Specific climatic signals recorded in earlywood and latewood $\delta^{18}$O of tree rings in southwestern China

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ABSTRACT

Earlywood and latewood form during different parts of the growing season and therefore capture climate of distinct time intervals. Here we present a comparison of earlywood and latewood $\delta^{18}$O in tree rings from the Yulong Snowy Mountains of southwestern China, covering the period from 1902 to 2005. Earlywood and latewood $\delta^{18}$O exhibit different long-term behaviour obviously during the past century. Climate–response analysis indicates that the dominant parameters for earlywood $\delta^{18}$O are temperature and relative humidity during the early part of the monsoon season (May to July); however, for latewood, it is the moisture condition (precipitation and relative humidity) from August to October. Sea-surface temperatures over the Indian Ocean and the Pacific Ocean have imprinted their different influences on the earlywood and latewood $\delta^{18}$O. The $\delta^{18}$O of source water were reconstructed from the earlywood and latewood $\delta^{18}$O. We found that the source of the water synthesised into earlywood was mainly contributed by current precipitation, while for latewood it is more complicated. The signals from the Indian Summer Monsoon and the East Asian Summer Monsoon are temporally superimposed (though differently) on the source water of earlywood and latewood, as well as the El Niño–Southern Oscillation events.

Keywords: tree-ring $\delta^{18}$O, earlywood, latewood, source water, atmospheric circulation

1. Introduction

Tree rings comprise earlywood produced at the start of the growing season and latewood produced at the end of the growing season, which are produced by a complex sequence of interactions between a plant’s genetic and physiological attributes and the local environment (Downes and Drew, 2008; Pallardy, 2008). Kagawa et al. (2006a,b) reported that the stored photosynthate carried over from the previous year is likely to be used for the production of earlywood in spring and early summer (i.e., at the beginning of the growing season), whereas latewood is mainly composed of photoassimilate from the current year (i.e., the summer and autumn). Therefore, the climatic signals preserved in earlywood and latewood are expected to differ because of how they respond to their immediate environment, including climate influence, physical stresses, and other factors at the time of their formation (Larson, 1969; Miina, 2000).

Investigations of earlywood and latewood density have led to significant advances in tree-ring research (Parker and Henoch, 1971; Zhang, 1997; D’Arrigo and Jacoby, 1999; Lebourgeois, 2000; Miina, 2000; Fries and Ericsson, 2009). Additionally, a smaller but growing number of studies have investigated the climatic significance of tree-ring isotopes in earlywood and latewood (Epstein and Yapp, 1976; Leavitt and Long, 1991; Brabander et al., 1999; Li et al., 2005; Kagawa et al., 2006a,b; Kress et al., 2009). Among the more recent important findings, Kress et al. (2009) established high inter-annual carbon isotope variability in earlywood and latewood and found high coherence between them for two tree species in Europe. Furthermore, studies by Weigl et al. (2008) and Vaganov et al. (2009) indicated that the whole-ring $\delta^{13}$C may provide analytical advantages compared with the separation of earlywood and latewood. Despite this, Kagawa et al. (2006a) reported that it was necessary to separate the...
two types of wood in climate reconstruction work using the narrow rings of boreal species in a high-latitude permafrost zone near Yakutsk City. The importance of separating earlywood from latewood may therefore differ depending on the species and the magnitude of the climate variability between the phases of earlywood and latewood formation.

Because of more potential environmental influences on oxygen isotopes (McCarroll and Loader, 2004), the interpretation of stable oxygen isotopes (δ18O) in tree rings is more complicated than carbon isotopes, and there have been fewer climatically relevant investigations on the relationship between earlywood and latewood δ18O in tree rings. Miller et al. (2006) found that additional climatic relationships can be identified by comparison of earlywood and latewood δ18O with various climate indices when they examined the record of past hurricanes in tree-ring cellulose in the southeastern USA. Li et al. (2011a) reported that remarkable intra-annual isotopic variation (a 5.6% change in δ18O) existed. Thus, interesting results can be expected as a result of examining tree-ring δ18O of earlywood and latewood from regions where isotopic fractionation is controlled by different climate systems as the seasons change.

The source of water for trees is soil moisture, which derives from precipitation (Saurer et al., 2000), so part of the signal in the water isotopes (δ18O and δD) in trees will be determined by the isotopic signature of precipitation and any modification it undergoes in the soil (McCarroll and Loader, 2004). Because of evaporation effects that occur during transpiration through stomata, isotopic enrichment (i.e., an increase in the 18O content) of leaf water is a critical fractionation process and accounts for as much as 20% of the isotopic discrimination (Dongman et al., 1974; Saurer et al., 1997). Differences in ambient temperature and humidity conditions also substantially influence the process of leaf water enrichment (Roden and Ehleringer, 2000).

The subsequent biological fractionation that occurs between cellulose and the source water, as well as exchanges between xylem water and oxygen in sucrose, is more complex (DeNiro and Epstein, 1979; Sternberg et al., 1986; Barbour et al., 2001; Miller, 2005). The tree-ring O- and H-isotope model (Roden et al., 2000) predicts three major controls on the δ18O of tree rings: the isotopic signal in the source water, enrichment in the leaf through evapotranspiration, and exchanges with xylem water during the synthesis of cellulose. Therefore, δ18O variations in tree-ring α-cellulose mainly reflect the isotopic composition of the source water combined with physiological isotope effects that include carbon–water interactions during biosynthesis, xylem water–sucrose exchange, and evaporative enrichment of leaf water (Saurer et al., 1997; Roden et al., 2000; Anderson et al., 2002); the latter is mainly influenced by climatic conditions during the period of earlywood and latewood cellulose formation in the tree’s growth ring. Consequently, it is possible to extract meaningful and interpretable records of climatic information from tree-ring δ18O, as well as evidence of water-vapour source dynamics caused by changes in various atmospheric circulation systems.

