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# Tree-ring based winter temperature reconstruction for the lower reaches of the Yangtze River in southeast China

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ABSTRACT: Two robust tree-ring width chronologies were developed for the western Tianmu Mountains and the Xianyu Mountains of southeast China. Both chronologies were significantly correlated with each other and were arithmetically averaged to build a regional chronology (RC). The RC had significant and positive correlations with winter temperature before the growing season. Based on this relationship, the average temperatures of the previous December to the current March were reconstructed using the RC chronology for the period 1852 to 2006. The temperature reconstruction was significantly correlated with the winter half-year temperature in the eastern Qinling Mountains of central China, 720 km west of the study region, suggesting a large-scale coherence of winter temperature variability. The reconstruction corresponds well with an East Asian winter monsoon (EAWM) index in extreme years and reflects the strong influences of the EAWM in this study region. Thus, there is great potential to use tree-ring chronologies to reconstruct past climate change in southeast China, where little dendroclimatic work has been done until now.

KEY WORDS: Taiwan pine · Winter temperature · Southeast China · East Asian winter monsoon

## 1. INTRODUCTION

Southeast China is characterized by a subtropical humid climate and alternations of the East Asian summer and winter monsoon circulations that dominate the wet-dry and cold-warm variations. In January 2008, a freezing disaster occurred in southern China and the Yangtze River catchments that persisted for an exceptionally long time, unprecedented in the meteorological history of China (Ding et al. 2008). This disaster caused great losses both economically and in terms of disrupting people's lives. It is necessary to put this disaster in a long-term context to evaluate its strength and the frequency of similar disasters. However, meteorological records for this region are sparse and cannot be used to accomplish this task. Therefore, proxy records must be employed to extend the meteorological records back in time for understanding climate changes and the behavior of the monsoon circulation.

Tree rings have been widely used to reconstruct past climate on regional, hemispheric, or even global scales over a few hundred to thousands of years (Esper et al. 2002, Mann & Jones 2003, Cook et al. 2004, Mann et al. 2008). In China, dendroclimatic work has mainly focused on semi-arid regions in northern China and the Qinghai-Tibetan Plateau (Zhang et al. 2003, Shao et al. 2005, Liu et al. 2006, Gou et al. 2007, Li et al. 2008, Liang et al. 2008, Shi et al. 2008, Fang et al. 2009), generating an abundance of tree-ring data for that region. Unfortunately, little tree-ring work has been carried out in heavily populated southeast China, largely due to the scarcity of old-growth forests and the complexity of the relationship between tree growth and climate in this humid region. For instance, previous research found a complex

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relationship between climate and tree-ring $\delta^{13}C$ series of *Cryptomeria fortunei* Hooibrenkex Otto et Dietr (Qian et al. 2002), which makes it difficult to conduct reliable climate reconstructions from this data set. After this preliminary investigation, no further dendroclimatic research has been performed in the region.

Taiwan pine *Pinus taiwanensis* Hayata is a dominant tree species in southeast China, generally growing ≥800 m above sea level (a.s.l.). Our preliminary investigation revealed many trees of this species older than 100 yr. Thus, this species provides an opportunity to conduct dendrochronological research in this typical monsoon region.

The objectives of this study were: (1) construction of 2 robust tree-ring width chronologies, (2) exploration of the relationships between tree growth and climate, (3) high frequency reconstruction of past climate changes, and (4) cross-validation of the reconstruction with other climatic indices.

