

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

By WENLING AN^{1,2}, XIAOHONG LIU^{1*}, STEVEN W. LEAVITT³, JIAWEN REN¹, WEIZHEN SUN¹, WENZHI WANG^{1,2}, YU WANG¹, GUOBAO XU^{1,2}, TUO CHEN¹ and DAHE QIN¹, ¹State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Lanzhou 730000, China; ²Graduate University of Chinese Academy of Sciences, Beijing 100049, China; ³Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ 85721, USA

(Manuscript received 20 November 2011; in final form 21 March 2012)

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 $\delta^{18}\text{O}$ in tree rings from the Yulong Snowy Mountains of southwestern China, covering the period from 1902 to 2005. Earlywood and latewood $\delta^{18}\text{O}$ exhibit different long-term behaviour obviously during the past century. Climate–response analysis indicates that the dominant parameters for earlywood $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$. The $\delta^{18}\text{O}$ of source water were reconstructed from the earlywood and latewood $\delta^{18}\text{O}$. 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 $\delta^{18}\text{O}$, 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, phy-

sical 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 Henschel, 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 $\delta^{13}\text{C}$ 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

*Corresponding author.
email: liuxh@lzb.ac.cn

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 ($\delta^{18}\text{O}$) in tree rings is more complicated than carbon isotopes, and there have been fewer climatically relevant investigations on the relationship between earlywood and latewood $\delta^{18}\text{O}$ in tree rings. Miller et al. (2006) found that additional climatic relationships can be identified by comparison of earlywood and latewood $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$) existed. Thus, interesting results can be expected as a result of examining tree-ring $\delta^{18}\text{O}$ of earlywood and latewood from regions where isotope 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 ($\delta^{18}\text{O}$ 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 ^{18}O 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 $\delta^{18}\text{O}$ 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, $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$, 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, $\delta^{18}\text{O}$ in these two components could be separated easily. The established $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ signatures, and to explore the potential connections of earlywood and latewood $\delta^{18}\text{O}$ 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

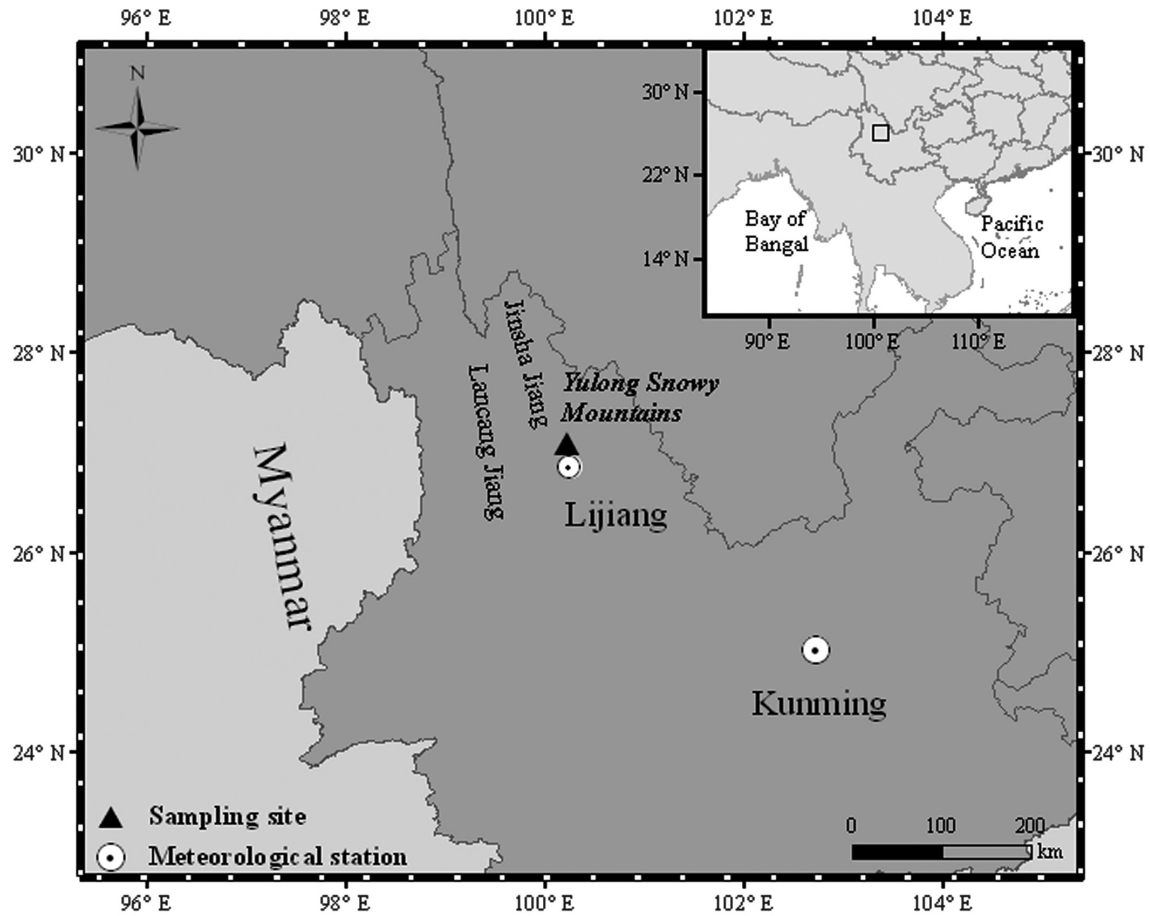


Fig. 1. Map showing the location of the sampling site in the Yulong Snowy Mountains.

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 $\delta^{18}\text{O}$ 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 (Haglöf, 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

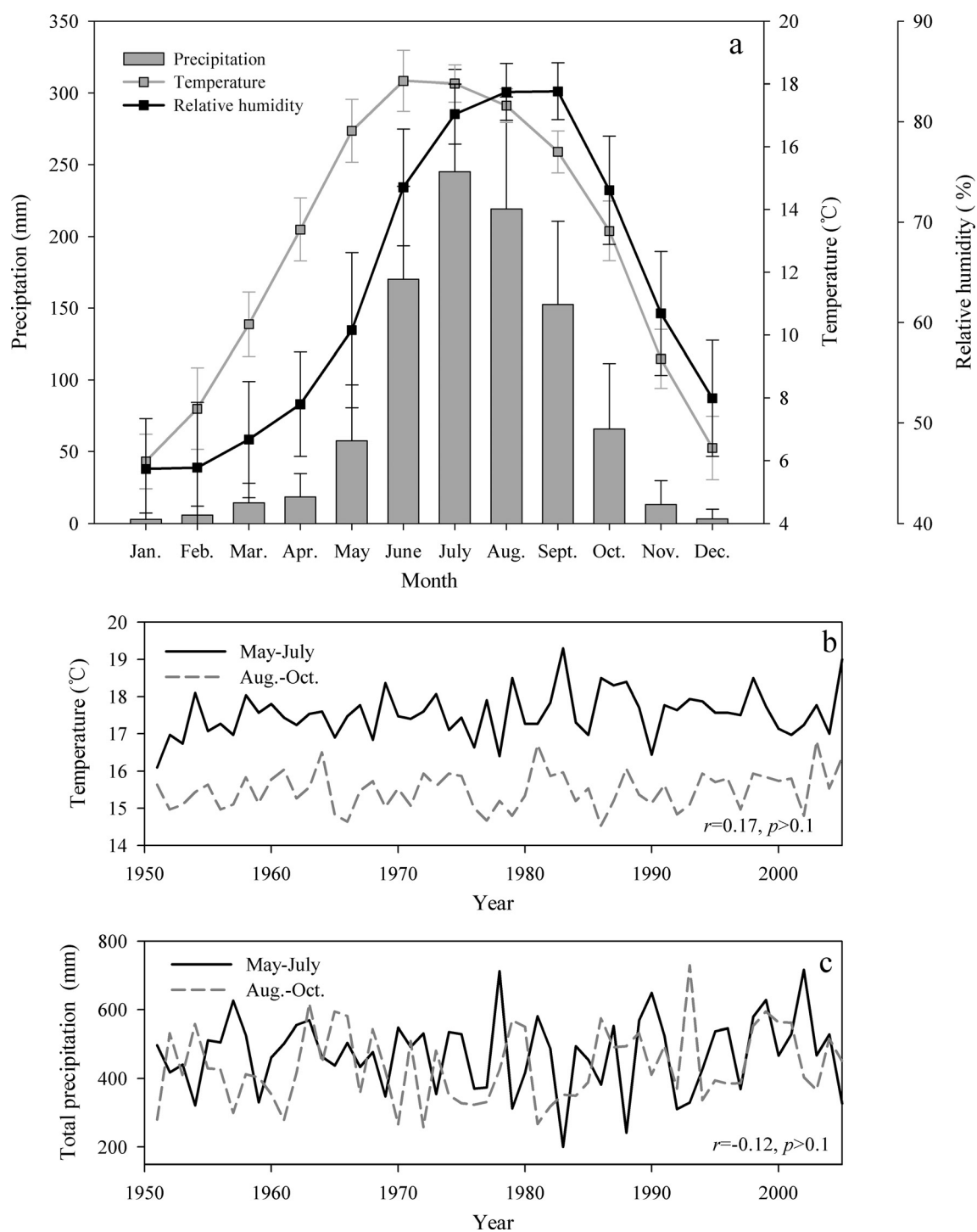


Fig. 2. (a) Monthly mean temperature, precipitation, and relative humidity values from 1951 to 2004 at the Lijiang meteorological station. The inter-annual variations of (b) temperature and (c) total precipitation during the early growing season (May to July) and the late growing season (August to October).