Wang and Lin (2002) studied the influence of complicated monsoonal climatic systems, and found that in the temperate-humid region of southwestern China, which means a long growing season and tree rings would be wider than in colder regions and provided a clear boundary between the earlywood and latewood; thus, δ18O in these two components could be separated easily. The established δ18O patterns in earlywood and latewood in this region may therefore provide detailed information about past climate changes. Hence, the aims of the present study were to examine whether the oxygen isotopic signatures of earlywood and latewood show similar statistical characteristics, to detect detailed climatic information contained in the earlywood and latewood tree-ring δ18O signatures, and to explore the potential connections of earlywood and latewood δ18O with the atmospheric circulation patterns that dominate southwestern China.

2. Materials and methods

2.1. The environment at the sampling site

The tree-ring samples used in this study were collected from the Yulong Snowy Mountains of southwestern China (Fig. 1), which have the southernmost glacier that is affected by Eurasian monsoons and have a mild subtropical highland climate owing to their low latitude and high elevation. The mean annual air temperature in this region is 12.7°C and the total annual precipitation amounts to ca. 807 mm based on data collected from 1951 to 2005 at the Lijiang meteorological station (26°52′N, 100°13′E, 2392 m.a.s.l.), which is about 15 km away from our sampling site. The highest temperature is in June, with an average of 18.1°C, and the lowest is in January, with an average of 6.0°C (Fig. 2a). The rainfall is mainly concentrated in the summer months (from June to September), and the relative humidity is correspondingly high during these months. Interestingly, the highest values of temperature, rainfall, and relative humidity do not co-occur, and instead fall in June, July, and from August to September, respectively (Fig. 2a).

In a previous study, He (2000) reported that the Lijiang fir (Abies forrestii) trees in the study area begin to grow when the ambient temperature was 6°C and above and stopped when the temperature falls below 5°C. On the
basis of the climate response analyses and the climatic conditions in the study area (Fig. 2a), we finally divided the growing season for Lijiang fir into two growth periods: May to July for earlywood growth (EWG) and August to October for latewood growth (LWG). This distinction is not exact because instrumental monitoring of local tree growth is lacking, but it is a reasonable first approximation to help to understand the climate conditions recorded in tree-ring earlywood and latewood δ¹⁸O compared with other parameters. Fig. 2b,c provides a detailed comparison of the temperature and total precipitation during these periods from 1951 to 2005. The mean temperature from May to July was clearly higher than that from August to October throughout the study period, and there was a weak relationship between the temperature \((r = 0.17, p > 0.1)\) and precipitation \((r = -0.12, p > 0.1)\) of the two periods. This indicates that the climate during the early growing season (the EWG period) bore little relationship to that during the late growing season (the LWG period).

2.2. Tree-ring sampling and crossdating

The vegetation of the Yulong Snowy Mountains is complex. The main tree species are Lijiang fir, spruce \((Picea likiangensis)\), pine \((Pinus densata)\), and Chinese hemlock \((Tsuga dumosa)\). In the present study, we collected cores from dominant fir trees in the temperate forest \((27°6.1'N, 100°13.4'E, ca. 3260 m.a.s.l.)\) located at Yulong Snowy Mountains, in the northwestern Lijiang in July 2005 (Fig. 1). We obtained two cores from each of 20 trees, regularly spaced around the circumference at a height of ca. 1.30 m, using 5-mm increment borers (Hagløf, Mora, Sweden). All cores taken from the 20 trees were processed using standard dendrochronological techniques (Stokes and Smiley, 1968); they were measured at a resolution of 0.01 mm and were crossdated to obtain a reference chronology. For all the samples, cross-correlations were checked with the COFECHA software (Holmes, 1983), and the ultimate standard chronology for the tree-ring width indices were detrended with a negative exponential and modelled with the autoregressive model by the ARSTAN
Fig. 2. (a) Monthly mean temperature, precipitation, and relative humidity values from 1951 to 2004 at the Lijiang meteorological station. The inter-annual variations of (b) temperature and (c) total precipitation during the early growing season (May to July) and the late growing season (August to October).
software (Cook and Holmes, 1986). The final tree-ring width chronology showed good correlations to another chronology that is close to sampling site (see Fig. S1).

2.3. α-cellulose extraction and oxygen isotopic measurement

Nine tree-ring cores (each one from different trees) with homogeneous growth patterns and no evident growth aberrations were selected for isotope analysis. The boundary between earlywood and latetwood was sharp, and they could be separated with a razor blade under a binocular microscope based on differences in cell colour. For obtaining enough wood material to extract purified cellulose, measure isotopic values and minimise the possible influence of outliers caused by potential ecological differences between the individual trees (Borella and Leuenberger, 1998), the earlywood and latetwood fractions sampled trees for each year was carefully pooled prior to cellulose extraction. Potential uncertainties in pooled stable isotope time series from tree rings have been suggested by many researchers (Borella and Leuenberger, 1998; Leavitt, 2010; Liñán et al., 2011; Woodley et al., 2012). Nonetheless, pooling saves time/resources and has been successfully employed to extract climatic information from tree rings in Europe and North America (Treydte et al., 2006; Leavitt, 2008; Loader et al., 2008; Leavitt, 2010), as well as on the Tibetan Plateau (Grießinger et al., 2005; Shi et al., 2011; Liu et al., 2012).

