Sampling strategy and climatic implications of tree-ring stable isotopes on the southeast Tibetan Plateau

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ABSTRACT

We explore the potential of tree-ring cellulose $\delta^{18}O$ and $\delta^{13}C$ records for reconstructing climate variability in the southeast Tibetan Plateau. Our sampling strategy was designed to investigate intra and inter-tree variability, and the effects of the age of tree on $\delta^{18}O$ variation. We show that intra-tree $\delta^{13}C$ and $\delta^{18}O$ variability is negligible, and inter-tree coherence is sufficient to build robust tree-ring $\delta^{18}O$ or $\delta^{13}C$ chronologies based on only four trees. There is no evidence of an age effect regarding $\delta^{18}O$, in contrast with tree-ring width. In our warm and moist sampling site, young tree $\delta^{13}C$ is not clearly correlated with monthly mean meteorological data. Tree-ring $\delta^{18}O$ appears significantly anti-correlated with summer precipitation amount, regional cloud cover, and relative humidity. Simulations conducted with the ORCHIDEE land surface model confirm the observed contribution of relative humidity to tree cellulose $\delta^{18}O$, and explain the weak correlation of $\delta^{13}C$ with climate by the non-linear integration linked with photosynthesis. Altogether, the tree-ring cellulose $\delta^{18}O$ is shown to be a promising proxy to reconstruct regional summer moisture variability prior to the instrumental period.

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1. Introduction

The Indian summer monsoon (ISM) controls the precipitation amounts in a vast area of tropical and subtropical Asia. Its large inter-annual and decadal variability has profound influence on the spatiotemporal distribution of water resource and human activities (Kale et al., 1994; Sinha et al., 2007). The eastern trajectory of ISM, originating from the Bay of Bengal, carries moisture into southeast Tibetan Plateau (TP) along the Brahmaputra River Valley (Hren et al., 2009). The ISM activity affects the isotopic composition of precipitation through the "amount effect" (Araguas-Araguas et al., 1998), with more depleted precipitation $\delta^{18}O$ for heavier rainfall in south TP (Tian et al., 2001, 2003). Precipitation $\delta^{18}O$ can also reflect changes in moisture origin or air mass trajectories (Breitenbach et al., 2010; Le Grande and Schmidt, 2009; Sturm et al., 2010; Tian et al., 2007). The inter-annual and long-term variability of precipitation $\delta^{18}O$ has indeed been suggested to be controlled by changes in regional water vapor transport rather than local processes (Kurita et al., 2009). Past monsoon variability has therefore been investigated using stable isotopes archived in various paleoclimate proxies such as ice-cores, stalagmites and lake sediments (Burns et al., 2003; Cai et al., 2006; Duan et al., 2004; Dykoski et al., 2005; Fleitmann et al., 2003; Ji et al., 2005; Neff et al., 2001; Sinha et al., 2005). But tree-ring isotopic studies are still scarce in the TP.

Temperature and moisture reconstructions have been produced in the southeast TP using tree-ring width records (Cook et al., 2010; Liang et al., 2009; Yang et al., 2010). Here, we explore the moisture information archived in tree-ring stable isotopes in this region. Tree-ring $\delta^{18}O$ exhibits advantages to tree-ring width for long-term climate reconstructions, such as weaker impacts of individual tree physiological character (Raffalli-Delerce et al., 2004), and limited effect of age and auto-correlation (Liu et al., 2008; Liu et al., 2009; Masson-Delmotte et al., 2005; McCarroll and Loader, 2004; Tsuji et al., 2006).

Tree-ring $\delta^{18}O$ has already demonstrated its potential to reconstruct either the isotopic composition of precipitation (Danis et al., 2006; Kress et al., 2010; Liu et al., 2008; Robertson et al., 2001) or various climate variables such as growing season temperature or water stress in

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temperate areas (McCarroll and Loader, 2004). Tree-ring cellulose $\delta^{18}O$ is primarily determined by the isotopic composition of source water and secondly by the evaporative enrichment in leaf water. The soil water signal is provided by the integration of precipitation isotopic composition through soil hydrology, and used as source water without fractionation through the root system (Roden et al., 2000). The evaporative enrichment of leaf water is related to the ratio of ambient to intercellular vapor pressures (Barbour et al., 2001; Cuntz et al., 2007). In the southeast TP, April–October precipitation $\delta^{18}O$ variability is mainly affected by precipitation amount at the event basis with an event-scale observed slope of $-0.34‰/mm$ ($R = -0.26$, $P = 0.047$) (Gao et al., 2010), suggesting a good potential for past precipitation reconstruction if tree-ring $\delta^{18}O$ variability is related to precipitation $\delta^{18}O$ variability.

Tree-ring cellulose $\delta^{13}C$ is controlled by the ratio of intercellular to ambient CO_2 concentrations, imprinting complementary climate signals (Farquhar et al., 1989). At dry sites, $\delta^{13}C$ variability is determined by humidity and soil water, which influence leaf stomatal conductance and discrimination against $^{13}CO_2$ during photosynthesis. At wet sites, $\delta^{13}C$ variability is dominated by irradiance and temperature, the former having direct effect on photosynthetic rate, while the impacts of the later is indirect (McCarroll and Loader, 2004), especially under independent and relatively stable canopy temperature (Helliker and Richter, 2008; Sternberg, 2009). Although both $\delta^{18}O$ and $\delta^{13}C$ isotopes can be used as indicators of past climate variation, uncertainties exist in assessing 1) the intra and inter-tree variability 2) effects due to the age of trees, and 3) their relationships with climate variables.

