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ORIGINAL ARTICLE

# Inter- and intra-annual tree-ring cellulose oxygen isotope variability in response to precipitation in Southeast China

**Chenxi Xu[1,2] · Huaizhou Zheng[3,4] · Takeshi Nakatsuka[1] · Masaki Sano[1] · Zhen Li[1] · Junyi Ge[5,6]**

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**Abstract**

***Key message*** **Compared with annual tree-ring cellulose $\delta^{18}O$, intra-annual cellulose $\delta^{18}O$ has potential to reconstruct precipitation with higher resolution and stronger signal intensity.**

*Abstract* Annual tree-ring cellulose oxygen isotope values ($\delta^{18}O$) of *Fokienia hodginsii* provide a promising proxy of monsoon-season precipitation in Southeast China. Measuring intra-annual cellulose $\delta^{18}O$ values may reveal the seasonal variability of precipitation and the associated climate influences. Here, we examine intra-annual variation of cellulose $\delta^{18}O$ values in *Fokienia hodginsii* and *Cryptomeria fortune* from Fujian Province, Southeast China. Both species exhibited considerable intra-annual variations in cellulose $\delta^{18}O$ (range ~6 ‰) with a consistent pattern of enriched values near the annual ring boundary and depleted values in the central portion of the ring. Seasonal patterns in the tree-ring $\delta^{18}O$ values generally followed changes in precipitation $\delta^{18}O$ values. Compared with annual tree-ring cellulose $\delta^{18}O$, intra-annual cellulose $\delta^{18}O$ has potential to reconstruct precipitation with higher resolution and stronger signal intensity. July tree-ring cellulose $\delta^{18}O$ is significantly correlated ($r = -0.58$, $p < 0.05$) with July precipitation, and June–August tree-ring cellulose $\delta^{18}O$ and annual tree-ring cellulose $\delta^{18}O$, respectively, explain 52 and 41 % of the actual variance of April–August precipitation. In addition, May–October cellulose $\delta^{18}O$ values during El Niño years are higher than in La Niña years, and April to October rainfall is lower in El Niño years than in La Niña years. Combining the significant correlations between inter-annual cellulose $\delta^{18}O$ values and sea surface temperatures in the central tropical Pacific, our results support the hypothesis that El Niño–Southern Oscillation affects tree-ring cellulose $\delta^{18}O$ in Southeast China by modulating seasonal precipitation.

**Keywords** Tree-ring cellulose oxygen isotope · *Fokienia hodginsii* · *Cryptomeria fortune* · Precipitation · El Niño–Southern Oscillation

## Introduction

The Asian Summer Monsoon (ASM) greatly influences densely populated regions of monsoonal Asia (Ding and Chan 2005; Lau and Yang 1997) and has influenced social

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✉ Chenxi Xu
xuchenxi@gmail.com

1 Research Institute for Humanity and Nature (RIHN), 457-4 Motoyama, Kamigamo, Kita-ku, Kyoto 603-8047, Japan

2 Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

3 State Key Laboratory of Subtropical Mountain Ecology (Funded by Ministry of Science and Technology and Fujian Province), Fujian Normal University, Fuzhou 350108, China

4 College of Geographical Sciences, Fujian Normal University, Fuzhou 350108, China

5 Key Laboratory of Vertebrate Evolution and Human Origins of the Chinese Academy of Sciences, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing 100044, China

6 CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China

change in recent centuries (Zhang et al. 2008; Buckley et al. 2010). The Coupled Model Intercomparison Project Phase 5 (CMIP5) generally reproduces the observed spatial patterns of monsoon precipitation on seasonal time scales; however, it underestimates the extent and intensity of precipitation, especially over monsoonal Asia (Stocker et al. 2013). Furthermore, observed records are often too short to substantiate model variability on multi-annual to multi-decadal time scales. Therefore, high-resolution and long-term precipitation-related proxy records are needed.

Although long-term lake sediment (Chu et al. 2011) and stalagmite (Wang et al. 2008) records have been used to reconstruct the history of ASM, these relatively low-resolution records are difficult to compare directly with climate parameters at annual resolution. Trees are widespread and have the potential for high-resolution climate reconstruction due to their climate sensitivity and accurate dating (Fritts 1976). Recent studies show that tree-ring cellulose oxygen isotope ($\delta^{18}O$) values, which usually exhibit negative correlations with summer precipitation, can be calibrated with observed precipitation data in Southeast China (Xu et al. 2013a) and Southwest China (Grießinger et al. 2011), Laos (Xu et al. 2013b), Vietnam (Sano et al. 2012), Bhutan (Sano et al. 2013), and Thailand (Xu et al. 2015).

Intra-annual tree-ring cellulose $\delta^{18}O$ variations, which are associated with the growing season climate (Barbour et al. 2002; Verheyden et al. 2004; Evans and Schrag 2004), can provide climate information with exceptional resolution (i.e., monthly, often weekly, and extreme events) (Berkelhammer et al. 2009). For example, $\delta^{18}O$ values of teak associated with the middle and end of the growing season in southern India are related to the $\delta^{18}O$ values of Southwest and Northeast Indian monsoonal precipitation, respectively (Managave et al. 2010a). Elsewhere, two hurricanes in 2004 were identified from intra-annual changes in pine $\delta^{18}O$ values in Tennessee, United States (Li et al. 2011). The 1997–1998 El Niño Southern Oscillation (ENSO) warm-phase event was recorded as an 8 ‰ anomaly by intra-annual cellulose $\delta^{18}O$ of *Prosopis* sp. in coastal Peru (Evans and Schrag 2004). In addition, intra-annual cellulose $\delta^{18}O$ variations for trees with or without ring boundaries have distinct annual cycles, and the formation of annual cycles of cellulose $\delta^{18}O$ values is influenced by the seasonal dry climate in monsoon Asia (Poussart et al. 2004; Zhu et al. 2012; Xu et al. 2014). Moreover, the study of intra-annual tree-ring $\delta^{18}O$ values can improve our understanding of climate variability observed in tree-ring $\delta^{18}O$ values on inter-annual time scales (Schollaen et al. 2013).