In order to remove the juvenile effect, the inner 20 rings of each core were discarded (Savard et al., 2005). We pooled the annual rings from the samples by mixing all latewood (or earlywood) from the same year and storing them in a microcentrifuge tube (Leavitt, 2010). According to the standard procedures of Green (1963) and Loader et al. (1997), ground samples were processed to extract α-cellulose. To obtain better homogenisation of the cellulose, we used an ultrasound machine (JY92-2D; Scientz Industry, Nihgbo, China) to break the cellulose fibres according to the method of Laumer et al. (2009). The α-cellulose was then freeze-dried for 72 hours using a vacuum-freeze dryer (Labconco Corporation, Kansas City, MO, USA) prior to the isotope analysis.

About 0.14 to 0.16 mg of α-cellulose of each sample were packed in silver capsules, and then conveyed into a High-Temperature Conversion Element Analyzer (TC/EA) linked to a mass spectrometer (MAT-253, Thermo Electron Corporation, Bremen, Germany) to determine the oxygen isotopic ratios δ¹⁸O(¹⁸O/¹⁶O) for each earlywood and latetwood sample. Each sample was analysed four times to obtain a precise result. The final tree-ring δ¹⁸O values were calculated as the mean from the runs after first excluding outliers. The replicate runs yielded an SD for each sample of less than 0.3%. The oxygen isotope ratios were expressed as δ¹⁸O, which represents the per mil deviation relative to the Vienna Standard Mean Ocean Water (VSMOW). We measured the ratio for a benzoic acid working standard with a known δ¹⁸O value (IAEA-601, δ¹⁸O = 23.3%) every seven measurements to monitor the analytical precision and to calibrate the samples for analytical accuracy (Liu et al., 2009; 2012). The isotope values were then expressed as the ratio of the value in the sample to that in the cellulose standard IAEA-C3 (32.2%) to calibrate the tree-ring oxygen measurements.

\[
\delta^{18}O = \left(\frac{R_{sample}}{R_{standard}} - 1\right) \times 1000
\]  

This analysis produced tree-ring δ¹⁸O chronologies spanning the period from 1902 to 2005 for the earlywood and from 1902 to 2004 for the latetwood (Fig. 3).

2.4. Isotope modelling

We used correlation analysis to identify the relationships between tree-ring δ¹⁸O and climatic variables. The climatic variables used in the analysis are the monthly mean temperature, amount of precipitation, relative humidity, and total cloud cover from the previous October to the current October. All climatic data are obtained from the Lijiang meteorological station. In addition, we used the fractionation model proposed by Waterhouse et al. (2002) to reconstruct the source water δ¹⁸O during the different growth periods for the earlywood and latetwood. The equation for the δ¹⁸O in tree-ring cellulose (δ¹⁸Ocell) is as follows:

\[
\delta^{18}O_{cell} = (1 - f_0) [\delta^{18}O_s + (e_k + e_o) (1 - h) + e_o] \\
+ f_0 (\delta^{18}O_s + e_o)
\]  

where \(f_0\) is a damping factor, \(\delta^{18}O_s\) is the δ¹⁸O in the source water (i.e., soil water originating from precipitation), \(e_k\) is the equilibrium fractionation factor, \(e_o\) is the kinetic fractionation factor, \(h\) is the relative humidity, and \(e_o\) is the biochemical fractionation factor. The values we used here for the constants in this equation are discussed in Section 3.5. Thus, source water δ¹⁸O can be calculated in different seasons, and can be used to seek connections between local and regional precipitation δ¹⁸O during the EWG and LWG periods. Using eq. (2), δ¹⁸Ocan be expressed as:

\[
\delta^{18}O_s = \delta^{18}O_{cell} - e_o - (1 - f_0)(e_k + e_o)(1 - h)
\]  

We also calculated the weighted mean δ¹⁸O of precipitation at the nearest Global Network of Isotopes in Precipitation (GNIP) station, in Kunming (World Meteorological Organization station #5677800; 25°02’N,
102°43'E, at 1895 m elevation) from 1986 to 2004, except for the period from 1993 to 1995, which had no observed values.

We computed temporal and spatial correlations between the earlywood and latewood δ18O values and sea-surface temperature (SST) over Indian Ocean (HadISST, http://www.metoffice.gov.uk/hadobs/hadisst/) to identify the connections between large-scale atmospheric circulation patterns and tree-ring δ18O. These indices are all detrended by linear regression and standardised to be dimensionless by SPSS analysis software. Moreover, we investigated the response of reconstructed source water δ18O to the dominant atmospheric circulation patterns and provide a comparison with previous research on latewood δ18O (Liu et al., 2012). We used the southern oscillation index (SOI) as an indicator of the El Niño–Southern Oscillation (ENSO) strength (SOI, http://www.bom.gov.au/climate/current/soihtm1.shtml), as well as the Indian Summer

Fig. 3. Standard ring-width index series of fir from the Yulong Snowy Mountains since 1827 (a); values of tree-ring cellulose δ18O from 1902 to 2005 for (b) earlywood, (c) latewood and (d) the sample size.
Monsoon (ISM) index (from June to July) defined by Webster and Yang (1992) and the East Asian Summer Monsoon (EASM) index (from June to August) defined by Li and Zeng (2005) for further analysis. We calculated a 10-year running average on the original tree-ring $\delta^{18}O$ and the ISM and EASM index time series to detect the low-frequency variation patterns at decadal scales, and then performed the correlation analysis on the running average chronologies. Due to the strong autocorrelation in the low-frequency time series, the degrees of freedom (DF) for significance testing were adjusted as follows (Bretherton et al., 1999):

$$\text{DF} = N \frac{1 - r_1 \cdot r_2}{1 + r_1 \cdot r_2},$$  \hspace{1cm} (4)

where $N$ is the number of observations and $r_1$ and $r_2$ are the first-order autocorrelations of the two series, respectively.