## 2. DATA AND METHODS

We sampled Taiwan pine trees from 3 sites in the lower reaches of the Yangtze River in southeast China (Fig. 1). Two sites (QLF03, 30° 06′ N, 118° 54′ E, 1000 to 1050 m a.s.l.; QLF04, 30° 07′ N, 118° 54′ E, 1000 to 1050 m a.s.l.) are located in the western Tianmu Mountains, Zhejiang province, and the third (XYS02, 30° 00′ N, 117° 17′ E, 1000 to 1050 m a.s.l.) in the Xianyu Mountains, Anhui province. The highest point in the Tianmu Mountains is 1787 m a.s.l. The Xianyu Mountains are in the western part of the Huangshan Mountains which is one of the most famous tourist sites in China, with the highest peak at 1376 m a.s.l. The sampled Taiwan pine sites are mixed broadleaf-conifer forests in the western Tianmu Mountains and Taiwan pine forest with a dense understory layer of *Indocalamus sinicus* in the Xianyu Mountains.

Following standard dendrochronological techniques (Cook & Kairiukstis 1990), 2 cores per tree were extracted using increment borers, and at least 22 trees were cored at each site. All samples were processed using standard procedures (Stokes & Smiley 1968), and were then visually cross-dated. Each tree-ring width was measured to 0.001 mm precision. Dating and measurement errors were further checked with the computer program COFECHA (Holmes 1983).

The linear correlation between the raw measurements of sites QLF03 and QLF04 was 0.74 ($p < 0.001$), and the first principal component explained 87.2% of their total variance. Considering the proximity (2 km apart) and similar elevations of the 2 sites and their high environmental homogeneity, we pooled all measurements to develop 1 composite ring-width chronology, QLF0304. The chronologies were developed using the program ARSTAN (Cook 1985) by removing biological growth trends while preserving variations that are likely related to climate. All measurement series were detrended by fitted negative exponential curves or linear regression curves of any slope. A cubic spline with a 50% frequency-response cutoff equal to 67% of the series length was also used in a few cases (2 of 86 cores from site QLF0304 and 7 of 53 cores from site XYS02) when anomalous growth trends occurred. Detrending applied this way preserves low-frequency variations due to climate that are resolvable from trends in the tree-ring series (Cook 1985), but inevitably loses any lower-frequency trends due to climate. Autoregressive modeling was used to remove much of the autoregressive properties in the detrended series. The detrended and prewhitened series were then robustly averaged to produce a residual chronology for each site. The residual chronology contains the least amount of disturbance-related growth, has one of the cleanest expressions of climate, and lacks autocorrelation that can make statistical hypothesis testing difficult (Cook 1985). As the sample size generally declines in the early portion of a tree-ring chronology, we used the subsample signal strength (SSS; Wigley et al. 1984) with a threshold of 0.85 to evaluate the most reliable time span of each chronology. The QLF0304 (XYS02) residual chronology spanned the period 1837 to 2006 (1872 to 2006), with the most reliable time span from 1852 to 2006 (1896 to 2006). During the common reliable period of both chronologies (1896 to 2006), the correlation coefficient was

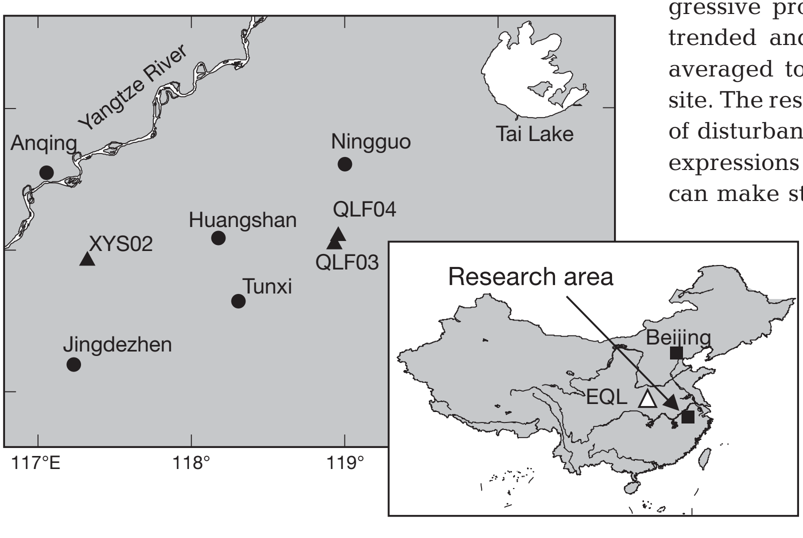

Fig. 1. Locations of the 3 tree-ring sampling sites (solid triangles) and 5 meteorological stations (solid circles) in this study. Inset: a tree site (open triangle, EQL) of Shi et al. (2009) from the eastern Qinling Mountains