Our previous work indicated that tree-ring $\delta^{18}O$ values of *Fokienia hodginsii* in Southeast China can be used for precipitation reconstruction, which show significant relationships with ENSO (Xu et al. 2013a). In this study, we analyzed intra-annual variations in tree-ring $\delta^{18}O$ values for *Fokienia hodginsii* and *Cryptomeria fortune* in Fujian Province, Southeast China, to investigate (1) seasonal patterns of tree-ring cellulose $\delta^{18}O$ variations, (2) how the growing season climate influences the intra-annual isotopic variability of whole-ring samples, and (3) how ENSO events affect intra-annual tree-ring $\delta^{18}O$ variability.

## Materials and methods

### Sampling site and climate data

We sampled five *Fokienia hodginsii* and ten *Cryptomeria fortune* (the dominant tree species) from forests near Shoushan Town, Fuzhou City, Fujian Province, Southeast China (26°15′N, 119°16′E; 660 m a.s.l.; Fig. 1), using 12-mm diameter increment borers at breast height. One core was collected from most of trees. The two species *Fokienia hodginsii* and *Cryptomeria fortune* were chosen to analyze the intra-annual variations in cellulose $\delta^{18}O$ values because of their shallow root systems (Su 1991; Li et al. 2013), which would result in higher correspondence of intra-annual tree-ring $\delta^{18}O$ to seasonal climate change than trees with deep root system. Approximately 60 % (80 %) of fine lateral roots of *Fokienia hodginsii (Cryptomeria fortune)* are in the upper 0–20 cm (0–40 cm) of the soil profile (Su 1991; Li et al. 2013). Tree-ring cellulose $\delta^{18}O$ shows higher climate sensitivity than ring widths (Xu et al. 2011), and the cost of intra-annual cellulose $\delta^{18}O$ analysis from multiple samples is high. Therefore, several previous intra-annual cellulose $\delta^{18}O$ studies had employed one rather than four trees to explore the relationships between cellulose $\delta^{18}O$ and climate. For example, Evans and Schrag (2004) used one *Hyeronima alchorneoides* from the eastern Costa Rican to compare seasonal patterns of cellulose $\delta^{18}O$ for normal years and ENSO years. Berkelhammer and Stott (2009) measured season patterns of cellulose $\delta^{18}O$ during the different periods (155–172 BC; AD 1106–1122; AD 1827–1834), and cellulose $\delta^{18}O$ data of each period are from one tree. Although Anchukaitis and Evans (2010) reconstructed hydroclimate (1900–2002) in Costa Rica using two *Pouteria*, the overlapped period of two trees is around 20 years. Therefore, one tree of *Fokienia hodginsii* growing in the terrace and one tree of *Cryptomeria fortune* growing in the steep slope were selected for isotopic analysis.

Records from Fuzhou meteorological station (26°05′N, 119°17′E; 10 m a.s.l.) show that mean annual precipitation between 1953 and 2011 was 1361.2 mm, while mean relative humidity was 78 % (Fig. 2a). In this region, 72.3 % of the annual precipitation is received during the growing season of *Fokienia hodginsii* and *Cryptomeria fortune*

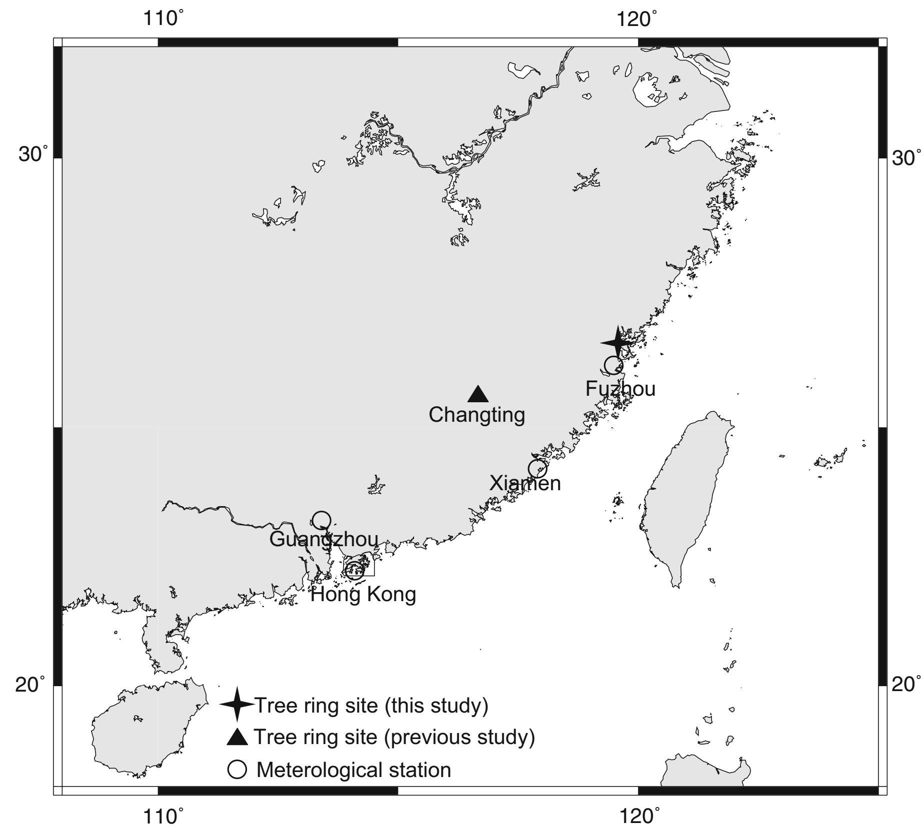


**Fig. 1** Map of the study area. The study site is shown as a *black cross*, the location of previous data from Changting (Xu et al. 2013a) is shown as a *black triangle*, and the GNIP station at Fuzhou is marked as an *open circle* near the sampling site

(April–October). In March–April, the rainfall is generated by collision between the warm and cold air masses. From May to September, the region is mainly influenced by the East Asian, Indian, and western North Pacific summer monsoons characterized by hot summers and plentiful rain. Mean monthly temperature is above 10 °C.