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 latewood 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 latewood 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, Nibgbo, 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 $\delta^{18}\text{O}/^{16}\text{O}$ for each earlywood and latewood sample. Each sample was analysed four times to obtain a precise result. The final tree-ring $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$, 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 $\delta^{18}\text{O}$ value (IAEA-601, $\delta^{18}\text{O} = 23.3\%$) 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.

$$\delta^{18}\text{O} = (\text{R}_{\text{sample}}/\text{R}_{\text{standard}} - 1) * 1000 \quad (1)$$

This analysis produced tree-ring $\delta^{18}\text{O}$ chronologies spanning the period from 1902 to 2005 for the earlywood and from 1902 to 2004 for the latewood (Fig. 3).

2.4. Isotope modelling

We used correlation analysis to identify the relationships between tree-ring $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ during the different growth periods for the earlywood and latewood. The equation for the $\delta^{18}\text{O}$ in tree-ring cellulose ($\delta^{18}\text{O}_{\text{cell}}$) is as follows:

$$\delta^{18}\text{O}_{\text{cell}} = (1 - f_0) [\delta^{18}\text{O}_s + (\varepsilon_e + \varepsilon_k) (1 - h) + \varepsilon_0] + f_0 (\delta^{18}\text{O}_s + \varepsilon_0) \quad (2)$$

where f_0 is a damping factor, $\delta^{18}\text{O}_s$ is the $\delta^{18}\text{O}$ in the source water (i.e., soil water originating from precipitation), ε_e is the equilibrium fractionation factor, ε_k is the kinetic fractionation factor, h is the relative humidity, and ε_0 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 $\delta^{18}\text{O}$ can be calculated in different seasons, and can be used to seek connections between local and regional precipitation $\delta^{18}\text{O}$ during the EWG and LWG periods. Using eq. (2), $\delta^{18}\text{O}_s$ can be expressed as:

$$\delta^{18}\text{O}_s = \delta^{18}\text{O}_{\text{cell}} - \varepsilon_0 - (1 - f_0)(\varepsilon_e + \varepsilon_k)(1 - h) \quad (3)$$

We also calculated the weighted mean $\delta^{18}\text{O}$ of precipitation at the nearest Global Network of Isotopes in Precipitation (GNIP) station, in Kunming (World Meteorological Organization station #5677800; 25°02'N,

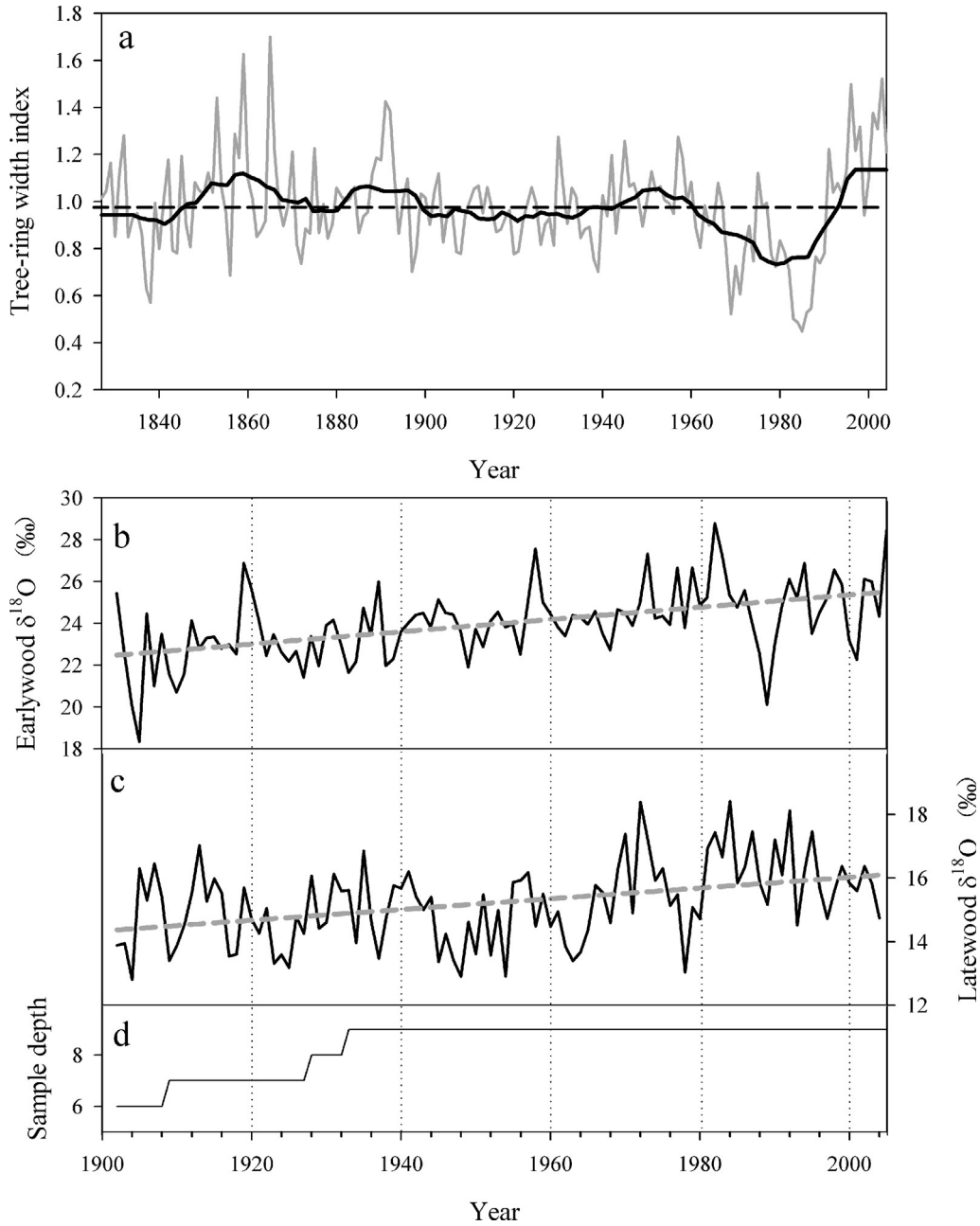


Fig. 3. Standard ring-width index series of fir from the Yulong Snowy Mountains since 1827 (a); values of tree-ring cellulose $\delta^{18}\text{O}$ from 1902 to 2005 for (b) earlywood, (c) latewood and (d) the sample size.

102°43'E, at 1895m 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$. 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 $\delta^{18}\text{O}$ to the dominant atmospheric circulation patterns and provide a comparison with previous research on latewood $\delta^{18}\text{O}$ (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/soihtml.shtml>), as well as the Indian Summer

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 $\delta^{18}\text{O}$ 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):

$$\text{DF} = N \frac{1 - r_1 * r_2}{1 + r_1 * r_2}. \quad (4)$$

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 (R_{bar}) 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 ($\text{MS} = 0.16$) and high first-order autocorrelation ($\text{AC1} = 0.49$), 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 $\delta^{18}\text{O}$ chronologies

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

The earlywood $\delta^{18}\text{O}$ ranged from 18.3 to 28.8‰, and averaged 24.0‰; the latewood cellulose $\delta^{18}\text{O}$ 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; Hiltasvuori et al., 2009; Liu et al., 2009). This may be a result of lower precipitation $\delta^{18}\text{O}$, resulting from the high levels of precipitation in southwestern China and the high relative humidity (Liu et al., 2012). The first-order autocorrelations for the earlywood and latewood $\delta^{18}\text{O}$ series were 0.42 and 0.38 ($p < 0.001$; Table 2), respectively.