3. Results

3.1. Tree-ring growth

The tree-ring width chronology developed for the Yulong Snowy Mountains extends from 1827 to 2002 (Fig. 3a). The mean inter-series correlations (Rbar) and the expressed population signal (EPS) statistics of the chronology signal strength are 0.45 and 0.95, respectively, and the EPS exceeds 0.90 since 1880. The chronology shows a low mean sensitivity (MS = 0.16) and high first-order auto-correlation (AC1 = 0.49), which are typical and have been reported in warm and humid environments (Fan et al., 2008). There are weak or no obvious correlations between the tree-ring-width index chronology and the climate variables (Table 1), except the mean temperature during winter, the precipitation amount in January and the relative humidity in April. Thus, the ability of tree-ring width to record the influence of climate variables appears very limited.

3.2. The earlywood and latewood $\delta^{18}O$ chronologies

Table 2 summarises the statistical characteristics of the earlywood and latewood $\delta^{18}O$ chronologies. Linear increases were observed for both the earlywood and latewood $\delta^{18}O$ values from 1902 to 2005 (Fig. 3b,c), and the annual rate of increase for earlywood $\delta^{18}O$ (0.03%/yr) was slightly higher than that for latewood $\delta^{18}O$ (0.02%/yr). The SE of the earlywood $\delta^{18}O$ (1.75%) was higher than that of the latewood $\delta^{18}O$ (1.32%), indicating the fluctuations in earlywood $\delta^{18}O$ were larger than those in latewood $\delta^{18}O$. We found a weak but significant agreement between the earlywood and latewood $\delta^{18}O$ ($r = 0.30, p < 0.01, 1902$ to $2004$). The $\delta^{18}O$ signature of the current year’s earlywood is also significantly correlated with the previous year’s latewood $\delta^{18}O$ ($r = 0.28, p < 0.01$) (Table 2).

The earlywood $\delta^{18}O$ ranged from 18.3 to 28.8%, and averaged 24.0%; the latewood cellulose $\delta^{18}O$ had a narrower range, from 12.8 to 18.6% (Table 2), and a lower overall mean of 15.2%, which is significantly lower than the values in most previous studies (Treydte et al., 2006; Wright and Leavitt, 2006; Reynolds-Henne et al., 2007; Hilasvuori et al., 2009; Liu et al., 2009). This may be a result of lower precipitation $\delta^{18}O$, resulting from the high levels of precipitation in southwestern China and the high relative humidity (Liu et al., 2012). The first-order auto-correlations for the earlywood and latewood $\delta^{18}O$ series were 0.42 and 0.38 ($p < 0.001$; Table 2), respectively.

3.3. Climatic response of earlywood and latewood $\delta^{18}O$

Correlation analyses were carried out between earlywood and latewood $\delta^{18}O$ with climatic parameters (Fig. 4).

| Table 1. Correlation coefficients between ring-width series and climate data of fir from Yulong Snowy Mountains ($^*p < 0.05; ^{*}^*p < 0.01$) |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Month           | Monthly temperature | Monthly precipitation | Monthly relative humidity | Monthly cloud cover |
| Previous November | 0.33*            | 0.00             | 0.10             | 0.06            |
| Previous December | 0.17             | 0.17             | 0.02             | 0.23            |
| January          | 0.16             | 0.43**           | 0.00             | 0.13            |
| February         | 0.08             | 0.08             | 0.12             | 0.01            |
| March            | 0.12             | 0.16             | 0.07             | 0.11            |
| April            | 0.30*            | 0.02             | 0.37**           | 0.40**          |
| May              | 0.23             | 0.18             | 0.23             | 0.21            |
| June             | 0.05             | 0.01             | 0.03             | 0.05            |
| July             | 0.02             | 0.24             | 0.08             | 0.18            |
| August           | 0.13             | 0.29             | 0.11             | 0.09            |
| September        | 0.03             | 0.09             | 0.00             | 0.13            |
| October          | 0.20             | 0.25             | 0.14             | 0.05            |
The responses of earlywood and latewood $\delta^{18}O$ to the climate factors differed to some extent (Fig. 4a,b). As shown in Fig. 4a, we found high and significant correlations between earlywood $\delta^{18}O$ and monthly temperature during the early growing season (April to July). Moreover, relative humidity and precipitation in May were significantly negatively correlated with earlywood $\delta^{18}O$, as was relative humidity in the previous October and precipitation in the previous November (Fig. 4a). These results indicate opposite influences of temperature and moisture conditions on earlywood $\delta^{18}O$ values. We found a significant and positive correlation between earlywood $\delta^{18}O$ and the May–July temperature, and significantly negative correlations between earlywood $\delta^{18}O$ and the

![Fig. 4. Correlation coefficients between monthly temperature, precipitation, relative humidity, and total cloud cover and (a) earlywood $\delta^{18}O$, (b) latewood $\delta^{18}O$. Dotted lines indicate the 95% confidence interval. Months with a “p” prefix indicate values from the previous year.](image)

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**Table 2. Statistical characteristics of the tree-ring earlywood (EW) and latewood (LW) $\delta^{18}O$ values for Lijiang fir (*p < 0.1; **p < 0.001). ‘Current’ and ‘previous’ refer to the current and previous growing seasons.**

|         | Number of years | Range of values | Mean value | SE | First-order autocorrelation | $r$ (EW<sub>current</sub> with LW<sub>current</sub>) | $r$ (EW<sub>current</sub> with LW<sub>previous</sub>) |
|---------|-----------------|-----------------|------------|----|-----------------------------|-----------------------------------------------|-----------------------------------------------|
| EW $\delta^{18}O$ | 104 | 18.34–28.78 | 23.99 | 1.75* | 0.42** | 0.30* | 0.28* |
| LW $\delta^{18}O$ | 103 | 12.8–18.4 | 15.23 | 1.32* | 0.38** | | |

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May–July cloud cover, relative humidity, and precipitation (Table 3).