Given the fact that precipitation $\delta^{18}O$ is a main controlling factor of tree-ring cellulose $\delta^{18}O$, we obtained monthly precipitation $\delta^{18}O$ data for Fuzhou from the Global Network of Isotopes in Precipitation (GNIP, http://www.iaea.org/water) database, where data were available from 1985 to 1992 (Fig. 2b). Seasonal variations in precipitation $\delta^{18}O$ values in Fuzhou are clearly observed: precipitation $\delta^{18}O$ values are more depleted during summer and more enriched during winter (Fig. 2b), which is similar to seasonal patterns in precipitation $\delta^{18}O$ values at Xiamen, Guangzhou, and Hong Kong in South China (Chen et al. 2010; Xie et al. 2011). The negative correlation between rainfall amount and precipitation $\delta^{18}O$ values in the rainy season (Fig. 2c) in Fuzhou is considered as the "amount effect" (Dansgaard 1964). The amount effect is also observed in Xiamen, Guangzhou, and several sites in Southeast China (Chen et al. 2010; Liu et al. 2010; Xie et al. 2011).

To assess the relationship between ENSO and tree-ring $\delta^{18}O$ values, the sea surface temperature (SST) from the National Climatic Data Center v3b dataset (Smith et al. 2008) was employed. Since the tropical Pacific SST during both the preceding fall/winter and current spring can influence the monsoon season climate in subtropical areas (Xu et al. 2013b), we identified El Niño (warm phase of ENSO) and La Niña (cool phase of ENSO) events in the tropical Pacific by the following criteria: where the Nino 3.4 region SST anomalies were higher than +0.5 °C or lower than −0.5 °C from the previous July to the current March, a warm or cold phase, respectively, was identified. The El Niño (1992, 1998, 2003, and 2010) and La Niña (1989, 1999, 2000, and 2008) events were selected to evaluate how the tree-ring $\delta^{18}O$ values responded to different ENSO phases.

## Cellulose extraction and stable isotope analysis

Since traditional methods (Jayme-Wise method; Green 1963; Loader et al. 1997) that extract cellulose from individual rings are time- consuming, we used the modified plate method (Xu et al. 2011, 2013a). This method reduces the time required because the α-cellulose is extracted directly from the wood plate rather than from individual rings. We followed the chemical extraction protocol (removed lipids and resins with acetone, ethanol, and toluene; removed lignin with sodium chlorite and acetic acid; and

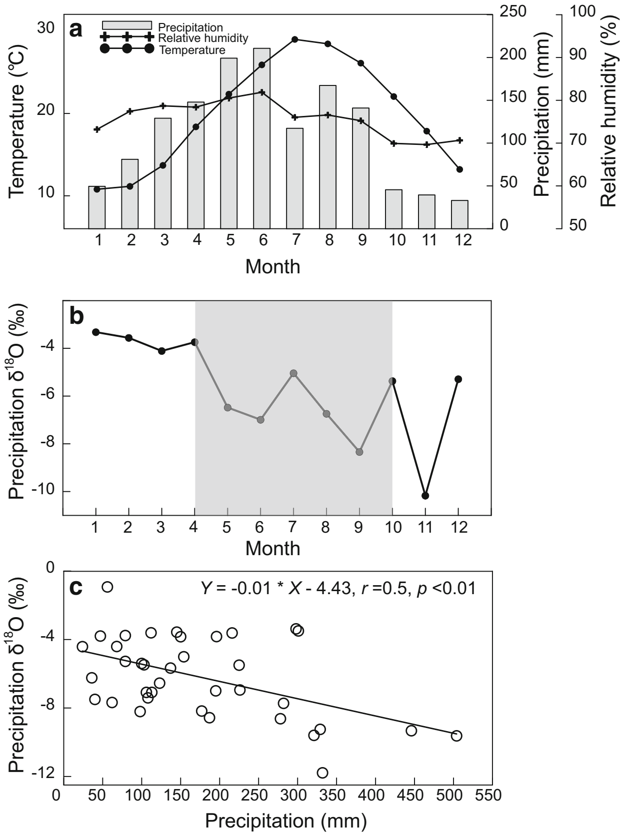


**Fig. 2** Climate in Fuzhou. **a** Monthly mean temperature (*black circles*), precipitation (*gray bar*), and relative humidity (*black crosses*) (1953–2011) at the Fuzhou instrumental station. **b** Mean monthly precipitation $\delta^{18}O$ values (1985–1992) from Fuzhou GNIP station. **c** Scatter plot of precipitation $\delta^{18}O$ values and precipitation amounts from April to October during the period of 1985–1992 in Fuzhou

removed hemicellulose with 17 % sodium hydroxide) of the Jayme-Wise method. The average ring width for *Fokienia hodginsii* and *Cryptomeria fortune* is 8.2 mm and 4.8 mm, respectively. To capture the high-resolution intra-annual variations in tree-ring $\delta^{18}O$ values, we cut and measured sub-samples at a resolution of approximately 0.5 ± 0.25 mm. Due to wood shrinkage during the process of chemical treatment, a simple method to maintain the 0.5 mm resolution of the original sample was employed, whereby we measured the length of the original wood ($L_o$) and cellulose plates ($L_c$), then calculated the ratio of shrinkage ($L_c/L_o$), and subsequently cut samples from the cellulose plate under a microscope by hand with a razor knife with a resolution of $L_c/L_o$. The average number of sections per ring for *Fokienia hodginsii* and *Cryptomeria fortune* are about 16 and 10, respectively. The number of samples per year is shown in Table S1.