For tree-ring $\delta^{13}C$, earlier studies have shown that analyzing four trees with four cores per tree is adequate to represent a population signal, and that pooling trees produces results similar to those obtained by averaging individual tree records (Leavitt, 2008; Leavitt and Long, 1984). Such pooling strategy was also widely used in tree-ring $\delta^{18}O$ studies, although a large inter-tree dispersion was reported (Raffalli-Delerce et al., 2004; Treydte et al., 2006). No consensus is yet available on the adequate number of trees to obtain a robust record, due to lack of inter-tree variability study. A few studies reported the influence of physiological age on tree-ring $\delta^{18}O$ (Marshall and Monserud, 2006; Treydte et al., 2006), while in other cases no age effect was detected (Etien et al., 2008, 2009; Liu et al., 2008; Masson-Delmotte et al., 2005; Raffalli-Delerce et al., 2004). Previous studies have shown a temperature-driven tree-ring $\delta^{18}O$ in the dry northeast TP edge (Liu et al., 2009), and a monsoon precipitation driven tree-ring $\delta^{18}O$ in north Nepal (Sano et al., 2010). However, little is known on the climatic drivers of tree-ring $\delta^{18}O$ in the inner TP.

In this study, we explore the potential of extracting climate signals from stable isotopes in spruce tree rings of the southeast TP. Our sampling and analysis strategy was designed to assess the intra and inter-tree variability, the effectiveness of pooling a few number of trees, and the effect of age on the oxygen isotope composition of cellulose. With a focus on the past 50 years, spanning the local instrumental period, our study allows correlation analyses and identification of the relationships between the isotopic composition of cellulose, local climate parameters, and ISM variability.

2. Material and method

2.1. Study area

The tree-ring materials used in this study were collected in Gangcun Natural Forest Reserve (95.55°E, 29.87°N, 2759 m), an area sensitive to summer monsoon influence, which is located 20 km west of Bomi city and 60 km from the turning point of the Brahmaputra River (Fig. 1). According to the 1961–2005 meteorological record from Bomi weather station (95.77°E, 29.87°N, 2743 m), the annual mean temperature is 8.7 °C and total annual precipitation is 696 mm, most

of which falls between March and October with a large inter-annual variability (Fig. 2). Over this time period, total annual precipitation and mean annual temperature exhibit increasing trends of 7 mm/yr ($R^2 = 0.25$, $P < 0.01$, $n = 50$) and 0.023 °C/yr ($R^2 = 0.46$, $P < 0.01$, $n = 50$).

Linzhi spruce (Picea likiangensis var. linzhiensis) is the dominant sub-alpine evergreen conifer in southeast Tibet. This species is usually found in moist areas with mean temperatures ranging from -6 °C to 16 °C in the coldest/warmest months (Song et al., 2004).

2.2. Tree-ring sampling and cross-dating

Field work was conducted in June 2007. Trees selected for sampling were in a mature forest stand growing on the hillside with a moderate slope and thick soil depth. Using an increment borer of 5.14 mm inner diameter, core samples were collected at breast height from a young and an old groups of trees. The average ages of old and young trees are respectively of 215 and 101 years. For the group of "young" trees whose diameters range between 40 and 60 cm, four trees (coded as Y1 to Y4) were sampled with four cores per tree along opposite directions. For the group of "old" trees whose diameters range between 60 and 80 cm, one core per tree was collected in 27 trees (coded as O1–O27). Most of the cores reached the pith of the tree.

Core samples were air dried and polished with progressively finer sandpaper until rings were clearly visible. Tree-ring widths (TRW) were measured using the videoment® system with a resolution of 0.01 mm, and cross-dated under microscope by visual inspection of the ring-width pattern. The cross-dated tree-ring series were quality-checked using the COFECHA software (Holmes, 1998). A standard TRW chronology of old trees was developed with the Arstan40c software using the detrending method of 50% response cutoff at half of the series length.

2.3. Tree selection for isotopic analyses and pooling strategies

All the 16 core samples of the four young trees and 11 core samples selected from the 27 old trees (having regular ring boundaries and no missing rings) were used for isotopic analysis (Table 1).The mean age of the selected 11 trees is 241 years. Each ring of these samples in the period 1956–2005 was cut using a scalpel blade under a binocular microscope. Because the boundary between early and late wood is unclear, whole rings were used in the cutting procedure. Individual isotopic analyses could not be conducted on each of these 1350 tree-ring samples because of 1) the requirement for a minimum cellulose mass for replicate isotopic analyses (around 0.5 mg for both $\delta^{18}O$ and $\delta^{13}C$) and 2) the analytical capacity.