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

Correlation analyses were carried out between earlywood and latewood $\delta^{18}\text{O}$ 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

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

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

The responses of earlywood and latewood $\delta^{18}\text{O}$ to the climate factors differed to some extent (Fig. 4a,b). As shown in Fig. 4a, we found high and significant correlations between earlywood $\delta^{18}\text{O}$ and monthly temperature during the early growing season (April to July). Moreover, relative humidity and precipitation in May were significantly negatively correlated with earlywood $\delta^{18}\text{O}$, 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 $\delta^{18}\text{O}$ values. We found a significant and positive correlation between earlywood $\delta^{18}\text{O}$ and the May–July temperature, and significantly negative correlations between earlywood $\delta^{18}\text{O}$ and the

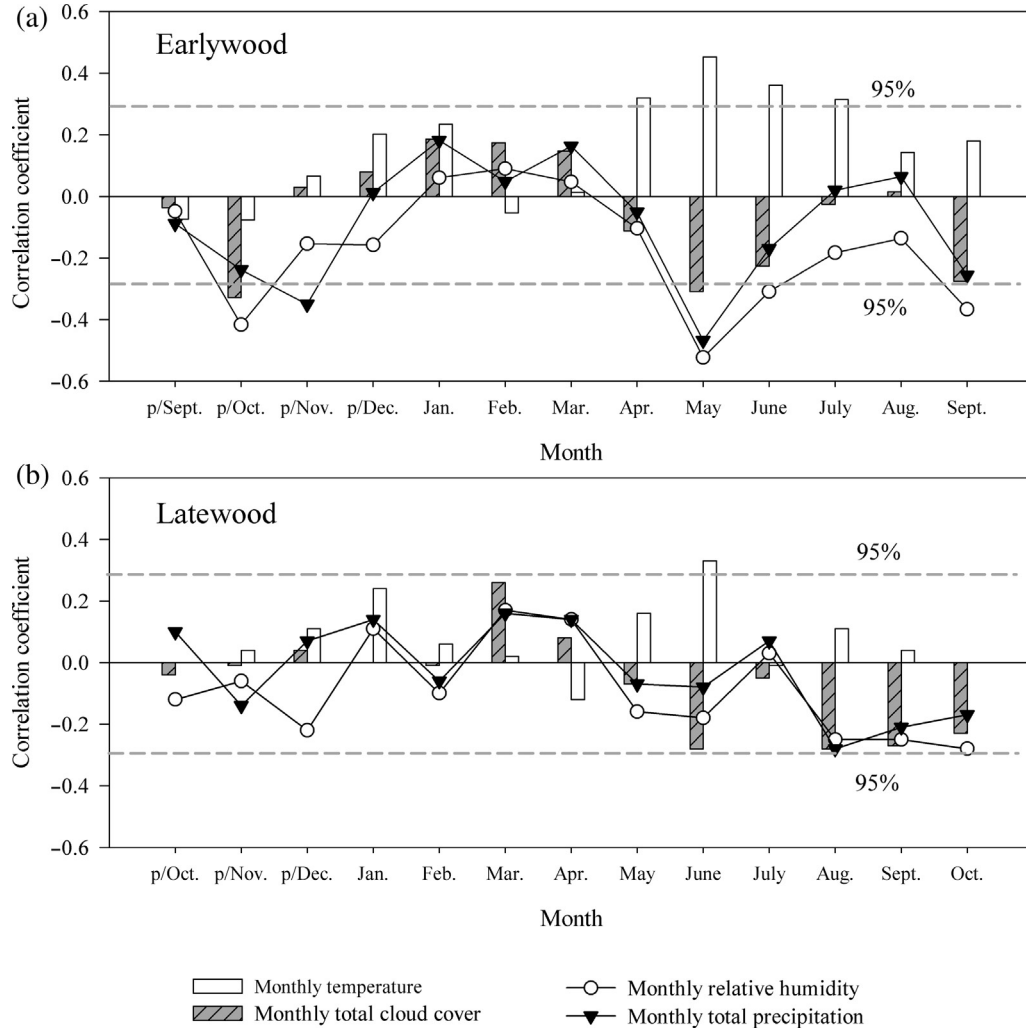


Fig. 4. Correlation coefficients between monthly temperature, precipitation, relative humidity, and total cloud cover and (a) earlywood $\delta^{18}\text{O}$, (b) latewood $\delta^{18}\text{O}$. Dotted lines indicate the 95% confidence interval. Months with a 'p' prefix indicate values from the previous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

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

We found weak relationships between latewood $\delta^{18}\text{O}$ and monthly temperature except during the current June (Fig. 4b), suggesting that temperature has a smaller effect on latewood $\delta^{18}\text{O}$ than on earlywood $\delta^{18}\text{O}$ throughout the growing season. The total cloud cover, relative humidity, and precipitation showed synchronous relationships with latewood $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ ($r = -0.45$, $n = 54$, $p < 0.01$), and latewood $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$, whereas moisture conditions during the late growing season were recorded more strongly in the latewood $\delta^{18}\text{O}$.

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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ ($r = 0.29$, $n = 104$, $p < 0.001$) (Fig. 6a). Similarly, we found a positive correlation between the Indo-SST in the current May to October and latewood $\delta^{18}\text{O}$ ($r = 0.34$, $n = 103$, $p < 0.001$) (Fig. 6b).

Spatial and temporal patterns of earlywood and latewood $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$. The influence of SST in the Indian Ocean on the earlywood and latewood $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ inferred from the tree-ring cellulose $\delta^{18}\text{O}$

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 $\delta^{18}\text{O}$ will come from the isotopic signature of precipitation (McCarroll and Loader, 2004). At the sampling site, tree-ring $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ during the EWG and LWG periods using the average climate parameters from 1951 to 2005 as fixed values. The equilibrium fractionation factor (ϵ_e) 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 (ϵ_k) and the biologic fractionation factor (ϵ_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 $\delta^{18}\text{O}$, the average EWG and LWG relative humidity, and other parameters into eq. (3).

Table 3. Correlations between earlywood and latewood $\delta^{18}\text{O}$ 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		Latewood	
	May to July		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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ of precipitation over China was influenced by the altitude effect as $-0.15\%/100\text{ m}$ based on the observed data of the Chinese Network of Isotopes in Precipitation. We estimated the precipitation $\delta^{18}\text{O}$ as -10.53% and -14.57% for EWG and LWG in the sampling site (1365m 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ during EWG (1951–2005) and LWG (1951–2004) are based on the $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}_s$ for EWG, but it is poor for LWG. These results demonstrate that the source water vapour signals in reconstructed source water $\delta^{18}\text{O}$ for EWG and LWG are different. First, earlywood $\delta^{18}\text{O}$ records more precipitation $\delta^{18}\text{O}$ information than the latewood $\delta^{18}\text{O}$. Additionally, earlywood $\delta^{18}\text{O}$ in the present study actually retains more temperature information, which can be explained by the fact that the fractionation of precipitation $\delta^{18}\text{O}$ is dominated by the instantaneous air temperature (Dansgaard, 1964). Second, water vapour sources providing precipitation during latewood development are more