Cellulose samples, wrapped in silver foil, were analyzed using an isotope ratio mass spectrometer (Delta V Advantage) interfaced with pyrolysis-type elemental analyzers (TC/EA) at the Graduate School of Environmental Studies, Nagoya University, Japan. The oxygen isotopes are presented in δ notation as per mill (‰) relative to VSMOW (Vienna Standard Mean Ocean Water); $\delta^{18}O = [(R_{sample}/R_{standard}) - 1] \times 1000$ ‰, where $R_{sample}$ and $R_{standard}$ are the $^{18}O/^{16}O$ ratios in the sample and standard, respectively. The cellulose $\delta^{18}O$ values were calculated by comparison with the laboratory working standard (Merck cellulose), which was inserted every eight samples during the analysis process. The analytical uncertainties associated with repeated measurements of the Merck cellulose were ± 0.14 ‰ ($n = 66$).

All subdivisions in each ring were analyzed. Hence, the whole-year tree-ring $\delta^{18}O$ value ($\delta^{18}Oy$) could be calculated as a weighted average of all parts of 1 year using the following equation:

$$\delta^{18}O_y = \frac{\sum_{i=1}^{n} w_i \delta^{18}O_i}{\sum_{i=1}^{n} w_i},$$

where $\delta^{18}O_i$ and $w_i$ are the tree-ring $\delta^{18}O$ value and the sample weight, respectively, and $n$ is the number of samples in 1 year.

To assign the exact calendar date of formation to each sample is difficult, because there are no studies on growth pattern of *Fokienia hodginsii* and *Cryptomeria fortune* by dendrometer in Southeast China. Although tree-ring growth follows some sort of sigmoid function (Ogee et al. 2009; Song et al. 2014), Berkelhammer and Stott (2009) assigned a date to each sample using a linear equation, because more than 90 % of xylem growth of bristlecone pines is linear. So we followed the method of Berkelhammer and Stott (2009) to give a date to each sample according to the following function:

$$\text{Date} = g_i + (n_s/n_t) * g_s,$$

where $g_i$ is the date that growth begins, which we hold constant at April 1, $g_s$ is the whole growing season (214 days, April 1–October 31), $n_s$ is the sample number, and $n_t$ is the total number of samples in the ring.

To compare the sub-annual cellulose $\delta^{18}O$ values with monthly precipitation, high-resolution sub-annual cellulose $\delta^{18}O$ values are necessary. Here, these data were obtained by (1) constructing the fitting curve for every year from the high-resolution measured cellulose $\delta^{18}O$ values (examples are shown in Fig. S1) and (2) interpolation of the sub-annual cellulose $\delta^{18}O$ values at a resolution of 200 $\delta^{18}O$ values per year. Whether the interpolated $\delta^{18}O$ values represent the concurrent seasonal cellulose $\delta^{18}O$ depends on the resolution of measured cellulose $\delta^{18}O$ values used. We set semi-monthly resolution as a threshold for selecting measured cellulose $\delta^{18}O$ values. If we assume that the growing season is from April to October and that cellulose formation is linear, more than 14 samples per year are required. For *Fokienia* and *Cryptomeria*, 17 and 56 % of the total number of years contain ≥14 samples (Fig. S2), respectively. Given that only 4 years of data from *Fokienia* have ≥14 samples, *Cryptomeria* rather than *Fokienia* samples were used to produce the interpolated high-resolution cellulose $\delta^{18}O$ values.

## Results and discussion

### Inter-annual tree-ring cellulose $\delta^{18}O$ response to rainfall

The $\delta^{18}O$ values of cellulose for *Fokienia* and *Cryptomeria* during the period from 1988 to 2011 show similar inter-annual variations ($r = 0.75$, $p < 0.01$), which reflect the influence of common environmental factors (Fig. 3). Moreover, the correlation coefficients between cellulose $\delta^{18}O$ values of *Fokienia* and *Cryptomeria* from Fuzhou and the $\delta^{18}O$ values of *Fokienia* from Changting (Xu et al. 2013a) are 0.5 and 0.67, respectively. Previous studies have indicated that $\delta^{18}O$ values of *Fokienia* from Changting exhibit negative correlations with April–September precipitation (Xu et al. 2013a). Given that Fuzhou and Changting are located in the same climate zone, tree-ring $\delta^{18}O$ in Fuzhou is assumed to record the precipitation, so correlation analysis was carried out between tree-ring cellulose $\delta^{18}O$ values of *Fokienia*/*Cryptomeria* from Fuzhou and precipitation (Fig. 4).

The annual $\delta^{18}O$ values of *Fokienia* and *Cryptomeria* show highest negative correlations with April–July precipitation amount ($r = -0.44$, $p < 0.05$ for *Fokienia*; $r = -0.61$, $p < 0.05$ for *Cryptomeria*; Fig. S3). Similar negative correlations between tree-ring cellulose $\delta^{18}O$ values and precipitation during the growing season have been found at other sites in the Asian monsoonal areas (Xu et al. 2013a; Sano et al. 2013; Xu et al. 2015). Precipitation influences tree-ring cellulose $\delta^{18}O$ values in monsoonal

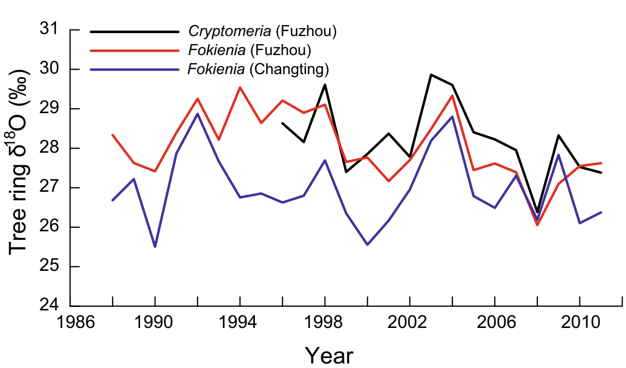


**Fig. 3** Inter-annual cellulose $\delta^{18}O$ values from *Cryptomeria fortune* and *Fokienia hodginsii* from Fuzhou and Changting