0.44 ($p < 0.001$), and the first principal component explained 72.1% of their total variance. Thus, a regional chronology (RC) was developed by averaging the 2 residual chronologies together over their most reliable common time period since 1896, and the RC chronology was further extended back to 1852 using the QLF0304 chronology. The period from 1852 to 1895 was normalized to have the same mean and SD as the period from 1896 to 2006 in the RC chronology.

The climate data used in this study include local monthly temperature and precipitation records. The instrumental data were obtained from 5 meteorological stations (Anqing, 30° 32′ N, 117° 03′ E, 19.8 m a.s.l.; Jingdezhen, 29° 18′ N, 117°12′E, 61.5 m a.s.l.; Huangshan, 30° 08′ N, 118° 09′ E, 1840 m a.s.l.; Tunxi, 29° 43′ N, 118° 17′ E, 143 m a.s.l.; Ningguo, 30° 37′ N, 118° 59′ E, 89.4 m a.s.l.) around the sampling sites (Fig. 1). They have a common interval from 1957 to 2004. We averaged the monthly mean temperature and monthly total precipitation data from these 5 meteorological stations to represent regional climate (Fig. 2). The following analysis is based on the averaged climate values.

The relations between tree growth and climate were explored by correlation analyses. The strongest influencing factor (i.e. winter temperature in this study) on tree growth was reconstructed using a linear regression model. The reconstructed winter temperature was compared to a winter half-year temperature reconstruction by Shi et al. (2009) and an East Asian winter monsoon (EAWM) index proposed by Zhu (2008). The EAWM is a member of the most active climate systems in the Northern Hemisphere, and its abnormal activity can induce a series of severe weathers such as cold waves and snow in East and Southeast Asia (Zhu 2008). Due to its complexity, several types of winter monsoon indices have been defined. However, the normalized EAWM index defined by Zhu (2008) has a better ability to describe winter temperatures in China. Consequently, it was used for comparison with the reconstructed winter temperature in this study.

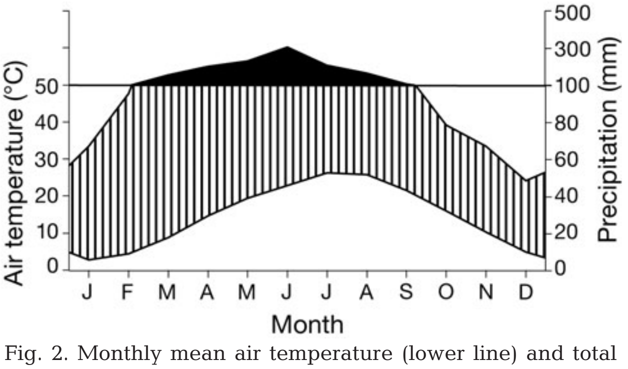

Fig. 2. Monthly mean air temperature (lower line) and total precipitation (upper line) records in the study region averaged over 1957 to 2004. Mean annual temperature is 14.8°C and mean annual precipitation is 1725.8 mm. Black shading indicates a shift in scale. Above 100 mm on the right vertical scale, one increment equals 200 mm of precipitation

## 3. RESULTS AND DISCUSSION

Climate-growth responses were analyzed for the common period when both meteorological records and tree-ring data were available (i.e. 1958 to 2004). The analyses were undertaken for the period of a biological year (i.e. previous October to current September). As shown in Fig. 3, the 2 chronologies and the RC had positive correlations with the monthly temperature