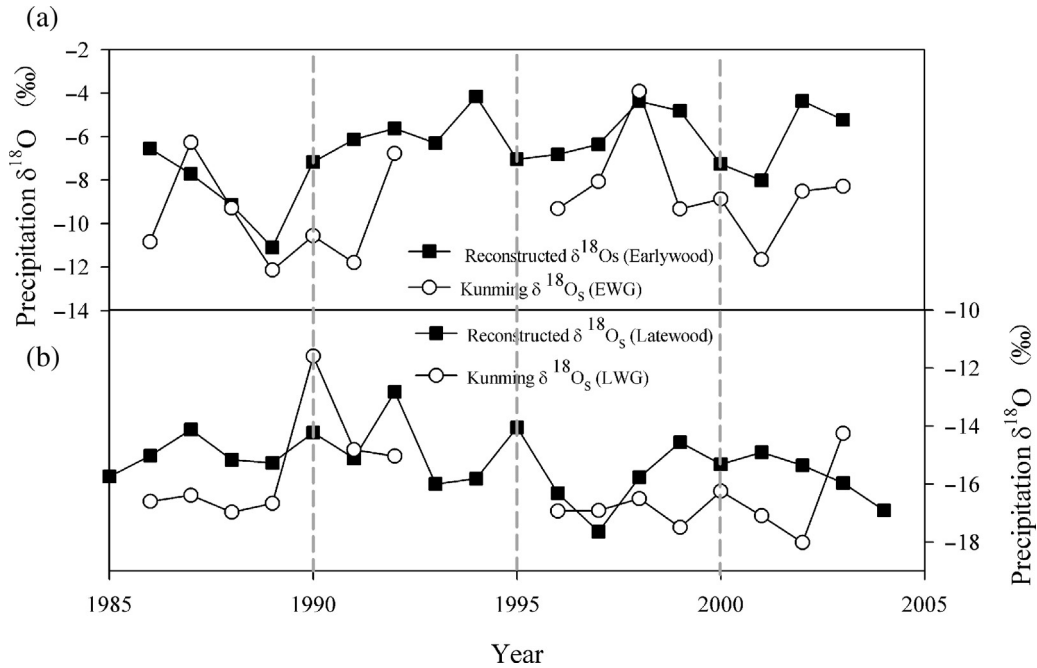


Fig. 5. Inter-annual variations in the observed precipitation $\delta^{18}\text{O}$ at the GNIP station closest to the study site (in Kunming) and the reconstructed precipitation $\delta^{18}\text{O}$ based on (a) earlywood $\delta^{18}\text{O}$ and (b) latewood $\delta^{18}\text{O}$. EWG and LWG represent the earlywood and LWG periods.

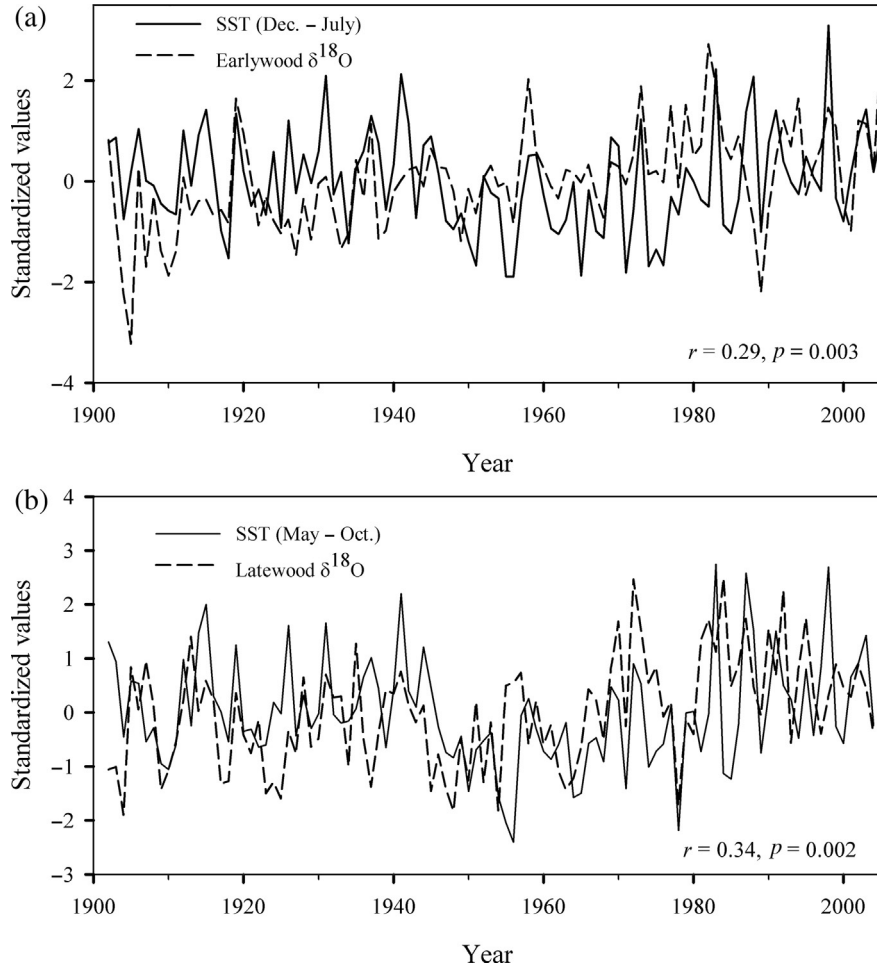


Fig. 6. (a) Comparison of inter-annual variations in earlywood (EW) $\delta^{18}\text{O}$ and the Indian Ocean SST (HadISST, from 50°E to 100°E , and from 10°S to 15°N) from the previous December to the current July, and smoothed values using a 10-year running average (black solid line for SST, and black dotted line for EW- $\delta^{18}\text{O}$). (b) Comparison of inter-annual variations in latewood (LW) $\delta^{18}\text{O}$ and the Indian Ocean SST (from 50°E to 100°E , and from 10°S to 15°N) from current May to current October, and smoothed values using a 10-year running average (black solid line for SST, and black dotted line for LW- $\delta^{18}\text{O}$). The y-axis for each parameter has been standardized to be dimensionless.

complex than those for earlywood development (Ding and Wang, 2008), resulting in a more complicated mosaic of information on precipitation $\delta^{18}\text{O}$ absorbed by the latewood $\delta^{18}\text{O}$.

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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ signal during latewood formation.

4. Discussion

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

The basic structure of wood anatomy is determined to a large extent by genetic factors (Fritts, 2001). However,