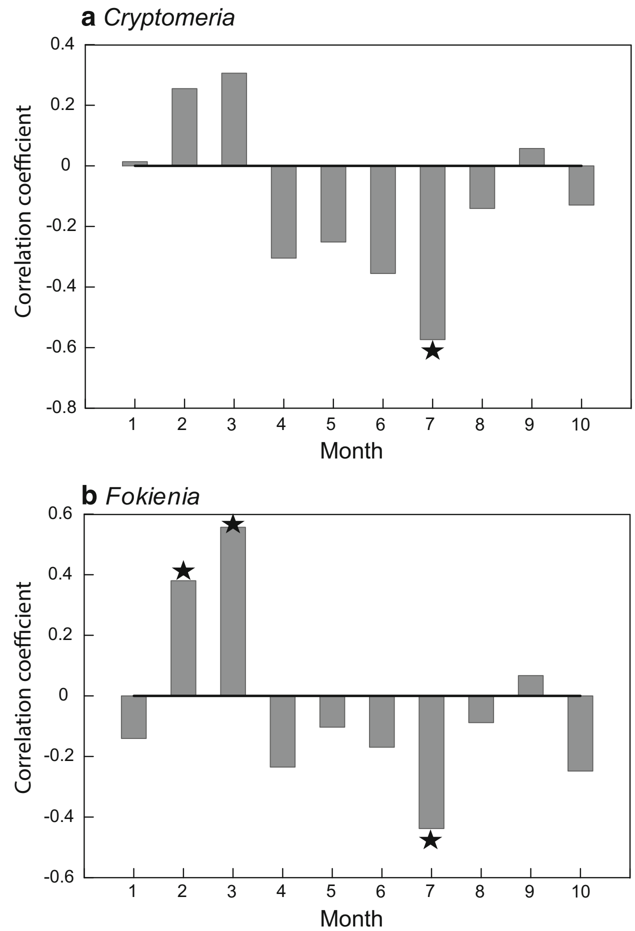


**Fig. 4** Correlations between monthly precipitation (January to October) and annual cellulose $\delta^{18}O$ values from **a** *Cryptomeria fortune* and **b** *Fokienia hodginsii*. *Star* indicates the correlation exceeds the 95 % confidence level

area mainly by the amount effect (negative correlation between precipitation $\delta^{18}O$ and rainfall amount, Fig. 2c).

Conversely, inter-annual $\delta^{18}O$ values of *Fokienia* and *Cryptomeria* are positively correlated with February–March precipitation amount ($r = 0.57$, $p < 0.05$ for *Fokienia*; $r = 0.35$, $p = 0.19$ for *Cryptomeria*; Fig. S3). A previous study on teak in Indonesia also found that tree-ring $\delta^{18}O$ is positively correlated with precipitation amount in pre-growing season (Schollaen et al. 2013). However, the mechanism enabling February–March precipitation amount to affect the annual tree-ring $\delta^{18}O$ values is not clear. Tree growth starts in April, and the February–March precipitation signal could be found in the tree-ring $\delta^{18}O$ because of the time-delayed nature of isotope signal transfer of rainfall water to leaf water to cellulose. First, the soil water taken up by trees during the growing season contains a mixture of rainfall from the preceding months, which is supported by observed and modeled data (Anchukaitis et al. 2008; Luo et al. 2008). This means that trees start to absorb soil water in April, which includes the rainfall water in March or February. Second, it takes 2.5–21 days for water at the trunk base to reach the crown in coniferous species, and residence times range from 36 to 79 days (Meinzer et al. 2006), which means that needle water in April contains an isotope signal of March precipitation, and the $\delta^{18}O$ signal was transferred from the leaf water to the tree ring with time lags of approximately 2 weeks for *Pinus sylvestris* (Gessler et al. 2009). All of these processes result in the February–March precipitation $\delta^{18}O$ signal preserved in the early or middle part of tree ring. The proportional exchange ($f_0$) between organic oxygen atoms of sucrose with unenriched xylem water in early growing season is higher than in late growing season (Gessler et al. 2009), which leads to a greater contribution of xylem water $\delta^{18}O$ to the $\delta^{18}O$ of xylem cellulose in spring than in summer and autumn (Gessler et al. 2009; Offermann et al. 2011). Both heavy February–March rainfall amount and enriched precipitation $\delta^{18}O$ values in February and March result in increased soil water $\delta^{18}O$ values and, therefore, tree-ring $\delta^{18}O$ values, which cause the positive relationship between February–March precipitation amount and tree-ring $\delta^{18}O$.

Although the inter-annual tree-ring $\delta^{18}O$ variations of the two species show similar climate response, there are also some differences between them. Compared with *Cryptomeria*, *Fokienia* shows weaker correlation with April–July precipitation, but better correlation with February–March precipitation. The microtopography may cause the difference. Soil in the steep slope drains better than soil in the terrace. Compared to soil water in the steep slope where *Cryptomeria* grows, soil water in the terrace where *Fokienia* grows contains more previous-month precipitation, so tree-ring $\delta^{18}O$ of *Fokienia* shows higher correlation with February–March precipitation than Cryptomeria.