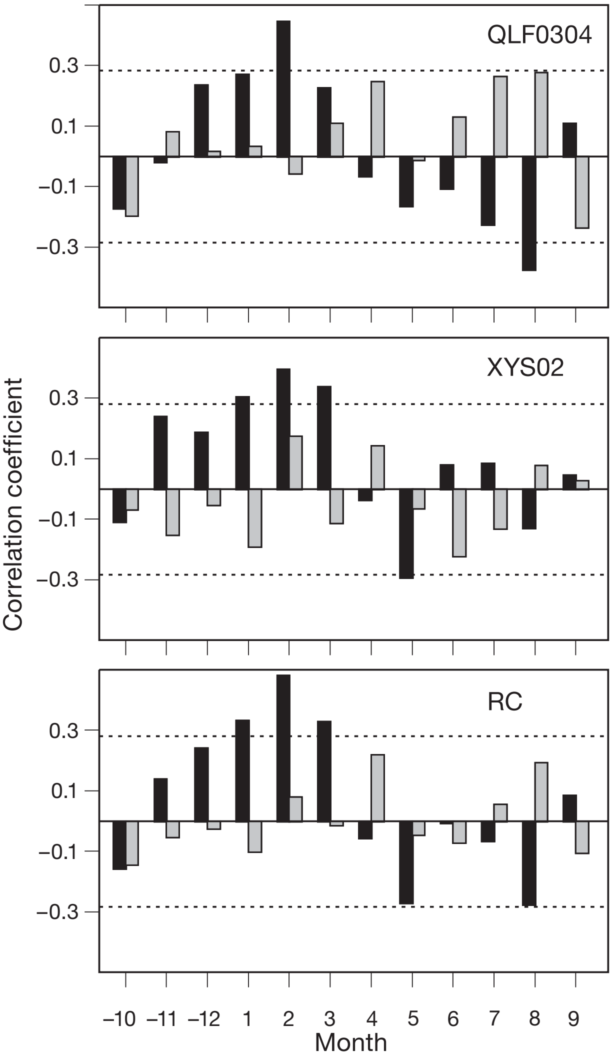

Fig. 3. Correlations of each tree-ring width chronology (sites QLF0304 and XYS02) and their regional average chronology (RC: regional chronology) with monthly mean air temperature (black bars) and monthly total precipitation (grey bars) from the previous October to the current September over the common period 1958-2004. The dotted lines indicate the 0.05 significance levels

from the previous December to the current March. Significant ($p < 0.05$) correlations between temperature and the RC were found in January ($r = 0.33$), February ($r = 0.48$), and March ($r = 0.33$). Meanwhile, there was no significant correlation between precipitation and tree-ring data. The highest correlation ($r = 0.56$) between the RC and seasonalized temperature was found from the previous December to the current March. Therefore, December to March was used as the reconstruction season.

We used a linear regression model (Cook & Kairiukstis 1990) to perform the reconstruction, and the statistical fidelity of this model was examined by split sample calibration-verification tests (Meko & Graybill 1995). As shown in Table 1, the values of the 2 most rigorous tests for model validation, the reduction of error (RE) and the coefficient of efficiency (CE), were mostly positive (except for CE in the verification period of 1958 to 1980). At any rate, the overall test results sufficiently demonstrate the validity of our regression model. The reconstruction accounts for 31.7% of the actual temperature variance during 1958 to 2004, which is not very strong but nonetheless statistically significant. An anomalous reduction in forest growth indices and temperature sensitivity has been detected in tree-ring width and density records from many circumpolar northern latitude sites since around the mid-20th century (i.e. Jacoby & D'Arrigo 1995, Briffa et al. 1998, Vaganov et al. 1999, Barber et al. 2000, Wilson & Luckman 2003, D'Arrigo et al. 2004, Driscoll et al. 2005, Wilmking et al. 2005, Büntgen et al. 2006). This phenomenon, also known as the 'divergence problem', is expressed as the offset between warmer instrumental temperatures and their underestimation in reconstruction models based on tree rings (D'Arrigo et al. 2008). However, the 'divergence problem' was not encountered in this study. Tree-ring reconstruction captures winter temperature relatively well at interannual and decadal time scales, and the temperature trend from 1984 to the present is traced quite well overall (Fig. 4). In our opinion, the underestimation of temperatures by tree rings since the late 1990s is not an expression of the 'divergence problem'. Rather, it is likely to be a consequence of the detrending and autoregressive modeling methods applied to the tree-ring data prior to reconstruction. Based on this model, the winter temperature history for the lower catchments of the Yangtze River was reconstructed with large sample depth for the period of 1852 to 2006 (Fig. 5a,b).