We randomly selected 10 years, i.e., 1958, 1960, 1966, 1972, 1979, 1980, 1984, 1991, 1993 and 1998, for detailed examination of intra and inter-tree $\delta^{18}O$ and $\delta^{13}C$ variability. For young trees, core by core measurements were conducted for three years (1960, 1979, and 1998) using the samples that have sufficient wood material. For the remaining seven years, all the four cores of the same young tree were grouped and tree by tree $\delta^{18}O$ and $\delta^{13}C$ measurements were conducted. For the same 10 years, tree by tree $\delta^{18}O$ analyses were conducted for a group of 5 randomly selected trees within the 11 old trees; the remaining 6 old tree samples were pooled. For the remaining 40 years in the interval 1956–2005, two series of $\delta^{18}O$ measurements were conducted, i.e., the pooled cores from the 4 young trees, and the pooled cores from the 11 old trees. $\delta^{13}C$ measurement was not conducted for old trees. Altogether, this represents 197 tree-ring samples (29 and 78 for the intra-tree and inter-tree analyses respectively, and 90 for the pooled samples) (Table 1).
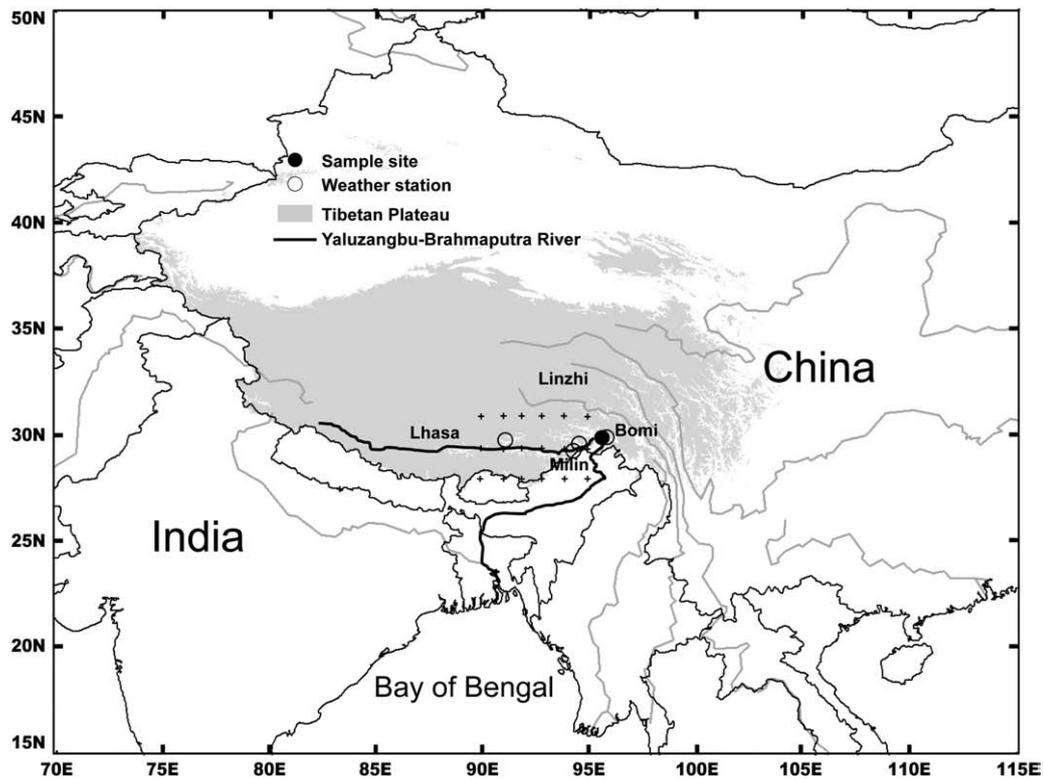
Fig. 1. Map of the study area showing the location of the sampling site and weather station. The shaded area depicts elevations above 3500 m. The crosses describe the grid of the CRU cloud data (28–31°N, 90–95°E) used in this study, The old tree δ^{18}O is significantly correlated with summer cloudiness in this large area (25–34°N, 85–100°E; $R < -0.4$, $P < 0.05$, $n = 46$).

2.4. Isotopic measurements

For each tree-ring sample, the wood was milled with an ultra-centrifugal crusher (ZM 100) to a fineness of <0.08 mm, and cellulose was extracted according to a chemical procedure derived from Leavitt and Danzer (1993). The δ^{18}O and δ^{13}C of the young tree group were measured with a CarloErba® elementary analyzer (EA) attached to a Finnigan MAT252 mass spectrometer (at LSCE, Gif/Yvette, France) according to the procedure described in Raffalli-Delerce et al. (2004).

With the target to have more precise δ^{18}O measurements, a high temperature analyzer (TC/EA) was acquired at LSCE and the experimental protocol showed better reproducibility. It was decided to run δ^{18}O measurements on the old tree samples using this new method. In order to compare the result of EA and TC/EA methods, twenty δ^{18}O samples of young trees were also processed with TC/EA.

0.09–0.15 mg of cellulose was loaded in tin-foil cups for carbon isotope ratios analysis, and respectively 0.2–0.3 mg and 0.1–0.2 mg in silver-foil cups for oxygen isotopic analysis using EA and TC/EA methods. The measured values were corrected from an internal laboratory reference of cellulose (Whatman® CC31) which had been inter-compared by the European laboratories involved in the ISONET European project (-25.54‰ for δ^{13}C and $+31.85$‰ for δ^{18}O)
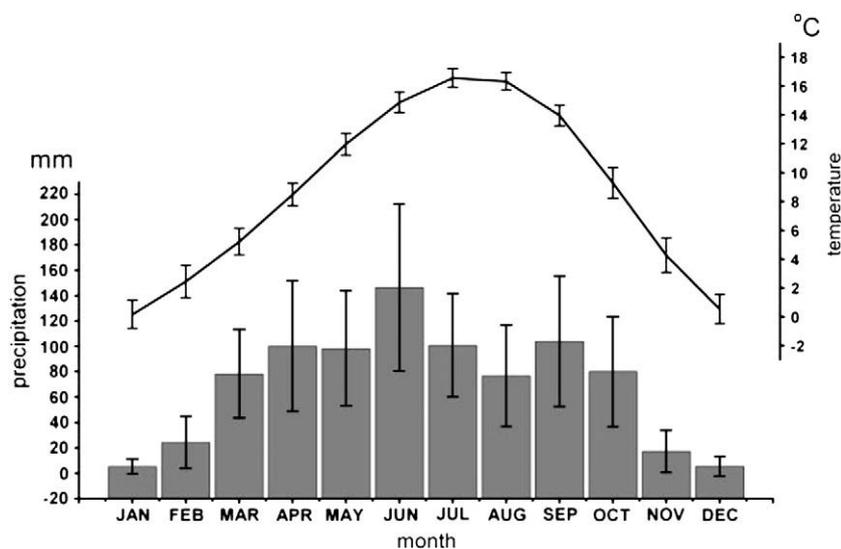

Fig. 2. Monthly mean and inter-annual standard deviation of temperature (°C) and precipitation (mm) in the study area during 1961–2005.

Table 1
Isotope measurement strategies for intra-tree, inter-tree and pooling samples from selected individual young (Y) and old (O) trees.