## Intra-annual variations in tree-ring cellulose $\delta^{18}O$ values and their response to rainfall

The intra-annual $\delta^{18}O$ values of cellulose from *Fokienia* and *Cryptomeria* show similar variations (Fig. 5), with mean $\delta^{18}O$ values of 28.04 and 28.20 ‰, respectively. Both *Fokienia* and *Cryptomeria fortune* show a distinct annual cycle in $\delta^{18}O$ values, characterized by a $\delta^{18}O$ maxima near the ring boundary and a $\delta^{18}O$ minimum in the middle portion of the ring (Fig. 5). Similar seasonal patterns were also found at other sites of monsoon Asia, such as Northern Laos, India, Thailand, and Cambodia (Poussart and Evans 2004; Managave et al. 2010b; Zhu et al. 2012; Xu et al. 2014).

The amplitudes of seasonal $\delta^{18}O$ variations of *Fokienia* and *Cryptomeria* are 6.18 and 6.05 ‰, respectively. The seasonality of tree-ring cellulose $\delta^{18}O$ values generally followed seasonal patterns of precipitation $\delta^{18}O$ values (Fig. 2b). We used the availability of precipitation $\delta^{18}O$ records from Fuzhou together with the $\delta^{18}O$ measurements

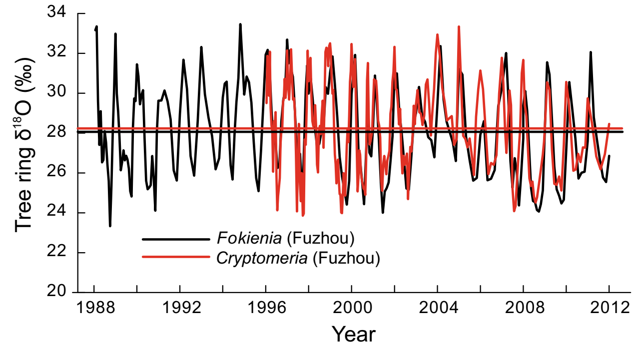


**Fig. 5** Intra-annual cellulose $\delta^{18}O$ values from *Cryptomeria fortune* and *Fokienia hodginsii*. The *horizontal lines* indicate the average value of *Cryptomeria fortune* (*red line*) and *Fokienia hodginsii* (*black line*) (color figure online)

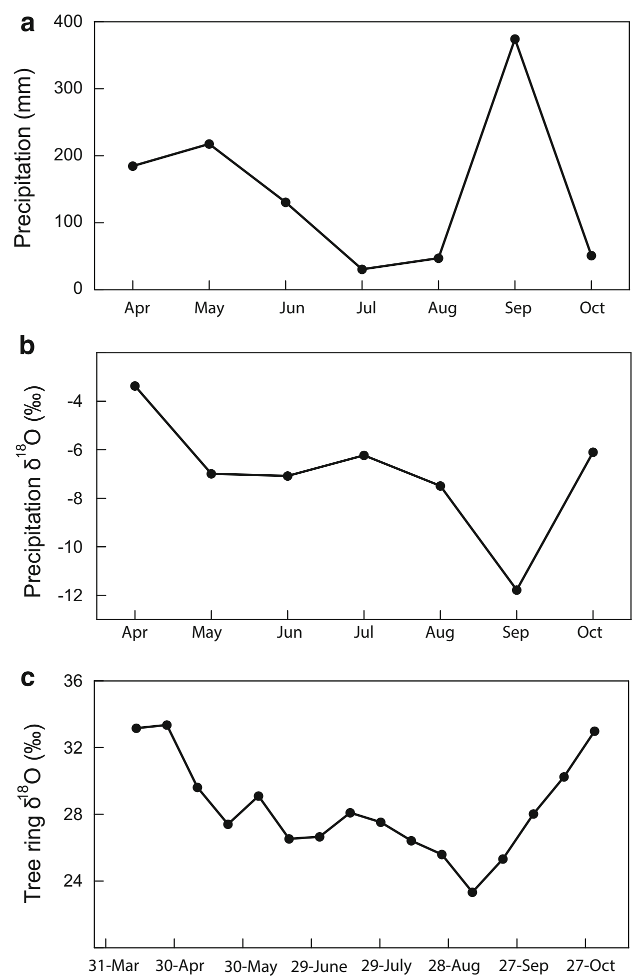


**Fig. 6** Intra-annual variations of precipitation (**a**), precipitation $\delta^{18}O$ (**b**), and cellulose $\delta^{18}O$ of *Fokienia hodginsii* (**c**) in year 1988

**Table 1** Correlations between monthly tree-ring $\delta^{18}O$ of *Cryptomeria fortune* and precipitation amount

| | | Precipitation | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | April | May | June | July | August | September | October |
| Tree-ring $\delta^{18}O$ | April | −0.10 | | | | | | |
| | May | −0.28 | −0.34 | | | | | |
| | June | −0.34 | −0.22 | −0.43 | | | | |
| | July | −0.28 | −0.10 | −0.44 | −0.58* | | | |
| | August | −0.12 | −0.02 | −0.24 | −0.35 | −0.50* | | |
| | September | −0.02 | −0.06 | −0.17 | −0.33 | −0.41 | −0.09 | |
| | October | −0.15 | −0.07 | −0.36 | −0.46 | −0.14 | 0.13 | 0.02 |

* $p < 0.05$

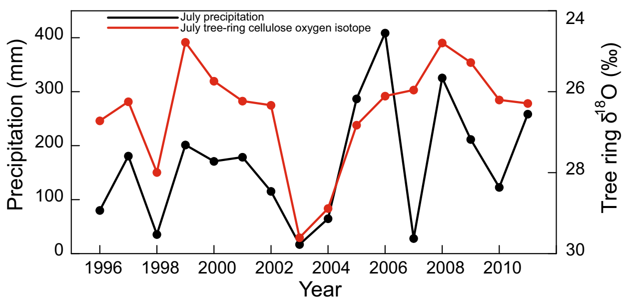


**Fig. 7** Time series of July precipitation and tree-ring $\delta^{18}O$ of *Cryptomeria fortune* during the period of 1996–2011

on a high number of intra-annual subdivisions in 1988 (Fig. 6) to investigate how precipitation amount and $\delta^{18}O$ affect the intra-annual tree-ring $\delta^{18}O$. The precipitation $\delta^{18}O$ in 1988 shows high values at the beginning and the end of growing season and lowest value in September due to the high rainfall in September. The tree-ring $\delta^{18}O$ generally followed the seasonal pattern of precipitation $\delta^{18}O$, which was also found in tree-ring cellulose $\delta^{18}O$ of *Larix decidua* in Switzerland (Treydte et al. 2014).