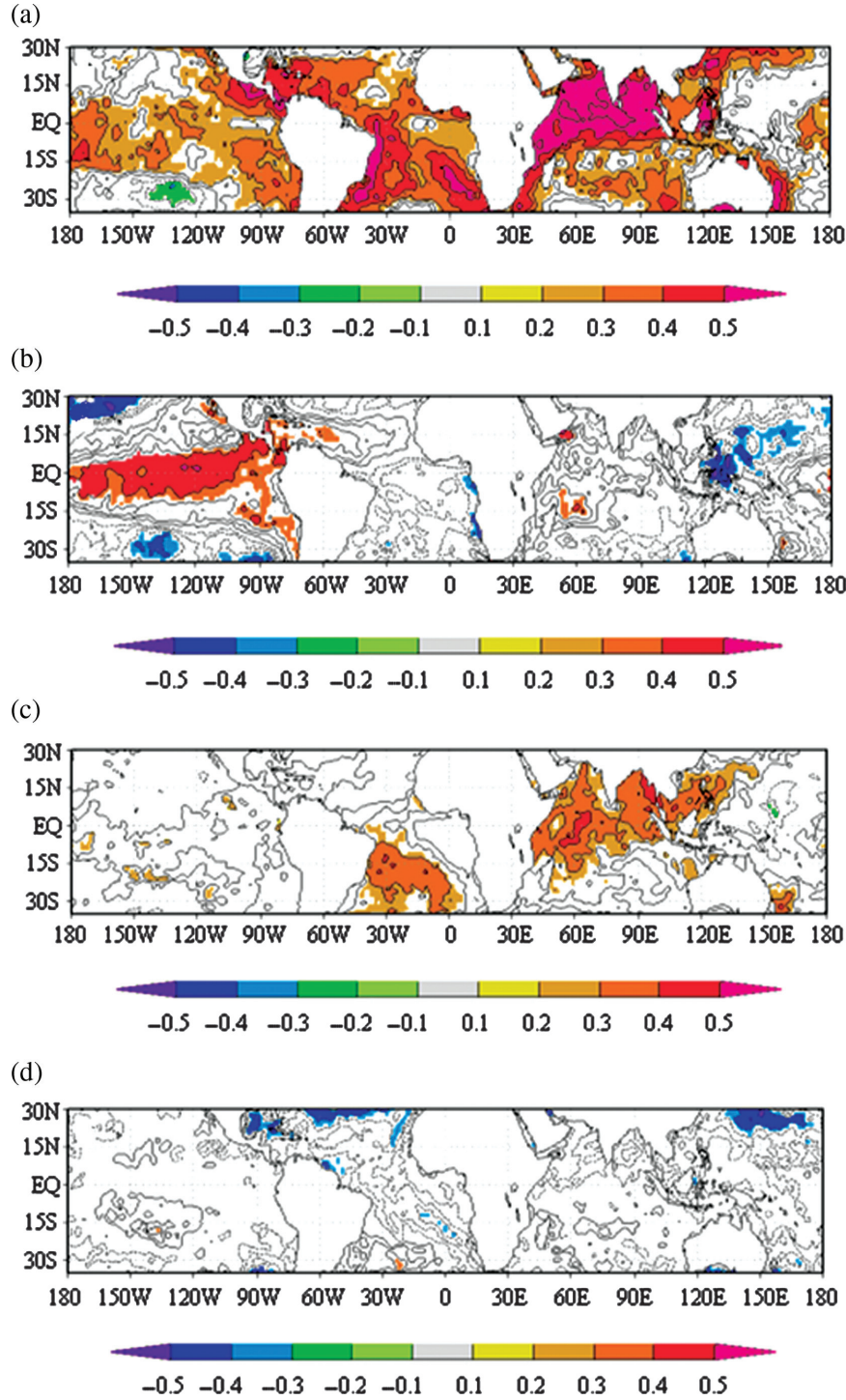


Fig. 7. Spatial distribution of the correlations between earlywood $\delta^{18}\text{O}$ (December to July), latewood $\delta^{18}\text{O}$ (May to October), and the HadISST grid data (<http://climexp.knmi.nl>) from 1902 to 1979 for (a) earlywood $\delta^{18}\text{O}$ and (c) latewood $\delta^{18}\text{O}$, and from 1980 to 2004 for (b) earlywood $\delta^{18}\text{O}$ and (d) latewood $\delta^{18}\text{O}$. 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 $\delta^{18}\text{O}$, 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ in northwestern China. The results of the present study show that separate earlywood and latewood analyses help differentiate climate factors controlling tree-ring $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ (Shu et al., 2005; Wright and Leavitt, 2006). In this study, the correlations between relative humidity and the earlywood and latewood $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ value in leaf water. It has been pointed out that tree-ring $\delta^{18}\text{O}$ is not a direct measure of precipitation $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ ($r = 0.53$, $n = 55$, $p < 0.001$; Table 3); for the latewood $\delta^{18}\text{O}$, 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 $\delta^{18}\text{O}$ enrichment in the soil water (through evaporation) and in organic matter synthesised by plants. Therefore, temperature becomes the dominant factor in determining tree-ring $\delta^{18}\text{O}$ during the EWG period.

4.2. Moisture source for earlywood and latewood $\delta^{18}\text{O}$

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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ values that are reflected in tree-ring $\delta^{18}\text{O}$ (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 $\delta^{18}\text{O}$ and these SSTs. Contrary to expectations, the correlation coefficient was positive (Fig. 6). The significant positive relationship between earlywood $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$. We compared the variability in the reconstructed source water $\delta^{18}\text{O}$ during the EWG and LWG periods with the ISM and EASM indices. The reconstructed source water $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ for EWG and the ISM/EASM indices are weak at the annual scale. The correlation coefficient between the reconstructed source water $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$, which covers the moisture signal and less of the water vapour information is retained in the earlywood $\delta^{18}\text{O}$ than in the latewood $\delta^{18}\text{O}$. However, the regression analysis demonstrates that the ISM affects earlywood $\delta^{18}\text{O}$ at a decadal scale (Table 4). Moreover, the reconstructed source water $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ is mainly affected by EASM, but the ISM may also have affected the latewood $\delta^{18}\text{O}$ 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

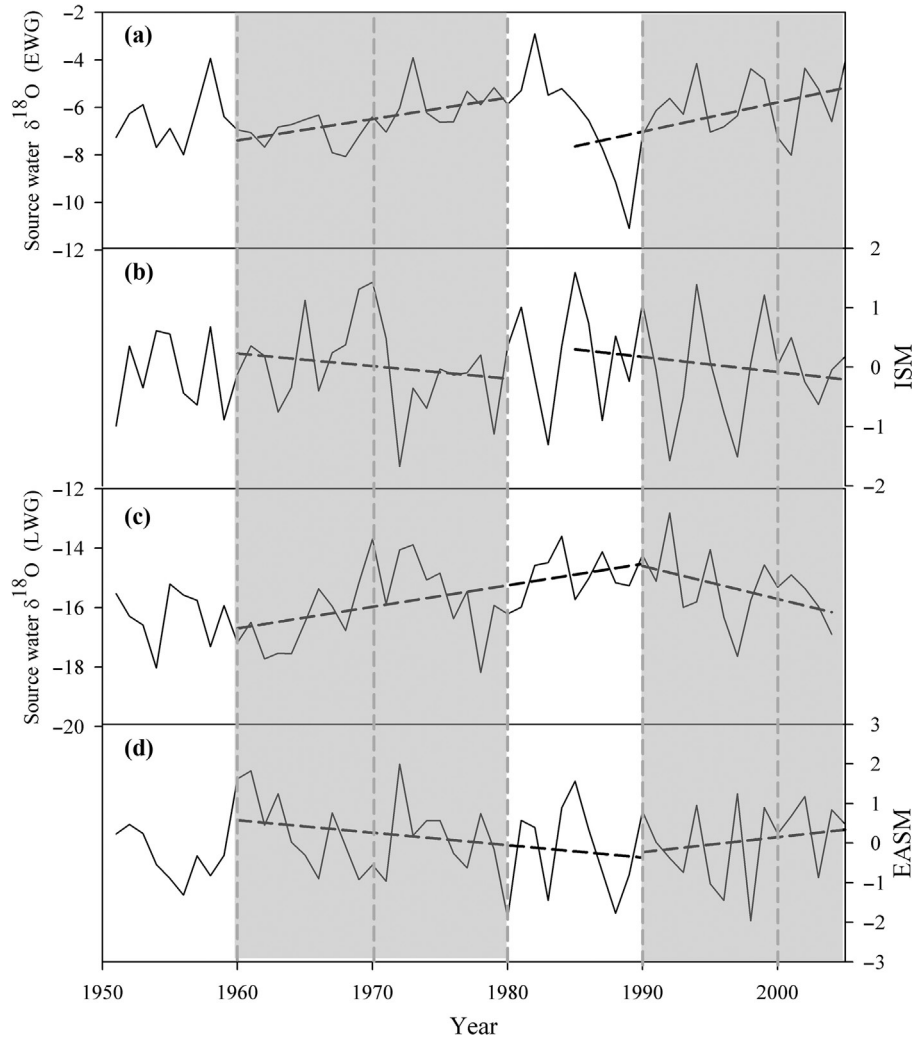


Fig. 8. Inter-annual variations in the source water $\delta^{18}\text{O}$ reconstructed from the (a) earlywood and (c) latewood $\delta^{18}\text{O}$ values from 1950 to 2005. (b) The ISM index and (d) the EASM index during the same period. EWG and LWG represent the earlywood and LWG periods, respectively. Dashed lines indicate linear increasing and decreasing trend at decadal scale during different periods.

Table 4. The coefficients of the linear regression for source water $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ for EWG	Slope	0.09	0.12	Source water $\delta^{18}\text{O}$ for LWG	Slope	0.07	−0.11
	r	0.58**	0.44*		r	0.53**	0.42
	p	0.006	0.04		p	0.002	0.12
ISM index	Slope	−0.02	−0.03	EASM index	Slope	−0.03	0.04
	r	0.17	0.18		r	0.28	0.18
	p	0.45	0.43		p	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.

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 ($\sim 25^\circ\text{N}$) 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 $\delta^{18}\text{O}$ for EWG and LWG (Fig. 9).

The spatial correlation analysis shows that the source water $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ and the SOI. Here we compared the relationship between source water $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ for EWG (Fig. 10a), whereas the correlation coefficients between source water $\delta^{18}\text{O}$ for LWG and SOI values were low (Fig. 10b). The significant relationship between source

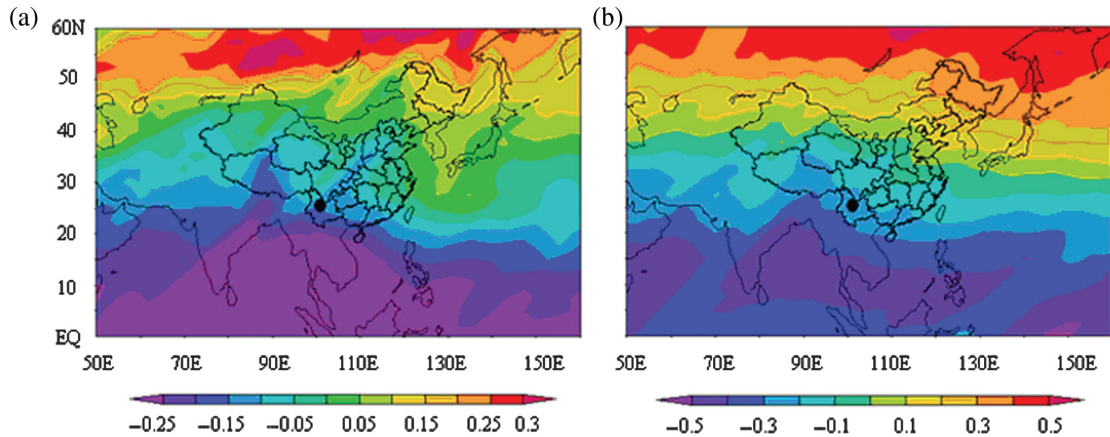


Fig. 9. Spatial distributions of correlations between the source water $\delta^{18}\text{O}$ and precipitable water vapour (<http://www.esrl.noaa.gov/>) from 1948 to 2005 for earlywood and from 1948 to 2004 for latewood. (a) current May to July for earlywood $\delta^{18}\text{O}$; (b) current May to October for latewood $\delta^{18}\text{O}$.

water $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ than that in latewood $\delta^{18}\text{O}$.