	Tree samples	Years
Intra-tree analyses	Y1 (cores 1–2), Y2 (cores 1–2), Y3 (cores 1–4)	1960
	Y1 (cores 1–3), Y2 (cores 1–4), Y3 (cores 1–4)	1979
	Y1 (cores 1–4), Y2 (cores 1–3), Y3 (cores 1–3)	1998
Inter-tree analyses	Y1, Y2, Y3, Y4	1958, 1966, 1972, 1980, 1984, 1991, 1993
	O3, O4, O8, O9, O10	1958, 1960, 1966, 1972, 1979, 1980, 1984, 1991, 1993, 1998
Pooled samples	O1, O2, O5, O6, O7, O11	1958, 1960, 1966, 1972, 1979, 1980, 1984, 1991, 1993, 1998
	Y1–Y4	1956–2005 excluding the 10 years
	O1–11	1956–2005 excluding the 10 years

(Boettger et al., 2007). Along the sequence of analyses, the isotopic composition of CC31 was measured every 3 samples.

The standard deviations (SD) obtained from the measurement of the isotopic composition of 10 consecutive CC31 standards (0 to 2 values being rejected) was typically: $\pm 0.25‰$ for $\delta^{18}O$ and $\pm 0.10‰$ for $\delta^{13}C$. Samples were analyzed when the operating conditions were good enough to produce such repeatability. The analysis of carbon and oxygen isotopes of each sample was repeated at least once and up to four times. Repeated measurements were conducted so that outlier measurements were rejected and final standard deviations of $\pm 0.20‰$ for $\delta^{18}O$ and $\pm 0.10‰$ for $\delta^{13}C$ were obtained.

2.5. Tree ring and climate analysis

Correlation analysis was conducted to identify the relationship between tree-ring isotopes and climate variables. The climate variables used in the analysis include monthly mean temperature, relative humidity and total monthly precipitation obtained from the Bomi weather station. Because water stress and cloudiness are expected to affect photosynthesis and tree growth, we included the gridded Palmer Drought Severity Indices (PDSI) (Dai et al., 2004) and regional cloud cover estimates over 28–31°N, 90–95°E (New et al., 2000) in our analysis. We also examined local cloudiness information available over 22 years (1984–2005) from the Bomi meteorological observations, and from satellite data (International Satellite Cloud Climatology Project), available with a resolution of $2.5 \times 2.5°$ (Rossow and Schiffer, 1999) The ISCCP D2 data were obtained from the International Satellite Cloud Climatology Project web site http://isccp.giss.nasa.gov maintained by the ISCCP research group at the NASA Goddard Institute for Space Studies, New York. For PDSI and ISCCP D2, the data of nearest grid to sampling site is extracted. The Indian precipitation data was downloaded from http://www.tropmet.res.in/ and the atmosphere and ice core CO_2 $\delta^{13}C$ data were obtained from Friedli et al. (1986) and Francey et al. (1995, 1999).

2.6. Land surface simulations using the ORCHIDEE-iso model

To quantify the effects of the processes in the soil–stem–atmosphere continuum, we performed offline simulations with the ORCHIDEE-iso land surface model (Ducoudre et al., 1993; Krinner et al., 2005), a component of the IPSL climate model (Marti et al., 2005), in which water stable isotopes have been implemented (Risi et al., 2010a). The model represents water and isotopes transfers between two layers of soil, the vegetation and the atmosphere. Fractionation is assumed during bare soil evaporation and leaf water enrichment is diagnosed using the Craig and Gordon equation (Craig and Gordon, 1965). Cellulose $\delta^{18}O$ is

calculated with the productivity-weighted leaf water and the soil water $\delta^{18}O$ using the formula developed by Anderson et al. (2002):

$$\delta^{18}O_{cellulose} = f \times \delta^{18}O_{sw} + (1-f) \times \delta^{18}O_{lw} + \varepsilon \tag{1}$$

Where f is the mixing factor and is set to 0.42 to optimize the average simulated cellulose $\delta^{18}O$. $\delta^{18}O_{sw}$ and $\delta^{18}O_{lw}$ are the soil water and leaf water $\delta^{18}O$ respectively. is the fractionation factor during cellulose formation and is set to 27‰ (Deniro and Epstein, 1979). The carbon isotope discrimination during leaf photosynthesis ($\Delta^{13}C$) is calculated according to the formulation described by Farquhar et al. (1982):

$$\Delta^{13}C = a + (b-a) \times C_i / C_a \tag{2}$$

where a ($= 4.4‰$) is the fractionation against $^{13}CO_2$ during the diffusion through stomatal cavity and leaf boundary layer, b ($= 27‰$) is the fractionation during the carboxylation step by Rubisco, C_i is the leaf internal CO_2 concentration and C_a is the atmospheric CO_2 concentration.

ORCHIDEE is forced by meteorological observations every 6 h and by the mean seasonal cycle of precipitation and vapor $\delta^{18}O$ extracted from a zoomed simulation over Tibet by the LMDZ-iso general circulation model (Gao et al., 2010; Risi et al., 2010b) averaged over 2005–2007. In our simulation, the precipitation and vapor $\delta^{18}O$ thus do not vary at the inter-annual scale, though, in reality, this may be an important source of cellulose $\delta^{18}O$ variations. We added 7.5‰ to the precipitation and vapor $\delta^{18}O$ to take into account the lower elevation of the observation site (2759 m) compared to that in LMDZ (4650 m), using the regional slope of $\delta^{18}O$ versus elevation (4‰/km) (Gao et al., 2010). The vegetation is assumed to be boreal needle leaf evergreen covering 98% of the surface, and bare soil covering 2%. The simulation covers the period 1961–2002, after a 5-year spin-up using the forcing condition in 1961. For comparison with annual tree-ring data, the isotopic compositions of cellulose are calculated as productivity-weighted averages of the half-hourly model outputs for both $\delta^{13}C$ and $\delta^{18}O$. This calculation does not include use of previous years reserves that may be an important factor regarding $\delta^{13}C$ variability (Damesin and Lelarge, 2003; Eglin et al., 2010; Helle and Schleser, 2004).