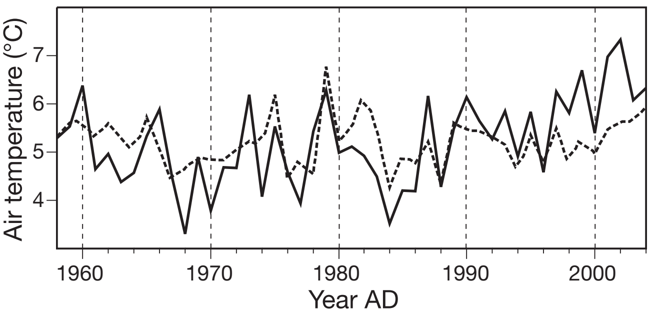

Fig. 4. Actual (solid line) and estimated (dashed line) average air temperature of the previous December to the current March for 1958 to 2004

Table 1. Statistics of calibration and verification test results for the common period of 1958 to 2004. RE: reduction of error, CE: coefficient of efficiency

| | Calibration (1958–1980) | Verification (1981–2004) | Calibration (1981–2004) | Verification (1958–1980) | Full calibration (1958–2004) |
|---|---|---|---|---|---|
| r | 0.598 | 0.572 | 0.572 | 0.598 | 0.563 |
| $r^2$ | – | – | – | – | 0.317 |
| RE | – | 0.264 | – | 0.273 | – |
| CE | – | 0.031 | – | −0.054 | – |

Our sampling sites are located at the northern 'species treeline' for Taiwan pine (Editorial Board of Forest in China 2003). Similarly, Pederson et al. (2004) found that winter temperature plays an important role in the growth of northern range margin tree species in the Hudson River Valley, New York, USA. Increased winter temperatures in areas of inconsistent snow pack may mean less winter damage to roots and, thus, less of a growth limitation. The influences of winter temperature on tree growth were also discovered for *Pinus armandii* Franch in the eastern Qinling Mountains (Shi et al. 2009), *P. tabulaeformis* in the southern Qinling Mountains (Liu et al. 2009), *Juniperus przewalskii* in the Xiqing Mountains of the northeastern Tibetan Plateau (Gou et al. 2007), *Sabina przewalskii* and *Picea crassifolia* on the northeast Tibetan Plateau (Liang et al. 2006), and *Abies chensiensis* in the Jiuzhaigou region of southwest China (Song et al. 2007). Therefore, winter temperatures have a strong influence on tree growth for many tree species on a large scale from subtropical to temperate climates. The effect of winter temperatures on the terrestrial carbon cycle should be considered, especially in the context of global warming.

It is interesting to note that relatively warm periods occurred around 1860, 1880, 1900, 1920, 1940, 1960, 1980, and 2000, showing a 20 yr quasi-period in the reconstructed winter temperature series (Fig. 5). This quasi-period is also illustrated using spectral analysis as follows.