We found weak relationships between latewood $\delta^{18}O$ and monthly temperature except during the current June (Fig. 4b), suggesting that temperature has a smaller effect on latewood $\delta^{18}O$ than on earlywood $\delta^{18}O$ throughout the growing season. The total cloud cover, relative humidity, and precipitation showed synchronous relationships with latewood $\delta^{18}O$ from August to October (Liu et al., 2012). The total cloud cover during the late growing season (August to October) had significant negative correlation with latewood $\delta^{18}O$ ($r = -0.45$, $n = 54$, $p < 0.01$), and latewood $\delta^{18}O$ is dominantly controlled by precipitation and relative humidity from August and October, respectively (Fig. 4b and Table 3). Overall, we found that the temperature signal may be better recorded in the earlywood $\delta^{18}O$, whereas moisture conditions during the late growing season were recorded more strongly in the latewood $\delta^{18}O$.

3.4. Linkage with the SST over Indo-Pacific Ocean

Gradients of SST within the oceans are important in determining the monsoon regions. We performed a comparison between the earlywood and latewood $\delta^{18}O$ values and SST through the Indian Ocean (HadISST, 50°E to 100°E, and 10°S to 15°N, calculated at http://climexp.knmi.nl/) from 1902 to 2005. We found that SST during the previous December to the current July was significantly correlated with earlywood $\delta^{18}O$ ($r = 0.29$, $n = 104$, $p < 0.001$) (Fig. 6a). Similarly, we found a positive correlation between the Indo-SST in the current May to October and latewood $\delta^{18}O$ ($r = 0.34$, $n = 103$, $p < 0.001$) (Fig. 6b).

Spatial and temporal patterns of earlywood and late-wood $\delta^{18}O$ showed generally positive correlations with the Indo-Pacific SST from 1902 to 1979 (Fig. 7a,c), and the correlations subsequently weakened from 1980 to 2004 (Fig. 7b,d), while a negative correlation arose between tree-ring $\delta^{18}O$ and SST in the North Pacific Ocean and the positive correlation with SST over the East Pacific Ocean strengthened. The positive and negative correlations were generally significant for earlywood $\delta^{18}O$. The influence of SST in the Indian Ocean on the earlywood and latewood $\delta^{18}O$ values has changed since the 1970s, indicating alteration of atmospheric circulation patterns over the region during this period. The results are consistent with reports that the Indian Ocean has undergone significant temperature variation associated with a climate shift that occurred during the 1970s (Clark et al., 2000; Pillai and Mohankumar, 2010).

3.5. Source water $\delta^{18}O$ inferred from the tree-ring cellulose $\delta^{18}O$

The source water for trees is soil moisture, which originates both from groundwater movement and precipitation and represents an integrated signal of local precipitation (Anderson et al., 2002), so part of the signal in the tree-ring $\delta^{18}O$ will come from the isotopic signature of precipitation (McCarroll and Loader, 2004). At the sampling site, tree-ring $\delta^{18}O$ may therefore provide detailed insights into the intra-seasonal differences in the water source by examination of the cellulose that developed during the EWG and LWG periods.

On the basis of the Waterhouse et al. (2002) model (eq. 3), we reconstructed the source water $\delta^{18}O$ during the EWG and LWG periods using the average climate parameters from 1951 to 2005 as fixed values. The equilibrium fractionation factor ($\varepsilon_o$) is temperature dependent but only changes slightly (Majoube, 1971), so it is regarded as a constant value of 9% (Allison et al., 1985). Additionally, the kinetic fractionation factor ($\varepsilon_k$) and the biologic fractionation factor ($\varepsilon_b$) are also considered to be constant with values of 28%, and 27%, respectively (Anderson et al., 2002). The dampening factor ($f_o$) is variable and depends on the tree species, as well as on the relative humidity (Anderson et al., 2002). Here we defined the $f_o$ values by substituting the average earlywood and latewood $\delta^{18}O$, the average EWG and LWG relative humidity, and other parameters into eq. (3).

Table 3. Correlations between earlywood and latewood $\delta^{18}O$ and the four climate variables for the May to July and August to October parts of the growing season. Climatic data are from the nearest meteorological station (at Lijiang) from 1951 to 2004 (*$p < 0.01$; **$p < 0.001$)

| Climate variables       | Earlywood May to July | Latewood August to October |
|-------------------------|------------------------|-----------------------------|
|                         | $r$        | Slope   | $r$  | Slope   |
| Monthly temperature     | 0.53**     | 0.14    | 0.06 | 0.01    |
| Monthly cloud cover     | $-0.36^*$  | $-0.14$ | $-0.45^*$   | $-0.09$ |
| Monthly relative humidity | $-0.49^*$  | $-0.33$ | $-0.40^*$  | $-0.19$ |
| Monthly precipitation   | $-0.38^*$  | $-0.002$| $-0.40^*$  | $-0.001$|
The weighted mean δ¹⁸O of precipitation in the nearest GNIP station of Kunming are calculated as −8.48% and −12.28% for EWG and LWG, respectively. Liu et al. (2008) suggested that the δ¹⁸O of precipitation over China was influenced by the altitude effect as −0.15%/100 m based on the observed data of the Chinese Network of Isotopes in Precipitation. We estimated the precipitation δ¹⁸O as −10.53% and −14.57% for EWG and LWG in the sampling site (1365 m higher than the Kunming station). The values are estimations and have no influence on the final temporal variability.