3. Results and discussion

3.1. Tree-ring width chronology

The tree-ring width (TRW) of all trees used for isotopic analysis is shown in Appendix (Suppl. Fig. 1). The standard chronology constructed with the 27 old trees is also displayed. Supplementary Table 1 shows the basic statistics of the tree-ring and meteorological records. Both the TRW and chronology indices (TRWi) show considerable auto-correlation. We also calculated the statistics of old trees (1821–1870) when they were roughly the same age as the young trees today (1956–2005). The mean TRW of the old trees (1821–1870) is significantly lower than for young trees (1956–2005), with similar standard deviation and auto-correlation (Suppl. Table 1).

3.2. Calibration of TC/EA and EA

Twenty samples of young trees were analyzed for $\delta^{18}O$ using both TC/EA and EA. The data are strongly correlated ($R^2 = 0.66$, $P < 0.01$, $n = 20$) (Fig. 3). The mean $\delta^{18}O$ measured with TC/EA is lower than that obtained with EA (25.31‰ with TC/EA versus 27.82‰ with EA) and the TC/EA signal shows a larger variability than the EA one (standard deviation of 1.16‰ for TC/EA compared with 0.83‰ for EA). These systematic differences have been confirmed while analyzing oak samples in the LSCE laboratory and while performing inter-laboratory comparisons (Boettger et al., 2007) (N. Loader, pers. comm.).
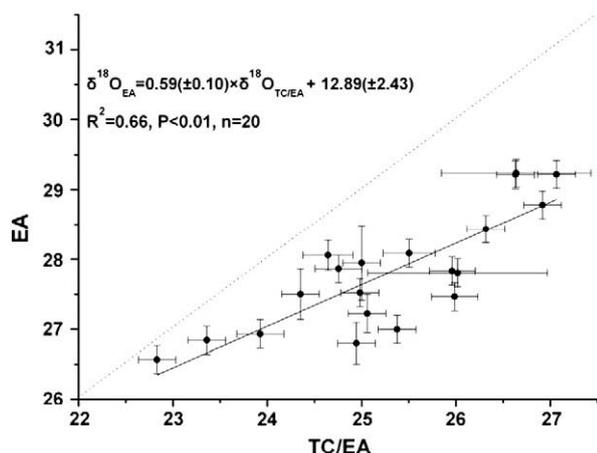
Fig. 3. Comparison of the $\delta^{18}O$ values of the twenty cellulose samples analyzed by TC/EA (x-axis) and EA (y-axis). Error bars display the experimental uncertainty.

In order to compare the $\delta^{18}O$ data obtained on young and old trees respectively by EA and TC/EA, we have used the linear fit between EA and TC/EA data acquired on the 20 samples to produce a regression which will be used for EA-TC/EA conversion. The equation of this fit is:

$$\delta^{18}O_{EA} = 0.59(\pm0.10) \times \delta^{18}O_{TC/EA} + 12.89(\pm2.43) \tag{3}$$

The R^2 and degree of freedom are 0.68 and 18 respectively. The RMSE (Root Mean Square Error) of $\delta^{18}O_{EA}$ is 0.48, more than twice the precision of $\delta^{18}O_{TC/EA}$. This calibration slope was further tested using other LSCE tree-ring samples and appears to be stable within a large cellulose $\delta^{18}O$ range.

3.3. Intra-tree and inter-tree variability of tree-ring $\delta^{18}O$

The intra-tree $\delta^{18}O$ (EA) test of young trees (Y1, Y2, and Y3) shows that the mean intra-tree variability (standard deviation) is 0.28‰ in these three years (1960, 1979 and 1998) (Suppl. Table 2). The intra-tree deviation is therefore ~ twice less than the inter-tree standard deviation and the inter-annual standard deviation observed on the same samples (typically 0.5‰), and hardly detectable with respect to the analytical uncertainties. This indicates that the $\delta^{18}O$ composition of the tree-ring cellulose can be considered as homogeneous within one given tree. These results suggest that pooling several cores per tree is a good sampling strategy, which provides more material for analyses without adding noise. Our findings are consistent with previous studies on sample replication and pooling for $\delta^{13}C$ (Borella et al., 1998; Leavitt, 2008; Leavitt and Long, 1984; McCarroll and Loader, 2004; Treydte et al., 2001).

The inter-tree $\delta^{18}O$ variability is shown in Figure 4a and b. The mean inter-tree correlation coefficients are 0.66 and 0.61 ($n = 10$, 4 and 5 series respectively) for young and old trees $\delta^{18}O$ respectively. These results are comparable with the same test for tree-ring $\delta^{18}O$ in north Pakistan (mean inter-tree correlation $R = 0.62$) (Treydte et al., 2006). If we consider that the signal is robust when the Expressed Population Signal (EPS) is above 0.85 (Wigley et al., 1984), then we conclude that four trees with one core per tree are sufficient to construct a robust $\delta^{18}O$ record. Despite the overall coherency, differences are observed between the individual old tree $\delta^{18}O$ data which may alter the representativity of a mean signal obtained from too few trees (Fig. 4b). This is further investigated in the next paragraph.

Finally, for old trees $\delta^{18}O$, we have compared the mean value of the five individual trees with that of the pooled samples (Fig. 4c). Although pooling trees is expected to generate bias due to the

difference in cellulose amount of each tree, the correlation coefficient between the averaged and the pooled measurements over the 10 years examined is 0.9 ($P < 0.01$, $n = 10$) The differences in the mean value and standard deviations (0.18‰ and 0.11‰) only account for 0.4–0.6% of the old trees $\delta^{18}O$ (TC/EA), and remain lower than the analytical precision ($\pm 0.20‰$). Our results suggest very limited impacts of the pooling method, supporting the hypothesis that pooling a few trees can produce nearly the same inter-annual $\delta^{18}O$ variability as averaging the individual records. This is consistent with the similar test conducted on cellulose $\delta^{13}C$ (Leavitt and Long, 1984). In the next sections, we therefore use two stacked records, combining all the available measurements, one from the old trees, and another from the young trees.