Shi et al. (2009) reconstructed winter half-year (previous December to current April) temperature in the eastern

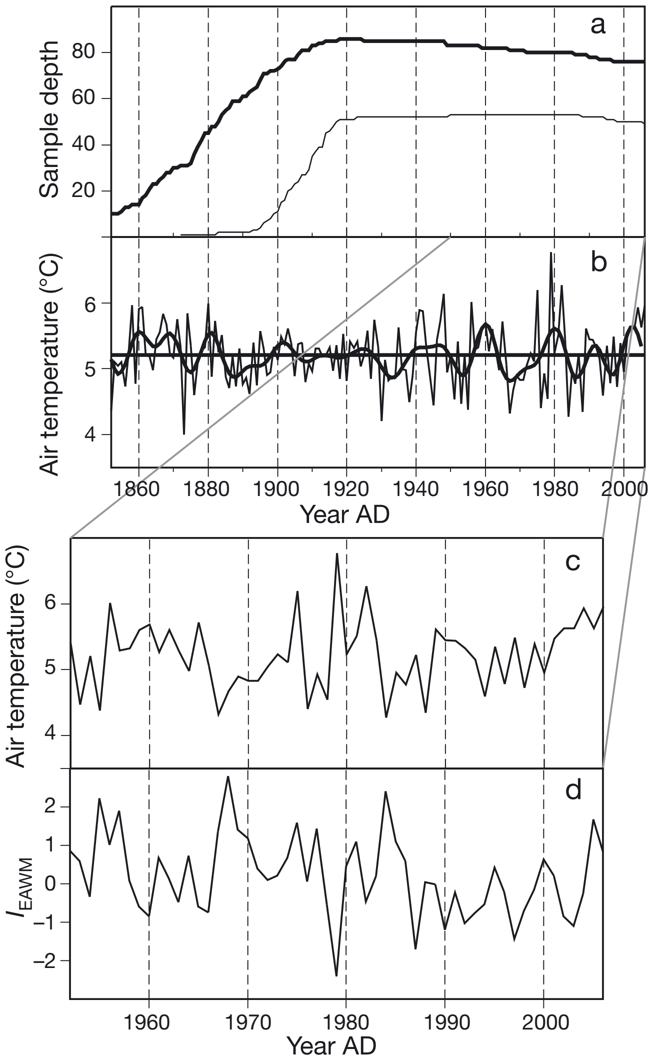

Fig. 5. No. of cores for Site QLF0304 (thick line) and Site XYS02 (thin line); (b) reconstruction of air temperature from the previous December to the current March (thin line), its 10 yr lower-pass filter (bold line), and its average value (horizontal line) for 1852–2006; (c) December–March air temperature reconstruction for 1952–2006; and (d) normalized index of the East Asian winter monsoon ($I_{EAWM}$) for 1952–2006 (Zhu 2008)

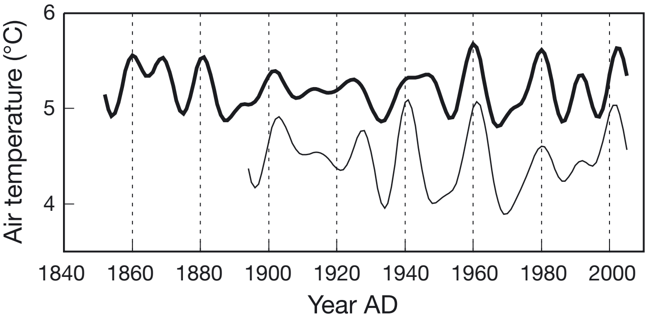

Fig. 6. Reconstruction of average air temperature from the previous December to the current March in this study (bold line) and that from the previous December to the current April in the eastern Qinling Mountains (thin line; Shi et al. 2009). Both curves are values of 10 yr low-pass filter

Qinling Mountains of central China, about 720 km west of our study region. The correlation between the reconstruction by Shi et al. (2009) and the one in this study is 0.21 (significant at the 0.05 level), and both reconstructions show similar decadal-scale temperature variation patterns (Fig. 6), which indicates that the current reconstruction contains a large-scale winter temperature signal.