The determination of $f_o$ value is important when using tree-ring isotopic models (Roden et al., 2000; Anderson et al., 2002; Gessler et al., 2009; Offermann et al., 2011). There is a 40% exchange between organic oxygen and xylem water oxygen during the cellulose synthesis (Gessler et al., 2009). However, Offermann et al. (2011) reported that this exchange rate was highly variable throughout the growth season with values decreasing from 0.76 to 0 between May and July, indicating that during ambient conditions with higher water vapour pressure, the exchange rate is the lowest. In the present paper, the calculated $f_o$ values were 0.24 and 0.58 for the earlywood and latewood in Yulong Snowy Mountains, respectively. Generally these values are uncertain, involving in the difference of Kunming and Lijiang in distance and elevation, as well as the sampling site. Furthermore, the relative humidity used in the models is an average value including both daytime and nighttime data, which will overestimate the effect of relative humidity on the actual amount of photosynthetic processes for the trees. Thus the reconstructed δ¹⁸O in source water is most reliable for the temporal variability, but the absolute values (including the $f_o$ values) still contain large uncertainties (Li et al., 2011b).

The reconstructions of source water δ¹⁸O during EWG (1951–2005) and LWG (1951–2004) are based on the δ¹⁸O of earlywood and latewood and the relative humidity. To examine the reliability of the reconstructions, we compared variations of the reconstructed source water and observed precipitation δ¹⁸O series at Kunming station of GNIP, which is about 200 km away from our sampling site, as shown in Fig. 5. The variation pattern is relatively consistent among the observed precipitation and reconstructed δ¹⁸O for EWG, but it is poor for LWG. These results demonstrate that the source water vapour signals in reconstructed source water δ¹⁸O for EWG and LWG are different. First, earlywood δ¹⁸O records more precipitation δ¹⁸O information than the latewood δ¹⁸O. Additionally, earlywood δ¹⁸O in the present study actually retains more temperature information, which can be explained by the fact that the fractionation of precipitation δ¹⁸O is dominated by the instantaneous air temperature (Dansgaard, 1964). Second, water vapour sources providing precipitation during latewood development are more

![Fig. 5. Inter-annual variations in the observed precipitation δ¹⁸O at the GNIP station closest to the study site (in Kunming) and the reconstructed precipitation δ¹⁸O based on (a) earlywood δ¹⁸O and (b) latewood δ¹⁸O. EWG and LWG represent the earlywood and LWG periods.](image-url)
complex than those for earlywood development (Ding and Wang, 2008), resulting in a more complicated mosaic of information on precipitation $\delta^{18}O$ absorbed by the latewood $\delta^{18}O$.

The above results suggest that the earlywood is using precipitation during the growing season and the dampening ($f = 0.24$) in the soil water is correspondingly minor, compared with the latewood ($f = 0.58$). The diverse variation pattern for reconstructed and observed $\delta^{18}O$ during LWG may be caused by the difference in distance and altitude between the GNIP station and the sampling site. The poor relationship also implies that at the annual scale, the precipitation $\delta^{18}O$ signal in the reconstruction for LWG is complicated and superimposed by source water other than monsoon precipitation contributing to latewood formation, including glacier melt water and snow melt water. Moreover, Pang et al. (2006) proposed that local and regional recycling of summer monsoon precipitation (evaporation and reprecipitation) influences the isotopic composition of precipitation at the end of summer monsoon in the Yulong Snowy Mountains, and this will confound the precipitation $\delta^{18}O$ signal during latewood formation.

4. Discussion

4.1. Climate factors that control earlywood and latewood $\delta^{18}O$

The basic structure of wood anatomy is determined to a large extent by genetic factors (Fritts, 2001). However,
Fig. 7. Spatial distribution of the correlations between earlywood $\delta^{18}O$ (December to July), latewood $\delta^{18}O$ (May to October), and the HadISST grid data (http://climexp.knmi.nl) from 1902 to 1979 for (a) earlywood $\delta^{18}O$ and (c) latewood $\delta^{18}O$, and from 1980 to 2004 for (b) earlywood $\delta^{18}O$ and (d) latewood $\delta^{18}O$. Values significant at $p < 0.10$ are shown.
environmental factors such as climate conditions during xylem development can also affect the anatomical features of woody tissues (Fonti et al., 2009). For tree-ring cellulose δ18O, climatic variables play an important role in the processes of evapotranspiration and biochemical integration of oxygen during different parts of the growing season. On the basis of whole-ring analysis, Li et al. (2011b) found that δ18O was significantly negatively correlated with precipitation and relative humidity during the growing season in northern semi-arid China. Liu et al. (2009) discovered that the mean temperature from the previous November to the current February significantly affected the whole-tree-ring δ18O in northwestern China. The results of the present study show that separate earlywood and latewood analyses help differentiate climate factors controlling tree-ring δ18O during different parts of the growth period.

On the basis of tree-ring isotope models, ambient relative humidity, which influences evapotranspiration, is considered to be a major factor that affects the enrichment of δ18O in leaf water relative to groundwater (Allison et al., 1985; Yakir et al., 1990). Variations in relative humidity can therefore be recorded in the variations of tree-ring δ18O (Shu et al., 2005; Wright and Leavitt, 2006). In this study, the correlations between relative humidity and the earlywood and latewood δ18O are both significant and negative, indicating that the relative humidity effect was operating throughout the growing season. As an explicit indicator of the water content of the atmosphere, relative humidity is also related to cloud cover and precipitation, especially in temperate and humid regions. Meteorological data from the Lijiang station (1951–2005) demonstrated that during the EWG period, relative humidity was correlated with total cloud cover and precipitation amount ($r = 0.69$ and $0.70$, respectively; $p < 0.001$); during the LWG period, the correlation coefficients were similarly high ($r = 0.75$ and $0.58$, respectively; $p < 0.001$), indicating a close linkage among the three variables.

With increased cloud cover, evapotranspiration of leaf water is reduced by the increased relative humidity and decreased stomatal conductance, causing a correspondingly low δ18O value in leaf water. It has been pointed out that tree-ring δ18O is not a direct measure of precipitation δ18O because the fractionation during different parts of the growing season is affected by differences in evapotranspiration and biochemical processes (McCarroll and Loader, 2004). The disparities between the δ18O components in earlywood and latewood can be caused by micrometeorological changes during the current growing season or by a stronger influence of biochemical fractionation during earlywood formation than during latewood production.