3.4. Age effects on cellulose $\delta^{18}O$

We compared the two stacked cellulose $\delta^{18}O$ records from the young and old trees (Fig. 5). With a mean age difference of 140 years, the two records are significantly correlated ($R^2 = 0.31$, $p < 0.01$, $n = 50$). Taking the TC/EA–EA correction (Eq. (3)) into account, the $\delta^{18}O$ of old and young trees have close mean values (resp. 25.24‰ and 25.31‰) and standard deviations (0.97‰ and 0.94‰ for old and young tree $\delta^{18}O$ respectively) (Suppl. Table 1). We conclude that there is no significant difference between young and old trees neither for their mean values nor for the magnitude of inter-annual variability (Fig. 5; Suppl. Table 1). In the next sections, the young tree $\delta^{18}O$ is converted to TC/EA with Eq. (3) and used for further analyses.

3.5. Auto-correlations of TRW and $\delta^{18}O$

We observe a high one year lag auto-correlation for TRW indices (0.79 to 0.34 for young trees TRW and old trees TRWi) (Suppl. Table 1). This auto-correlation may suggest that tree growth is strongly affected by the previous photosynthetic activity, but it can also results from other causes such as root or needle development, tree geometry, and the appropriateness of the detrending fit (Fritts, 1976). By contrast, neither the young nor the old tree $\delta^{18}O$ records show any significant auto-correlation, despite using whole rings. These findings are consistent with the same tests performed on cellulose $\delta^{18}O$ of European oaks (Etien et al., 2008). We note that local climate variables (growing season precipitation, PDSI, and humidity) do not exhibit any significant one year lag auto-correlation either.

3.6. Linear correlations between TRW/$\delta^{18}O$ and local climate

Bootstrap correlations are analyzed between all tree-ring proxies using the Dendroclim 2002 software (TRWi, cellulose $\delta^{18}O$ of young trees, old trees and their average) and local climate data (precipitation, relative humidity, surface air temperature of Bomi, local PDSI and regional cloud estimates) (Fig. 6).

TRWi is quite weakly correlated with all climate variables (Fig. 6a). This suggests an ambiguous tree-growth dependence on climate, without any distinct limiting factor, which is typical for moist and warm sites (Fritts, 1976). The weak climate imprints in ring width could also result from the thick soil depth and moderate slope in our sampling site.

By contrast, both the young and old trees $\delta^{18}O$ show significant negative correlations with precipitation, PDSI, humidity and cloud cover from May to September and a positive correlation with July and August temperature. The young and old trees display similar response patterns, albeit with weaker significance levels for the young trees (Fig. 6b, c). Correlations are stronger for the averaged cellulose $\delta^{18}O$, suggesting that mixing the young and old tree records improves the signal to noise ratio (Fig. 6d). The strongest anti-correlation is obtained between all the three $\delta^{18}O$ records (young trees, old trees and averaged record) and the regional June–August cloud cover ($R^2 = 0.26$, 0.40, 0.41 for young, old
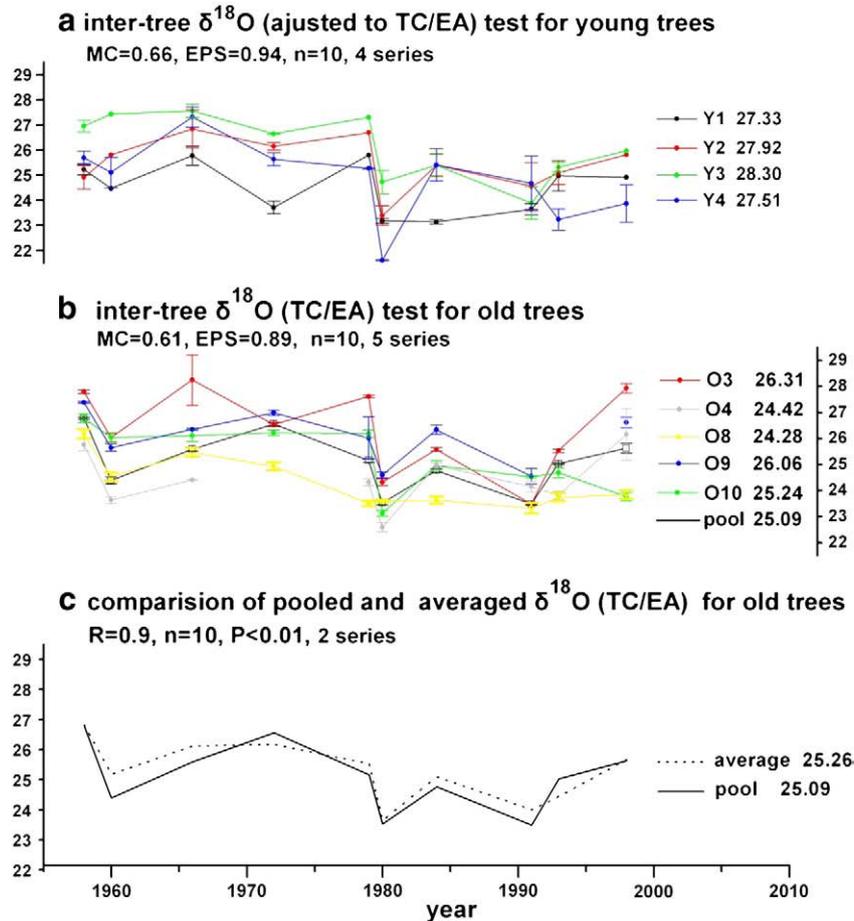
Fig. 4. The inter-tree variability of δ^{18}O in 10 years randomly selected (1958, 1960, 1966, 1972, 1979, 1980, 1984, 1991, 1993 and 1998) for young trees (a) and old trees (b), and, for comparison, in pooled and averaged δ^{18}O for old trees (c). MC = mean inter-core correlation coefficient, EPS = Expressed Population Signal. The standard deviations are displayed for inter-tree test. In the figure legend, the mean δ^{18}O values (averaged over these selected 10 years) are displayed for each tree or group of trees.