Zhu (2008) used 500 hPa zonal winds to define an index of the EAWM (Fig. 5d), which has a strong relationship with winter temperature in eastern China. The EAWM index is strong (weak) when it is greater (less) than +1 (–1). A greater index value indicates a lower winter temperature. The correlation coefficient between the reconstructed winter temperature and the EAWM index is −0.37 (significant at the 0.05 level). Of the 9 strong EAWM years common to our reconstruction, 6 correspond to years with below-average temperature (i.e. 1955, 1967, 1968, 1969, 1977, and 1984). All of the weak EAWM years correspond to above-average temperatures (i.e. 1979, 1987, 1990, 1992, 1997, and 2003; Fig. 5c,d). These results indicate that winter temperature in the study region is strongly influenced by the EAWM.

Multi-taper method (MTM) spectral analysis (Mann & Lees 1996) was employed to examine the frequency domain characteristics of temperature variability in our reconstruction. This analysis revealed some significant low- and high-frequency cycles (Fig. 7). Low-frequency peaks were found at 17.7 to 22.8 yr. Other significant peaks were found at 3.5, 3.3, and 2.1 yr. Peaks at 17.7 to 22.8 yr may correspond to similar periods found in a reconstructed Pacific decadal oscillation

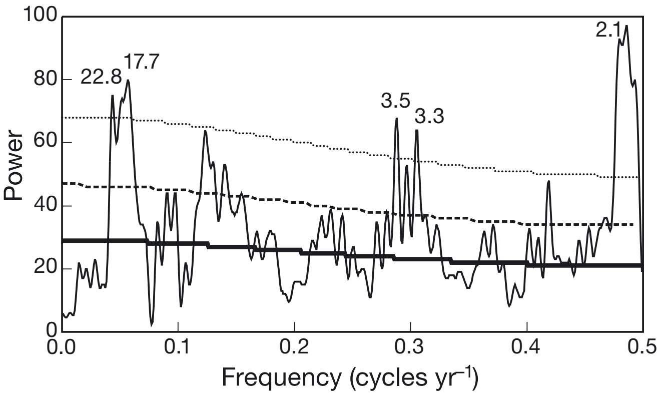

Fig. 7. Multi-taper method spectral density of the reconstructed air temperature. Bold line indicates the null hypothesis; dashed and dotted lines indicate the 90 and 95% significance levels, respectively. Numbers above peaks indicate cycle intervals (yr)

series from the Transverse Mountains of southern California (USA) to Sierra San Pedro Martir in northern Baja California (Mexico; Biondi et al. 2001). Peaks at ~2 to 3 yr cycles fall within the range of variability of the El Niño–Southern Oscillation (Allan et al. 1996), and the peaks at ~2 yr are also within the band of tropical biennial oscillation (TBO) variability (Meehl 1987). Collectively, these periods suggest that the reconstructed temperature variation has a teleconnection with large-scale atmospheric-oceanic variability.

## 4. CONCLUSIONS

Winter temperature (previous December to current March) was reconstructed using a robust regional Taiwan pine tree-ring width chronology developed from the lower reaches of the Yangtze River, southeast China. The reconstruction was significantly correlated ($p < 0.05$) with another independent winter temperature reconstruction from the eastern Qinling Mountains, 720 km away from the study region. It also corresponded well with an EAWM index in extreme years. Both comparisons support the validity of winter temperature reconstruction in this study. Besides this study region, winter temperature has a significant influence on tree growth in the Qinling Mountains, Tibetan Plateau, and the Hudson River Valley (USA), thus spanning subtropical to temperate climate regimes. These results together suggest that increasing winter temperatures must be considered in modeling tree growth in global carbon cycle models. Our research indicates great potential to further exploit dendroclimatic research in southeast China, where little successful research has been conducted to date.

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