5. Conclusions

Earlywood and latewood $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ of tree rings in a moist-temperate region of southwestern China. In our study area, earlywood $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$. We reconstructed the source water $\delta^{18}\text{O}$ for earlywood and latewood formation period and found that the reconstructed variation of source water $\delta^{18}\text{O}$ from earlywood $\delta^{18}\text{O}$ correlates well with that of contemporaneous precipitation $\delta^{18}\text{O}$, while it is different for that from latewood $\delta^{18}\text{O}$. We conclude that earlywood and latewood $\delta^{18}\text{O}$ may derive from different water sources. Water vapour transported by ISM and EASM has influenced the latewood formation, and at a

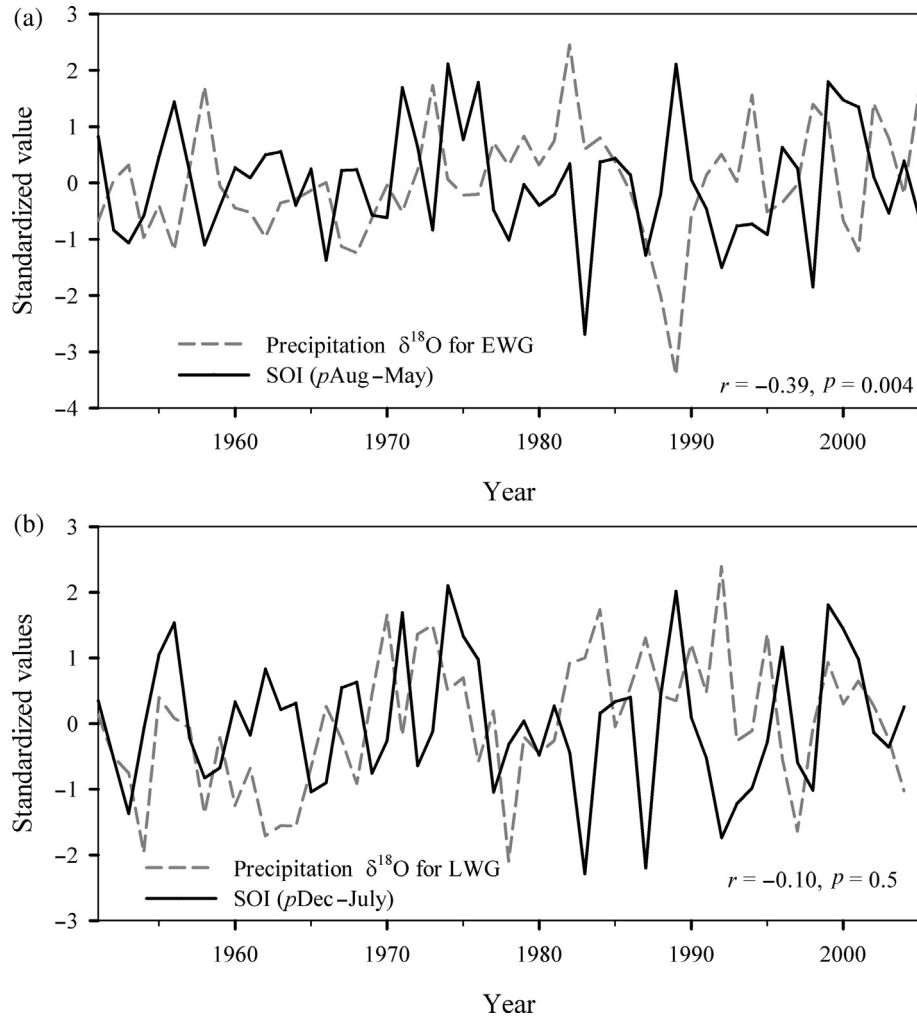


Fig. 10. (a) Comparison of inter-annual variations in source water $\delta^{18}\text{O}$ for EWG and the SOI from 1951 to 2005 and from 1902 to 2004. Months with a 'p' prefix indicate values from the previous year. (b) Comparison of inter-annual variations in source water $\delta^{18}\text{O}$ for LWG 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 $\delta^{18}\text{O}$ derives mainly from moisture carried by the ISM. The reconstructed source water $\delta^{18}\text{O}$ for EWG is more sensitive to variations in the SOI, indicating that the ENSO phenomenon can be detected in earlywood $\delta^{18}\text{O}$. The different response patterns of earlywood and latewood $\delta^{18}\text{O}$ 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.

6. Acknowledgements

This research was supported by the Knowledge Innovation Project of the Chinese Academy Sciences (KZCX2-YW-QN308), by the self-determination project of the State Key Laboratory of Cryospheric Sciences (SKLCS09-03), and by the National Natural Science Foundation of China (40871002, 41171167).