and averaged δ^{18}O resp., $P<0.01$, $n=46$) (Fig. 7). Although the regional cloudiness is related to the Bomi station cloud observations ($R^2=0.25$, $P<0.01$, $n=46$), we obtain no significant correlation between tree-ring δ^{18}O and local station or satellite cloud data. Significant correlations are also observed with June–August total precipitation ($R^2=0.20$, slope =
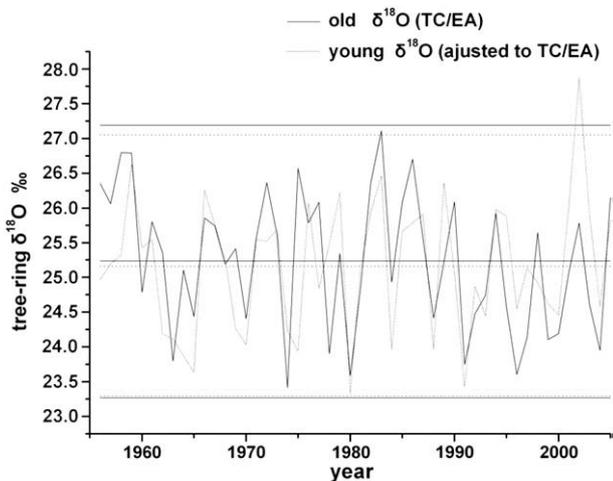

Fig. 5. Comparison of the tree-ring δ^{18}O of young and old trees cellulose. Horizontal lines are the average value of the series and the $\pm 2\sigma$ deviations (solid line for old trees, dotted line for young trees). Young tree δ^{18}O was adjusted to TC/EA using Eq. (3) derived from Fig. 3.

-0.04‰/mm, $P<0.05$, $n=50$, old tree δ^{18}O) and June–August averaged relative humidity ($R^2=0.21$, slope $=-0.17$‰/%, $P<0.05$, $n=50$, averaged δ^{18}O).

In order to indentify the leading climatic variable driving the tree-ring δ^{18}O, the interplay of all climate parameters is characterized (Suppl. Table 3). Humidity is significantly correlated with nearly all other parameters, especially with precipitation and temperature ($R^2=0.53$ and 0.25 resp., $P<0.01$, $n=50$). Cloud cover is highly correlated with PDSI ($R^2=0.37$, $P<0.01$, $n=46$), and weakly with humidity ($R^2=0.21$, $P<0.01$, $n=46$). These findings suggest that the highest correlation with regional cloudiness could arise from the linkage of tree-ring δ^{18}O with other factors such as relative humidity, precipitation amount and drought condition, or with regional moisture transport (Kurita et al., 2009). We note that the Bomi and Bomi–Linzhi averaged precipitation amounts are significantly correlated with northeast Indian precipitation, and negatively correlated with the central west Indian precipitation (derived from 15 sub-regions).

Several processes could explain the observed inter-annual variability of cellulose δ^{18}O. First, the enhanced depletion of cellulose δ^{18}O during wet summers can be explained by the source water (i.e. the precipitation) being more depleted in wetter conditions, as expected from the "amount effect" (Dansgaard, 1964). Precipitation δ^{18}O monitored in Bomi (Gao et al., 2010) indeed shows a negative correlation with local precipitation at the event basis. Similarly, the Lhasa precipitation, sharing with Bomi the same moisture source, exhibits an inter-annual slope of -0.026‰/mm between precipitation weighted δ^{18}O and mean precipitation amount from May to September over the 1999–2005 period ($R^2=0.19$, $P=0.36$, $n=7$). The slope of
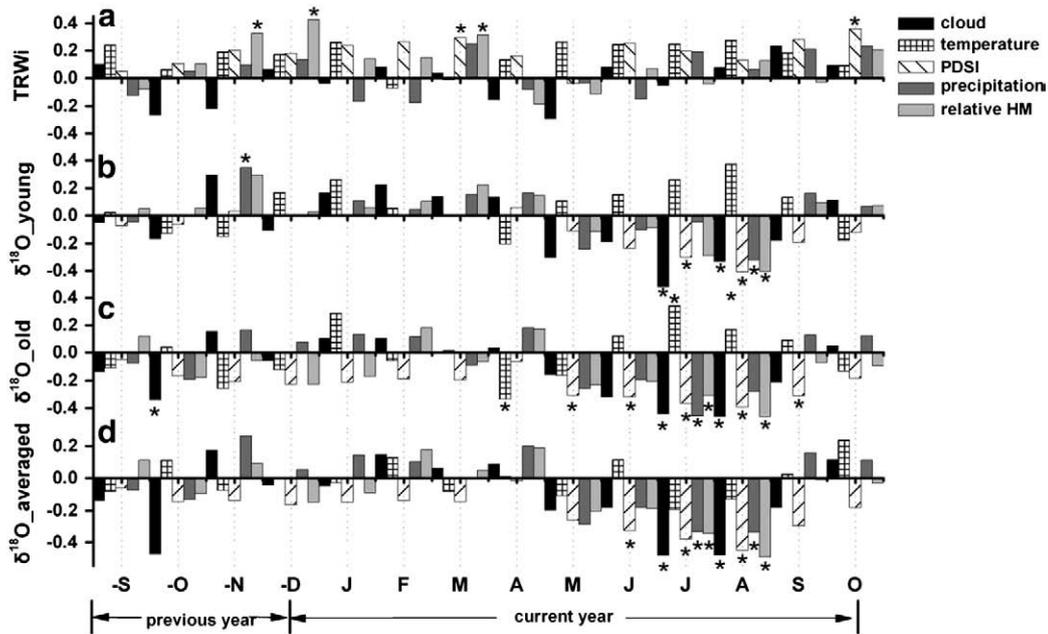
Fig. 6. Monthly correlation of climate parameters from previous September to current October with a) ring-with chronology, b) $\delta^{18}O$ of young trees, c) $\delta^{18}O$ of old trees, and d) averaged young and old trees $\delta^{18}O$,. Stars indicate that the correlations are significant above the 95% level using a bootstrap method. Months are displayed on the horizontal axis (with a negative sign for the previous year).

