997; Gong and Wang 1998; Sano *et al*. 2009). As discussed above, drought variations in southeastern China are probably related to ENSO and various parts of the remote ocean circulation.

A weakening Asian summer monsoon, observed from the 1970s to the early 1990s, can be attributed to the decreased thermal contrast between the Asian continent and the Indian and western

Pacific Oceans (Wang et al. 2001; Li & Zeng 2002). This weakening trend ,and the recent recovery of the East Asian summer monsoon (Liu *et al*. 2012), is precisely captured by our tree-ring series, and a significant correlation (r=0.35, n=63, p<0.01) also exists between our tree-ring width series and the monsoon index. The EASM has been shown to be strongly related to warm-season precipitation variations in China (Zhao et al. 2007; Zhou et al. 2009). On the inter-annual and inter-decadal scales, corresponding to a higher (weaker) EASM, the lower-troposphere low-pressure system over eastern Asia strengthens (weakens), and the western Pacific subtropical high strengthens (weakens) with its location shifting northwards (southwards), resulting in more (less) rainfall in the Yellow River valley and southeastern China, included in our study area, and less (more) rainfall in the Yangtze River valley (Zhou et al. 2009). The 500-hPa vector wind composite anomalies of the wet and dry years during the period 1948–2011 support the connection with the EASM intensity (Fig. 11C, D).

Conclusions

A ring-width chronology constructed from sampled Chinese Cedar (*Cryptomeria fortunei*) was developed from central Fujian, southeastern China. The record is most reliable from 1855 to 2011, based on various chronology statistics indicative of signal strength. This record was utalised in the construction of a regional PDSI record covering the period from previous July to concurrent February. Significant correlations were revealed with moisture conditions of the pre-growing season, indicative of the importance of moisture stress and its tree-growth limiting capacity in the region, and suggesting that the tree-ring chronolo can provide a valuable tool for exploring regional drought history. The reconstructed PDSI explains 36% of the actual variance for the common period of 1955–2011, a low % explained variance, but characteristic of trees growing in humid and warm environments. The reconstruction stands up to various tests of fit and comparisons to other regional reconstructions. Wet periods are reconstructed in AD 1855–1858, 1881–1898, 1912–1926, 1934–1945, 1960–1963, 1971–1986 and 1998–2011, and dry periods from 1859–1880, 1899–1911, 1927–1933, 1946–1959, 1964–1970 and 1987–1997. There is reasonable agreement with drought variations previously estimated from a tree-ring record constructed for Vietnam. Spectral peaks of 2.8–6.4 years indicate the possible influence of ENSO activity. Additionally, the negative correlations of the PDSI reconstruction with eastern equatorial and southeastern Pacific Ocean SSTs, and the extreme event analysis, also suggest the influence of ENSO on regional droughts in this area. Significant positive correlations between the drought and the EASM index further suggested the influences of the EASM on regional droughts in our study area.

The Chinese cedar (*Cryptomeria fortunei*) often forms large trees of up to 30 m in height, and individuals usually lives for up to 150 years. In appropriate circumstances (e.g., in the environments of the Tianmu Mountains), Chinese cedar can reach 2 meters in diameter at breast height. The species is common in low lying hills and at lower altitudes in such areas. Its distribution extends from the southeastern China to southwestern China. The tree-rings within Chinese cedar are clearly visible and the species was noted by Qian *et al*. (2002) as having good potential for dendroclimatic study as a widespread species with reliable growth. However, ,to date the species has only offered tree-ring isotope chronologies, with the oldest chronology extending to AD 1662 (Zhao *et al*. 2006). This study is, to our knowledge, the first tree-ring width-based PDSI reconstruction for southeastern China, which also identifies dry and wet periods for central Fujian over the past 157 years. The species has clear dendroclimatic potential and offers an opportunity for exploring regional climate dynamics over the recent past, as such future research efforts should be made to sample additional Chinese cedar sites and indeed to explore more species with dendroclimatic potential, and potentially greater ages, in southern China.

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Figure captions

Fig. 1. Map showing the tree-ring sampling sites and the meteorological station.

Fig. 2. Climate diagram for the meteorological station of Nanping in Fujian.

Fig. 3. Plot of the standard ring width chronology from Fujian, its running Expressed Population Signal (EPS), sample depth and mean inter-series correlation (Rbar).

Fig. 4. Response plots for the STD chronology with monthly total rainfall, mean monthly temperature and monthly PDSI for the period AD 1955–2011. The coefficients were calculated from the previous year January to the concurrent September. Horizontal dashed lines denote 95% significance levels.

Fig. 5. (A) Comparison of actual and reconstructed July–February PDSI from AD 1955 to 2011. (B) Comparison between the first differences (year-to-year changes) of instrumental and reconstructed July–February PDSI for their common period AD 1955–2011.

Fig. 6. (A) July–February PDSI reconstruction for central Fujian since AD 1855. The bold line indicates the smoothed data, with a 10-year low-pass filter, to emphasize long-term fluctuations. (B) The first differences (year-to-year changes) of the PDSI reconstruction. The central horizontal line shows the mean of the estimated values; inner horizontal lines (dotted) indicate one standard deviation; outer horizontal lines indicate one standard deviation. Diamonds indicate low values, each following a drought event. Round symbols indicate high values, each following a flood event.

Fig. 7. Spatial correlation fields of instrumental (A) and reconstructed (B) July–February PDSI with regional gridded July–February PDSI for the period AD 1955–2011. The numbers 1 and 2 denote our study area and a tree-ring study site in Vietnam (Buckley *et al*. 2010). (B) Correlation patterns of instrumental (C) and reconstructed (D) July–February PDSI with the gridded sea surface temperature (SST) dataset of HadISST1 over their overlapping periods from AD 1955 to 2011 and from AD 1900 to 2011.

Fig. 8. (A) Results of MTM spectral analysis of the PDSI reconstruction. The dashed and dotted lines indicate the 95% and 99% significance level. (B) The wavelet coherence between the PDSI reconstruction and ENSO index (Braganza et al., 2009). Arrows indicate the phase of the coherence, where right is in phase and left is antiphase; note that significant regions all show an in-phase relationship, which supports the idea that there may be a simple cause and effect relationship between the two phenomena.

Fig. 9 Comparison of our PDSI reconstruction (southern China) and tree-ring width series of *Fokienia hodginsii* from Vietnam (Buckley *et al*. 2010).

Fig. 10 Comparison of the July–February PDSI reconstruction with the June-August EASM index (Li and Zeng 2002).

Fig. 11 Composite maps of SST for the ten wettest (A) and ten driest (B) years for southern China July–February PDSI, 1981–2011. Composite anomaly maps of 500-hPa vector wind (from July of the prior year to February of the concurrent year) for the 10 wettest (C) and 10 driest (D) years for PDSI reconstruction during the period 1948–2008.