References

- Allan, R. J., Lindesay, J. A. and Reason, C. J. 1995. Multidecadal variability in the climate system over the Indian Ocean region during the Austral summer. *J. Clim.* **8**, 1853–1873.
- Allison, G. B., Gat, J. R. and Leaney, F. W. J. 1985. The relationship between deuterium and oxygen-18 delta values in leaf water. *Chem. Geol.* **58**, 145–156.
- Anderson, W. T., Bernasconi, S. M., McKenzie, J. A., Saurer, M. and Schweingruber, F. 2002. Model evaluation for reconstructing the oxygen isotopic composition in precipitation from tree ring cellulose over the last century. *Chem. Geol.* **182**, 122–137.
- Barbour, M. M., Andrews, T. J. and Farquhar, G. D. 2001. Correlations between oxygen isotope ratios of wood constituents of *Quercus* and *Pinus* samples from around the world. *Aust. J. Plant. Physiol.* **28**, 335–348.
- Borella, S. and Leuenberger, M. 1998. Reducing uncertainties in $\delta^{13}\text{C}$ analysis of tree-rings: pooling, milling and cellulose extraction. *J. Geophys. Res.* **103**, 19519–19526.
- Brabander, D. J., Keon, N., Stanley, R. H. R. and Hemond, H. F. 1999. Intra-ring variability of Cr, As, Cd, and Pb in red oak revealed by secondary ion mass spectrometry: implications for environmental biomonitoring. *PNAS* **96**(25), 14635–14640.
- Bretherton, C. S., Widmann, M., Dymnikov, V. P., Wallace, J. M. and Bladé, I. 1999. The effective number of spatial degrees of freedom of a time-varying field. *J. Clim.* **12**, 1990–2009.
- Clark, A. J., Cole, J. A. and Webster, P. J. 2000. Indian Ocean SST and Indian summer rainfall: predictive relationship and their decadal variability. *J. Clim.* **13**, 2503–2519.
- Cook, E. R. and Holmes, R. L. 1986. Users manual for Program ARSTAN. In: *Tree-ring Chronologies of Western North America: California, Eastern Oregon and Northern Great Basin* (eds. R. L. Holmes, R. K. Adams and H. C. Fritts). Chronology Series VI, Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona, pp. 50–60.
- Criss, R. E. 1999. Abundance and measurement of stable isotopes. In: *Principles of Stable Isotope Distribution* (ed. R. E. Criss). Oxford University Press, Oxford, p. 17.
- Dansgaard, W. 1964. Stable isotopes in precipitation. *Tellus* **16**, 436–468.
- D'Arrigo, R. D. and Jacoby, G. C. 1999. Northern North American tree-ring evidence for regional temperature changes after major volcanic events. *Clim. Change* **41**(1), 1–15.
- DeNiro, M. J. and Epstein, S. 1979. Relationship between the oxygen isotope ratios of terrestrial plant cellulose, carbon dioxide, and water. *Science* **204**, 51–53.
- Ding, Y. H. and Wang, Z. Y. 2008. A study of rainy seasons in China. *Meteorol. Atmos. Phys.* **100**(1–4), 121–138.
- Dongmann, G., Nurnberg, H. W., Forstel, H. and Wagener, K. 1974. On the enrichment of H_2^{18}O in the leaves of transpiring plants. *Radiat. Environ. Biophys.* **11**, 41–52.
- Downes, G. M. and Drew, D. M. 2008. Climate and growth influences on wood formation and utilisation. *Southern Forests*. **70**, 155–167.
- Epstein, S. and Yapp, C. J. 1976. Climatic implications of the D/H ratio of hydrogen in C-H groups in tree cellulose. *Earth Planet. Sci. Lett.* **30**, 252–261.
- Fan, Z. X., Bräuning, A. and Cao, K. F. 2008. Annual temperature reconstruction in the central Hengduan Mountains, China, as deduced from tree rings. *Dendrochronologia* **26**, 97–107.
- Fonti, P., Treydte, K., Osenstetter, S., Frank, D. and Esper, J. 2009. Frequency-dependent signals in multi-centennial oak vessel data. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **275**, 92–99.
- Fries, A. and Ericsson, T. 2009. Genetic parameters for early wood and latewood densities and development with increasing age in Scots pine. *Ann. For. Sci.* **66**(4), 404.
- Fritts, H. C. 2001. *Tree Rings and Climate*. Blackburn Press, Caldwell, NJ, p. 567.
- Gessler, A., Brandes, E., Buchmann, N., Helle, G., Rennenberg, H. and Barnard, R. L. 2009. Tracing carbon and oxygen isotopes signals from newly assimilated sugars in the leaves to tree-ring archive. *Plant Cell Environ.* **32**, 780–795.
- Green, J. W. 1963. Wood cellulose. In: *Methods in Carbohydrate Chemistry* (ed. R. L. Whistler), Academic Press, New York, pp. 9–12.
- Grießinger, J., Bräuning, A. and Schleser, G. H. 2005. Isotope studies along a high-elevation transect on the Tibetan Plateau. *TRACE* **3**, 117–123.
- Harzallah, R. and Sadourny, R. 1997. Observed lead-lag relationships between Indian summer monsoon and some meteorological variables. *Clim. Dynam.* **13**, 635–748.
- He, Q. T. 2000. The climatic ecology of main afforestation tree species in China. In: *China's Forestry Meteorology* (ed. Q. T. He), China Forestry Publishing House, Beijing, 273. (In Chinese)
- Hilasvuori, E., Berninger, F., Sonninen, E., Tuomenvirta, H. and Jungner, H. 2009. Stability of climate signal in carbon and oxygen isotope records and ring width from Scots pine (*Pinus sylvestris* L.) in Finland. *J. Quaternary Sci.* **24**(5), 469–480.

- Holmes, R. L. 1983. Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bull.* **43**, 69–78.
- Joseph, P. V. and Pillai, P. V. 1984. Air-sea interaction on a seasonal scale over north Indian Ocean Part I: Inter-annual variations of sea surface temperature and Indian summer monsoon rainfall. *Mausam* **35**, 323–330.
- Kagawa, A., Sugimoto, A. and Maximov, T. C. 2006a. ^{13}C pulse-labelling of photoassimilates reveals carbon allocation within and between tree rings. *Plant Cell Environ.* **29**, 1571–1584.
- Kagawa, A., Sugimoto, A. and Maximov, T. C. 2006b. Seasonal course of translocation, storage and remobilization of ^{13}C pulse-labeled photoassimilate in naturally growing *Larix gmelinii* saplings. *New Phytol.* **171**, 793–804.
- Kress A., Yong, G. H., Saurer, M., Loader, N. J., Siegwolf, R. T. and co-authors. 2009. Stable isotope coherence in the earlywood and latewood of tree-line conifers. *Chem. Geol.* **268**, 52–57.
- Larson, P. R. 1969. *Wood formation and the concept of wood quality*. Yale University School of Forestry, New Haven, Bulletin, p. 74.
- Laumer, W., Andreu, L., Helle, G., Schleser, G. H., Wieloch, T. and co-authors. 2009. A novel approach for the homogenization of cellulose to use micro-amounts for stable isotope analyses. *Rapid Commun. Mass Spectrom.* **23**, 1934–1940.
- Leavitt, S. W. 2008. Tree-ring isotopic pooling without regard to mass: no difference from averaging $\delta^{13}\text{C}$ values of each tree. *Chem. Geol.* **252**, 52–55.
- Leavitt, S. W. 2010. Tree-ring C-H-O isotope variability and sampling. *Sci. Total Environ.* **408**, 5244–5253.
- Leavitt, S. and Long, A. 1991. Seasonal stable-carbon isotope variability in tree rings: possible paleoenvironmental signals. *Chem. Geol.* **87**, 59–70.
- Lebourgeois, F. 2000. Climatic signals in earlywood, latewood and total ring width of Corsican pine from western France. *Ann. For. Sci.* **57**, 155–164.
- Li, Z. X., He, Y. Q., Pu, T., Jia, W. X., He, X. Z. and co-authors. 2010. Changes of climate, glaciers and runoff in China's monsoonal temperate glacier region during the last several decades. *Quatern. Int.* **218**, 13–28.
- Li, Z. H., Labbé, N., Driese, S. G. and Grissino-Mayer, H. D. 2011a. Micro-scale analysis of tree-ring $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ on α -cellulose spline reveals high-resolution intra-annual climate variability and tropical cyclone activity. *Chem. Geol.* **284**(1–2), 138–147.
- Li, Z. H., Leavitt, S. W., Mora, C. I. and Liu, R. M. 2005. Influence of earlywood-latewood size and isotope differences on long-term tree-ring $\delta^{13}\text{C}$ trends. *Chem. Geol.* **216**(3–4), 191–201.
- Li, Q., Nakatsuka, T., Kawamura, K., Liu, Y. and Song, H. M. 2011b. Regional hydroclimate and precipitation $\delta^{18}\text{O}$ revealed in tree-ring cellulose $\delta^{18}\text{O}$ from different tree species in semi-arid Northern China. *Chem. Geol.* **282**(1–2), 19–28.
- Li, J. P. and Zeng, Q. C. 2005. A new monsoon index, its interannual variability and relation with monsoon precipitation. *Clim. Environ. Res.* **10**(3), 351–365.
- Liñán, I. D., Gutiérrez, E., Helle, G., Heinrich, I., Andreu-Hayles, L. and co-authors. 2011. Pooled versus separate measurement of tree-ring stable isotopes. *Sci. Total Environ.* **409**, 2244–2251.
- Liu, X. H., An, W. L., Treydte, K., Shao, X. M., Leavitt, S. W. and co-authors. 2012. Tree ring $\delta^{18}\text{O}$ in southwestern China linked to variations in regional cloud cover and tropical sea surface temperature. *Chem. Geol.* **291**(6), 104–115.
- Liu, X. H., Shao, X. M., Liang, E. Y., Chen, T., Qin, D. H. and co-authors. 2009. Climatic significance of tree-ring $\delta^{18}\text{O}$ in the Qilian Mountains, northwestern China and its relationship to atmospheric circulation patterns. *Chem. Geol.* **268**(1–2), 147–154.
- Liu, Z. F., Tian, L. D., Chai, X. R. and Yao, T. D. 2008. A model-based determination of spatial variation of precipitation $\delta^{18}\text{O}$ over China. *Chem. Geol.* **249**, 203–212.
- Loader, N. J., Robertson, I., Barker, A. C., Switsur, V. R. and Waterhouse, J. S. 1997. An improved technique for the batch processing of small whole wood samples to α -cellulose. *Chem. Geol.* **136**, 313–317.
- Loader, N. J., Santillo, P. M., Woodman-Ralph, J. P., Rolfe, J. E., Hall, M. A. and co-authors. 2008. Multiple stable isotopes from oak trees in southwestern Scotland and the potential for stable isotope dendroclimatology in maritime climatic regions. *Chem. Geol.* **252**(1–2), 62–71.
- Majoube, M. 1971. Fractionnement en oxygène-18 et en deutérium entre l'eau et sa vapeur. *J. Chim. Phys.* **68**(7–8), 1423–1436.
- McCarroll, D. and Loader, N. J. 2004. Stable isotopes in tree rings. *Quaternary Sci. Rev.* **23**, 771–801.
- Miina, J. 2000. Dependence of tree-ring, earlywood and latewood indices of Scots pine and Norway spruce on climatic factors in eastern Finland. *Ecol. Model.* **32**, 259–273.
- Miller, D. L. 2005. A tree-ring oxygen isotope record of tropical cyclone activity, moisture stress, and long-term climate oscillations for the Southeastern U.S. Ph.D. thesis: Knoxville, University of Tennessee.
- Miller, D. L., Mora, C. I., Grissino-Mayer, H. D., Mock, C. J., Uhle, M. E. and co-authors. 2006. Tree-ring isotope records of tropical cyclone activity. *PNAS* **103**, 14294–14297.
- Offermann, C., Ferrio, J. P., Holst, J., Grote, R. and Siegwolf, R. 2011. The long way down – are carbon and oxygen isotope signals in the tree ring uncoupled from canopy physiological processes? *Tree Physiol.* **31**, 1088–1102.
- Pallardy, S. G. 2008. The woody plant body. In: *Physiology of Woody Plants* (ed. S. G. Pallardy). Academic press, London, 21–22.
- Pang, H. X., He Y. Q., Lu A. G., Zhao, J. D., Ning, B. Y. and co-authors. 2006. Variation in $\delta^{18}\text{O}$ of Lijiang precipitation in synoptic scale. *Chinese Sci. Bulletin.* **51**(10), 1218–1224.
- Parker, M. L. and Hensch, W. S. 1971. The use of Engelmann spruce latewood density for dendrochronological purposes. *Can. J. Forest. Res.* **1**(2), 90–98.
- Pillai, P. A. and Mohankumar, K. 2010. Effect of late 1970's climate shift on tropospheric biennial oscillation – role of local Indian Ocean processes on Asian summer monsoon. *Int. J. Climatol.* **30**, 509–521.
- Qin, J. and Yu, L. X. 2001. *Historical Data, Assessment and Consultation System about Meteorological Disasters in Yunnan Province*. China Meteorological Press, Beijing, pp. 64–65. (In Chinese)