Because amount effect during the rainy season (Fig. 2c) occurs in South China (Chen et al. 2010; Xie et al. 2011), seasonal tree-ring cellulose $\delta^{18}O$ variations should record changes in the seasonal precipitation amount. The correlations between monthly precipitation amount and tree-ring cellulose $\delta^{18}O$ are shown in Table 1. Monthly tree-ring cellulose $\delta^{18}O$ cellulose (from May to August) are negatively correlated with current-month precipitation amount. Significant negative correlation ($r = -0.58$, $p < 0.05$) between July precipitation and tree-ring cellulose $\delta^{18}O$ (Fig. 7) may be useful for monthly precipitation reconstruction, which is difficult to do with annual resolution tree-ring cellulose $\delta^{18}O$ records. Additionally, monthly tree-ring cellulose $\delta^{18}O$ also correlated with previous-month precipitation, although the correlations are lower than with current-month precipitation and not significant, which indicates that previous-month precipitation also contribute to current-month tree-ring cellulose $\delta^{18}O$. Residence time of precipitation water from previous month and time lags of $\delta^{18}O$ signal from leaf water to tree ring (Meinzer et al. 2006; Gessler et al. 2009; Offermann et al. 2011) result in such correlations. Based on these circumstances, combining tree-ring cellulose $\delta^{18}O$ from several months may increase the signal intensity of precipitation amount. For example, tree-ring cellulose $\delta^{18}O$ from June to August is negatively correlated with precipitation from April to August ($r = -0.72$, $p < 0.01$, $R^2 = 52$ %), while the correlation between precipitation from April to August and annual tree-ring cellulose $\delta^{18}O$ is −0.64 ($p < 0.01$, $R^2 = 41$ %).

## Response of intra-/inter-annual tree-ring cellulose $\delta^{18}O$ values to ENSO

Previous studies have shown that tree-ring cellulose $\delta^{18}O$ values in monsoonal Asia show a close relationship with tropical Pacific SST (Sano et al. 2012; Xu et al. 2013a, b). Spatial correlations between annual cellulose $\delta^{18}O$ values from *Fokienia* and *Cryptomeria* and SST (from the previous July to the current March) indicate the significant influence of ENSO on annual cellulose $\delta^{18}O$ values in Fuzhou (Fig. 8). Xu et al. (2013a) reported that ENSO modulates tree-ring cellulose $\delta^{18}O$ values from Changting, Southeast China (Fig. 1) through precipitation amount. West Pacific subtropical high intensity increases, and a high-pressure ridge extends westward in the years of El Niño events, which results in reduced precipitation in Fujian (Cai et al. 2003). Additionally, the East Asian and western north Pacific summer monsoon tends to be more strongly affected in years following the El Niño mature phase, as subsidence dominates over the Philippine Sea and Southeast Asia (Wang et al. 2000, 2001). In El Niño years, less rainfall in Fujian results in enriched precipitation $\delta^{18}O$ values, which in turn lead to higher tree-ring cellulose $\delta^{18}O$ values. However, we cannot verify this explanation precisely with only annual cellulose $\delta^{18}O$ data because

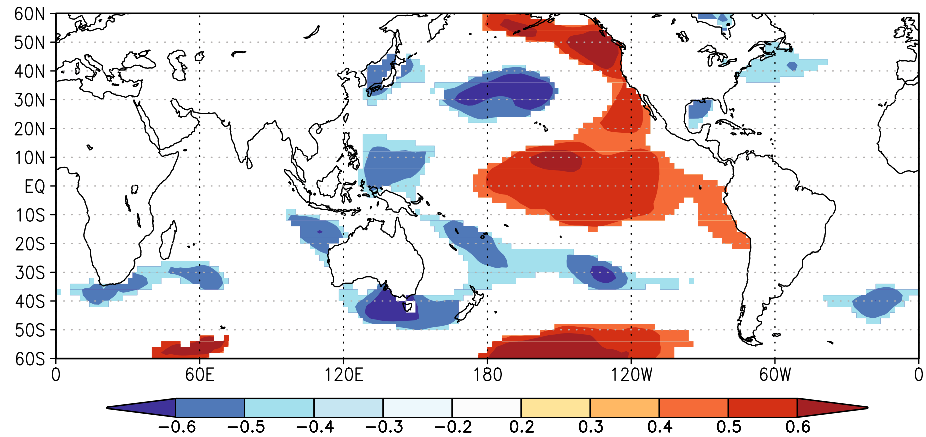


**Fig. 8** Spatial correlations between annual cellulose $\delta^{18}O$ values of *Fokienia hodginsii*/*Cryptomeria fortune* and SST (from the previous July to the current March) during the period 1988–2011. Correlations that are not significant at the 95 % level have been masked out