Correlation analysis indicates that temperatures from May to July during the early growing season were the most important factor that determined the earlywood δ18O ($r = 0.53$, $n = 55$, $p < 0.001$; Table 3); for the latewood δ18O, the cloud cover during the late growing season (from August to October) was most important ($r = -0.45$, $n = 54$, $p < 0.001$), and the influence of temperature was weak and not significant (Fig. 4b). Before being absorbed by plant, the isotopic fractionation processes associated with precipitation formation, and especially the equilibrium fractionation constant, depends directly on temperature variations (Criss, 1999). During the beginning of the growing season (May to July), the temperature at the study site is higher than it is later in the season (Fig. 2), but the monsoon rainfall peaks 1–2 months after the peak temperatures. Higher temperatures will result in more δ18O enrichment in the soil water (through evaporation) and in organic matter synthesised by plants. Therefore, temperature becomes the dominant factor in determining tree-ring δ18O during the EWG period.

4.2. Moisture source for earlywood and latewood δ18O

Southwestern China is a typical monsoonal climate region. Correspondingly, moisture transfer is characterised by marked seasonal changes (wet and dry seasons), generally from the winter and spring westerly winds to the summer monsoonal moisture originating from the Bay of Bengal and the South China Sea, and the autumn moisture obtained mainly from the western Pacific Ocean (Zhao, 1997; Li et al., 2010). In the present study, earlywood and latewood δ18O showed positive relationships with the pre-monsoon Indo-Pacific SST (Figs. 6 and 7).

Many studies have found generally positive correlations between Indian Ocean SSTs and rainfall before the onset of the monsoon (Joseph and Pillai, 1984; Allan et al., 1995; Clark et al., 2000). Wright et al. (2001) had previously found strong correlations of latewood δ18O in western North America with July SST in the eastern tropical Pacific. Harzallah and Sadourny (1997) found that positive SST anomalies exist in the Indian Ocean, and especially in the Arabian Sea, in the fall and winter before a strong monsoon, which is accompanied by more rainfall, resulting in depleted precipitation δ18O values that are reflected in tree-ring δ18O (i.e., the so-called ‘amount effect’). SSTs throughout the tropical Indian Ocean are positively correlated with subsequent monsoon rainfall (Clark et al., 2000), which would mean a possible negative relationship between tree-ring δ18O and these SSTs. Contrary to expectations, the correlation coefficient was positive (Fig. 6). The significant positive relationship between earlywood δ18O and SSTs over the Indian Ocean can be explained as a temperature effect that results from the
warm water vapour carried by this southwestern monsoon, especially during the early growing season.

Our sampling site is dominated by complicated monsoon systems during the rainy season and associated with the ISM and EASM (Zhao, 1997; Zhang et al., 1996; Qin and Yu, 2001). Thus, the moisture source region is likely to be complex, which contributes to variability in the source water $\delta^{18}O$. We compared the variability in the reconstructed source water $\delta^{18}O$ during the EWG and LWG periods with the ISM and EASM indices. The reconstructed source water $\delta^{18}O$ for EWG and LWG in this study have inverse trends with the EASM and ISM index from 1951 to 2005 (Fig. 8 and Table 4). The relationships between reconstructed source water $\delta^{18}O$ for EWG and the ISM/EASM indices are weak at the annual scale. The correlation coefficient between the reconstructed source water $\delta^{18}O$ for EWG and the ISM index can reach $-0.42$ after 10-year running average. The weak correlations may be due to the temperature signal retained in earlywood $\delta^{18}O$, which covers the moisture signal and less of the water vapour information is retained in the earlywood $\delta^{18}O$ than in the latewood $\delta^{18}O$. However, the regression analysis demonstrates that the ISM affects earlywood $\delta^{18}O$ at a decadal scale (Table 4). Moreover, the reconstructed source water $\delta^{18}O$ for LWG correlated with the EASM index significantly after 10-year running average ($r = -0.63, p < 0.05$), but the relationships with ISM index are weak at the annual/decadal scale. It can be concluded that the latewood $\delta^{18}O$ is mainly affected by EASM, but the ISM may also have affected the latewood $\delta^{18}O$ in some periods (Fig. 8 and Table 4).

The conclusion is supported by the research of Wang et al. (2003), who contrasted the different annual cycles.

Fig. 8. Inter-annual variations in the source water $\delta^{18}O$ reconstructed from the (a) earlywood and (c) latewood $\delta^{18}O$ values from 1950 to 2005. (b) The ISM index and (d) the EASM index during the same period. EWG and LWG represent the earlywood and LWG periods, respectively. Dashed lines indicate linear increasing and decreasing trend at decadal scale during different periods.
of the two monsoon systems; the ISM peaks in early June to mid-July and ends by late-September, whereas the EASM reaches its maximum intensity and northernmost extension (≈25°N) in August. This matches the peak rainfall that occurs in mid-August, and the Western Pacific rainy season ends in late October. This pattern suggests that latewood in the study area may have formed under the influence of this two-monsoon system. To further understand the influence of the water source on the growth of earlywood and latewood, we investigated the spatial relationships between precipitable water and the source water \( \delta^{18}O \) for EWG and LWG (Fig. 9).