- Reynolds-Henne, C. E., Siegwolf, R. T., Treydte, K. S., Esper, J., Henne, S. and co-authors. 2007. Temporal stability of climate-isotope relationships in tree rings of oak and pine (Ticino, Switzerland). *Global. Biogeochem. Cy.* **21**, GB4009.
- Roden, J. S. and Ehleringer, J. R. 2000. Hydrogen and oxygen isotope ratios of tree-ring cellulose for field grown riparian trees. *Oecologia* **123**, 481–489.
- Roden, J. S., Lin, G. and Ehleringer, J.R. 2000. A mechanistic model for interpretation of hydrogen and oxygen isotope ratios in tree-ring cellulose. *Geochimica et Cosmochimica Acta*. **64**(1), 21–25.
- Saurer, M., Borella, S. and Leuenberger, M. 1997. $\delta^{18}\text{O}$ of tree rings of beech (*Fagus silvatica*) as record of $\delta^{18}\text{O}$ of the growing season precipitation. *Tellus* **49B**, 80–92.
- Saurer, M., Cherubini, P. and Siegwolf, R. 2000. Oxygen isotopes in tree rings of *Abies alba*: The climatic significance of interdecadal variations. *J. Geophys. Res.* **105**, 12461–12470.
- Savard, M. M., Bégin, C., Smirnoff, A., Marion, J., Sharp, Z. and co-authors. 2005. Fractionation change of hydrogen isotopes in trees due to atmospheric pollutants. *Geochim. Cosmochim. Ac.* **69**, 3723–3731.
- Shi, C., Masson-Delmott, V., Risi, C., Eglin, T., Stievenard, M. and co-authors. 2011. Sampling strategy and climatic implications of tree-ring stable isotopes on the southeast Tibet Plateau. *Earth Planet Sci. Lett.* **301**, 307–316.
- Shu, Y., Feng, X., Gazis, C., Anderson, D., Faiia, A. and co-authors. 2005. Relative humidity recorded in tree rings: a study along a precipitation gradient in the Olympic Mountains, Washington, USA. *Geochimica et Cosmochimica Acta* **69**, 791–799.
- Sternberg, L., DeNiro, M. J. and Savidge, R. A. 1986. Oxygen isotope exchange between metabolites and water during biochemical reactions leading to cellulose synthesis. *Plant Physiol.* **82**, 423–427.
- Stokes, M. A. and Smiley, T. L. 1968. *An Introduction to Tree-Ring Dating*. The University of Chicago Press, Chicago.
- Treydte, K., Schleser, G. H., Helle, G., Winiger, M., Frank, D.C. and co-authors. 2006. The twentieth century was the wettest period in northern Pakistan over the past millennium. *Nature* **440**, 1179–1182.
- Vaganov, E., Schulze, E. D., Skomarkova, M., Knohl, A., Brand, W. and co-authors. 2009. Intra-annual variability of anatomical structure and $\delta^{13}\text{C}$ values within tree rings of spruce and pine in alpine, temperate and boreal Europe. *Oecologia* **161**(4), 729–745.
- Wang, B., Clemens, S. C. and Liu, P. 2003. Contrasting the Indian and East Asian monsoons: implications on geologic timescales. *Mar. Geo.* **201**, 5–21.
- Wang, B. and Lin, H. 2002. Rainy season of the Asian-Pacific summer monsoon. *J. Clim.* **15**, 368–398.
- Waterhouse, J. S., Switsur, V. R., Barker, A. C., Carter, A. H. C. and Robertson, I. 2002. Oxygen and hydrogen isotope ratios in tree rings: how well do models predict observed values? *Earth Planet Sci. Lett.* **201**, 421–430.
- Webster, P. J., Magana, V.O., Palmer, T. N., Shukla, J., Tomas, R. A. and co-authors. 1998. Monsoons: processes, predictability, and the prospects for prediction. *J. Geophys. Res.* **103**(7), 14451–14510.
- Webster, P. J. and Yang, S. 1992. Monsoon and ENSO: selectively interactive systems. *Q. J. Roy. Meteor. Soc.* **118**, 877–926.
- Weigl, M., Grabner, M., Helle, G., Schleser, G. H. and Wimmer, R. 2008. Characteristics of radial growth and stable isotopes in a single oak tree to be used in climate studies. *Sci. Total Environ.* **393**(1), 154–161.
- Woodley, E. J., Loader, N. J., McCarroll, D., Young, G. H. F., Robertson, I. and co-authors. 2012. Estimating uncertainty in pooled stable isotope time-series from tree-rings. *Chem. Geol.* **294–295**, 243–248.
- Wright, W. E. and Leavitt, S. W. 2006. Boundary layer humidity reconstruction for a semiarid location from tree ring cellulose $\delta^{18}\text{O}$. *J. Geophys. Res.* **111**, D18105.
- Wright, W.E., Long, A., Comrie, S.W., Leavitt, S.W., Cavazos, T. and co-authors. 2001. Monsoonal moisture sources revealed using temperature, precipitation, and precipitation stable isotope timeseries. *Geophys. Res. Lett.* **28**, 787–790.
- Xu, H., Hong, Y. T., Hong, B., Zhu, Y. X. and Wang, Y. 2009. Influence of ENSO on multi-annual temperature variations at Hongyuan, NE Qinghai-Tibet plateau: evidence from $\delta^{13}\text{C}$ of spruce tree rings. *Int. J. Climatol.* **30**, 120–126.
- Yakir, D., Deniro, M. J. and Ephrath, J. E. 1990. Effects of water stress on oxygen, hydrogen and carbon isotope ratios in two species of cotton plants. *Plant Cell Environ.* **13**, 949–955.
- Zhang, S.Y. 1997. Variations and correlations of various ring width and ring density features in European oak: implications in dendroclimatology. *Wood. Sci. Technol.* **31**, 63–72.
- Zhang, R. H., Sumia, A. and Kimoto, M. 1996. Impact of El Niño on the East Asian monsoon: a diagnostic study of the 86/87 and 91/92 events. *J. Meteor. Soc. Jpn.* **74**, 49–62.
- Zhao, R. Z. 1997. A study of the physico-geographical regionalization in Southwest region. *J. Southwest China Normal Univ.* **22**(2), 193–198. (In Chinese).