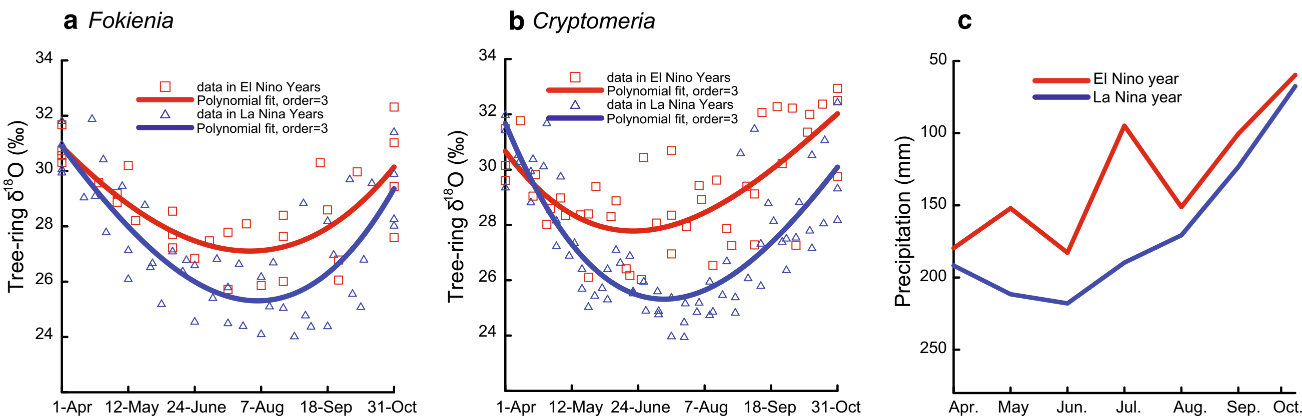


**Fig. 9** Intra-annual cellulose $\delta^{18}O$ variations from **a** *Fokienia hodginsii* and **b** *Cryptomeria fortune* during El Niño (1992, 1998, 2003, 2010) and La Niña (1989, 1999, 2000, 2008) years. **c** Precipitation in Fuzhou during El Niño and La Niña years

precipitation changes from ENSO are usually associated with changes in seasonal precipitation pattern. Intra-annual cellulose $\delta^{18}O$ data provide a chance to test this explanation. Since the rainfall amount from May to September in El Niño/La Niña years is less/more than the rainfall observed in normal years in Fujian Province (Chen 2000), such differences in precipitation during El Niño and La Niña years should be recorded in the seasonal cellulose $\delta^{18}O$ values.

Intra-annual cellulose $\delta^{18}O$ variations for *Fokienia* and *Cryptomeria* in El Niño years and La Niña years are shown in Fig. 9a and b. For *Fokienia*, cellulose $\delta^{18}O$ values from May to October in El Niño years are higher than values obtained in La Niña years. The difference of average values between El Niño and La Niña years is 1.3 ‰ ($t = 2.88$, $p < 0.01$). For *Cryptomeria*, cellulose $\delta^{18}O$ values from May to October in El Niño years are significantly higher than those in La Niña years, with a difference of average values about 1.9 ‰ ($t = 4.76$, $p < 0.0001$). Since cellulose $\delta^{18}O$ values of *Cryptomeria* have a higher resolution than those of *Fokienia* (Fig. S2), the higher resolution $\delta^{18}O$ values of *Cryptomeria* than those of *Fokienia* result in larger difference between the ENSO warm and cold phases.

The variations observed in cellulose $\delta^{18}O$ values from May to October between El Niño and La Niña years may be derived from different precipitation amounts from April to October (Fig. 9c). April–October precipitation amount in El Niño years is lower than in La Niña years. As stated above (Fig. 2c; Table 1), less rainfall from April to October will cause higher cellulose $\delta^{18}O$ values from May to October. Therefore, ENSO affects cellulose $\delta^{18}O$ values in Fuzhou by modulating seasonal precipitation amount.

## Conclusions and perspectives

We examined the response of inter- and intra-annual cellulose $\delta^{18}O$ variations to precipitation in Southeast China through high-resolution cellulose $\delta^{18}O$ measurements on samples of *Fokienia hodginsii* and *Cryptomeria fortune*. Each annual ring for both species was characterized by a $\delta^{18}O$ maximum near the ring boundary and a $\delta^{18}O$

minimum in the middle portion of the ring, which reflect the influences of seasonal changes in precipitation $\delta^{18}$O values. Such annual cycles of tree-ring cellulose $\delta^{18}$O values are also found in other sites of monsoon Asia (e.g., Laos, Thailand, and Cambodia).

Intra-annual cellulose $\delta^{18}$O offers two advantages for precipitation reconstruction. First, intra-annual cellulose $\delta^{18}$O can directly reconstruct monthly precipitation which is difficult for annual tree-ring cellulose $\delta^{18}$O, for example, July tree-ring cellulose $\delta^{18}$O is significantly correlated ($r = -0.58$, $p < 0.05$) with July precipitation. Second, intra-annual cellulose $\delta^{18}$O can extract a stronger signal than annual tree-ring cellulose $\delta^{18}$O, e.g., June–July–August and annual tree-ring cellulose $\delta^{18}$O, respectively, explain 52 and 41 % actual variance of April–August precipitation. For purposes of exploration of climate relationships, our use of isotopic results from single trees has been very helpful, and furthermore, the validity of our study is strengthened by the good correlation between the isotopic series of the single trees of each of the two species. Future robust climate reconstructions using these techniques may eventually require averaging intra-annual isotope records of several trees of a species.

The significant positive correlations between inter-annual cellulose $\delta^{18}$O values and SST in the tropical, central Pacific, reveal that ENSO influences tree-ring cellulose $\delta^{18}$O values in Southeast China. Furthermore, cellulose $\delta^{18}$O values from May to October during El Niño years are higher than during La Niña years because April to October rainfall is lower in El Niño years than in La Niña years. These results support the hypothesis that ENSO affects tree-ring cellulose $\delta^{18}$O values by modulating the precipitation amount. The production of long-term (>100 years) intra-annual cellulose $\delta^{18}$O data would provide monthly precipitation reconstruction, which is helpful to improve the understanding of Asian summer monsoon variability in the past.

**Author contribution statement** Conceived and designed the experiments: CX. Performed the experiments: CX ZH. Analyzed the data: CX ZH TN MS JG. Contributed reagents/materials/analysis tools: CX MS JG ZL. Wrote the paper: CX.

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**Compliance with ethical standards**

**Conflict of interest** The authors have declared that no competing interests exist.

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