The spatial correlation analysis shows that the source water \( \delta^{18}O \) for EWG has a weak negative linkage with the precipitable water (May to July) over the Indian Ocean, especially in the Bay of Bengal region from 1951 to 2005 (Fig. 9a). This result is in accordance with the fact that the EWG period (May to July) is the period when the ISM develops and expands into the Bay of Bengal (Wang et al., 2003). Spatial analysis also displays a distinct negative relationship between the source water \( \delta^{18}O \) for LWG and precipitable water vapour (August to October) over the Indian Ocean from 1951 to 2004 (Fig. 9b). This indicates that moisture conditions over the Indian Ocean significantly affect tree-ring \( \delta^{18}O \) throughout the monsoon season, because relative humidity in the monsoon air controls the stomatal conductance of leaves and evaporation from trees (Roden et al., 2000).

Variations of ISM and EASM are well known to be associated with ENSO events (Webster and Yang, 1992; Webster et al., 1998; Clark et al., 2000). Liu et al. (2012) proposed that the latewood \( \delta^{18}O \) in this region was positively correlated with the SST anomaly in the Niño3 region and the South China Sea, and detected an inverse correlation between latewood \( \delta^{18}O \) and the SOI. Here we compared the relationship between source water \( \delta^{18}O \) for EWG and LWG and the SOI. The SOI values from the previous August to the current May were significantly negatively correlated with source water \( \delta^{18}O \) for EWG (Fig. 10a), whereas the correlation coefficients between source water \( \delta^{18}O \) for LWG and SOI values were low (Fig. 10b). The significant relationship between source

### Table 4

The coefficients of the linear regression for source water \( \delta^{18}O \) during EWG and LWG and the Indian summer monsoon (ISM) index, Eastern Asian summer monsoon (EASM) index during different periods (*\( p < 0.05 \); **\( p < 0.01 \))

|                | 1960–1980 | 1985–2005 | 1960–1990 | 1991–2004 |
|----------------|-----------|-----------|-----------|-----------|
| Source water \( \delta^{18}O \) for EWG | | | | |
| Slope          | 0.09      | 0.12      | 0.07      | —0.11     |
| \( r \)       | 0.58**    | 0.44*     | 0.53**    | 0.42      |
| \( p \)       | 0.006     | 0.04      | 0.002     | 0.12      |
| ISM index      | | | | |
| Slope          | —0.02     | —0.03     | —0.03     | 0.04      |
| \( r \)       | 0.17      | 0.18      | 0.28      | 0.18      |
| \( p \)       | 0.45      | 0.43      | 0.13      | 0.51      |
| Source water \( \delta^{18}O \) for LWG | | | | |
| Slope          | —0.11     | —0.11     | 0.03      | 0.04      |
| \( r \)       | 0.58      | 0.44      | 0.53      | 0.42      |
| \( p \)       | 0.002     | 0.12      | 0.002     | 0.12      |
| EASM index     | | | | |
| Slope          | —0.02     | —0.03     | —0.03     | 0.04      |
| \( r \)       | 0.17      | 0.18      | 0.28      | 0.18      |
| \( p \)       | 0.45      | 0.43      | 0.13      | 0.51      |

Note: The \( r \) is the correlation coefficient of the investigated series against the time series and \( p \) is the \( p \)-value. The ISM and EASM index have been detrended by linear regression.

Fig. 9. Spatial distributions of correlations between the source water \( \delta^{18}O \) and precipitable water vapour (http://www.esrl.noaa.gov/) from 1948 to 2005 for earlywood and from 1948 to 2004 for latewood. (a) current May to July for earlywood \( \delta^{18}O \); (b) current May to October for latewood \( \delta^{18}O \).
water δⁱ⁸O for EWG and SOI may occur against a background of increasing temperature over China, and can be explained partly by linkages between ENSO and climate, particularly for temperature (Xu et al., 2009; Liu et al., 2012). This temperature information is better recorded in earlywood δ¹⁸O than that in latewood δ¹⁸O.

5. Conclusions

Earlywood and latewood δ¹⁸O respond quite differently to climatic factors early and late in the growing season. We found no statistical and physiological consistency between the earlywood and latewood δ¹⁸O of tree rings in a moist-temperate region of southwestern China. In our study area, earlywood δ¹⁸O is significantly correlated with the climatic conditions early in the growing season, and the best correlation was with the temperature from May to July. By comparing the earlywood δ¹⁸O with Indo-Pacific SSTs, we found that the significant temperature effect during the EWG period may be related to the intensity of the ISM. In contrast, latewood δ¹⁸O is significantly correlated with moisture conditions late in the growing season rather than with temperature. Relative humidity and cloud cover from August to October account for much of the variation in latewood δ¹⁸O. We reconstructed the source water δ¹⁸O for earlywood and latewood formation and found that the reconstructed variation of source water δ¹⁸O from earlywood δ¹⁸O correlates well with that of contemporaneous precipitation δ¹⁸O, while it is different for that from latewood δ¹⁸O. We conclude that earlywood and latewood δ¹⁸O may derive from different water sources. Water vapour transported by ISM and EASM has influenced the latewood formation, and at a

![Fig. 10.](image)

(a) Comparison of inter-annual variations in source water δ¹⁸O for EWG and the SOI from 1951 to 2005 and from 1902 to 2004. Months with a ‘p’ prefix indicate values from the previous year. (b) Comparison of inter-annual variations in source water δ¹⁸O for LWG and the SOI from 1951 to 2004 and from 1902 to 2004. Months with a ‘p’ prefix indicate values from the previous year.
multi-decade scale, the influence of the EASM is larger. However, earlywood $\delta^{18}O$ derives mainly from moisture carried by the ISM. The reconstructed source water $\delta^{18}O$ for EWG is more sensitive to variations in the SOI, indicating that the ENSO phenomenon can be detected in earlywood $\delta^{18}O$. The different response patterns of earlywood and latewood $\delta^{18}O$ to climatic variables and atmospheric circulation indices demonstrate that separate analyses of earlywood and latewood increase the amount of environmental information that can be extracted in isotopic dendroclimatological research in southwestern China.

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