tree-ring $\delta^{18}O$ versus averaged Bomi summer precipitation amount is 0.016‰/mm ($R^2 = 0.19$, $P<0.05$, $n = 50$, May to September). The anti-correlation observed between precipitation amount and water vapor $\delta^{18}O$ (Lawrence et al., 2004) can further amplify the cellulose depletion under wet conditions (Helliker and Griffiths, 2007) linked with local and/or regional moisture transport effects (Kurita et al., 2009). Secondly, wet conditions are expected to reduce soil and leaf water enrichment and therefore contribute to a more depleted cellulose $\delta^{18}O$. Soil water $\delta^{18}O$ has been shown to have a lower inter-annual variability than precipitation $\delta^{18}O$ (Jaggi et al., 2003).

Altogether, the variability of tree-ring $\delta^{18}O$ is much smaller than the May to September precipitation weighted $\delta^{18}O$ of Lhasa (standard deviation = 0.71‰, 0.74‰ and 1.78‰ for young, old trees and precipitation $\delta^{18}O$, 1999–2005). This is consistent with the slope of Bomi tree-ring $\delta^{18}O$ versus averaged summer precipitation amount

been smaller than that of Lhasa precipitation $\delta^{18}O$ versus summer precipitation amount. We therefore suggest that the strong correlation between tree-ring $\delta^{18}O$ and cloud cover arises from the fact that cloud cover is related to both moisture transport (linked with air mass distillation history) and local/regional precipitation (linked with precipitation $\delta^{18}O$), and is related to local surface relative humidity (linked with soil and leaf enrichment effects). The lack of correlation between tree-ring $\delta^{18}O$ and local cloudiness may imply that the tree-ring $\delta^{18}O$ is more linked with regional moisture transport than with local conditions; this coincides with one former study (Treydte et al., 2006).

3.7. Comparison with modeled tree-ring $\delta^{18}O$

ORCHIDEE-iso simulates a negative correlation between cellulose $\delta^{18}O$ and June–August relative humidity (slope = -0.12 ± 0.02‰/%, $R^2 = 0.30$, $P<0.01$) (Fig. 8a), which is comparable to the observed one (averaged tree-ring $\delta^{18}O$) but with a weaker slope (slope = -0.17 ± 0.037‰/%, $R^2 = 0.22$, $P<0.05$) (Fig. 8b). The slope that we observed at Bomi is similar to the simulated slope in tropical area (-0.20‰/%) (Anchukaitis et al., 2008), and is smaller than the slope of -0.50‰/% reported by Managave et al. (2010). The current modeling approach therefore captures well the control of relative humidity on the inter-annual variability of tree-ring $\delta^{18}O$. The ORCHIDEE-iso modeling allows quantifying the processes underlying this correlation, by keeping one parameter constant at the inter-annual scale and varying the others. Variations in soil water $\delta^{18}O$ explain 44% of the amplitude of inter-annual tree-ring $\delta^{18}O$ variations (leading to a slope of -0.05‰/%). These variations are due to enhanced evaporative enrichment of soil water in dry conditions and to the smaller proportion of precipitation occurring during monsoon season (i.e. when precipitation is most depleted) during dry years. The simulated effect of relative humidity alone on leaf water enrichment explains 51% of inter-annual $\delta^{18}O$ variations (leading to a slope of -0.6‰/%). These two processes thus contribute to the near-totality of the tree-ring cellulose $\delta^{18}O$ signal in ORCHIDEE. Inter-annual precipitation $\delta^{18}O$ variations are also expected to impact the tree-ring cellulose signal but their effect could not be estimated as these were not

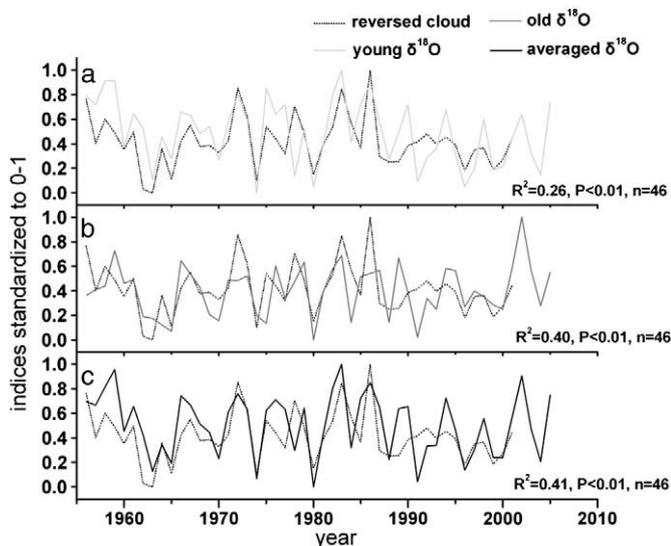**Fig. 7.** Comparison of young trees, old trees and averaged $\delta^{18}O$ with reversed cloud cover averaged over June–August. All variables are standardized to 0–1.
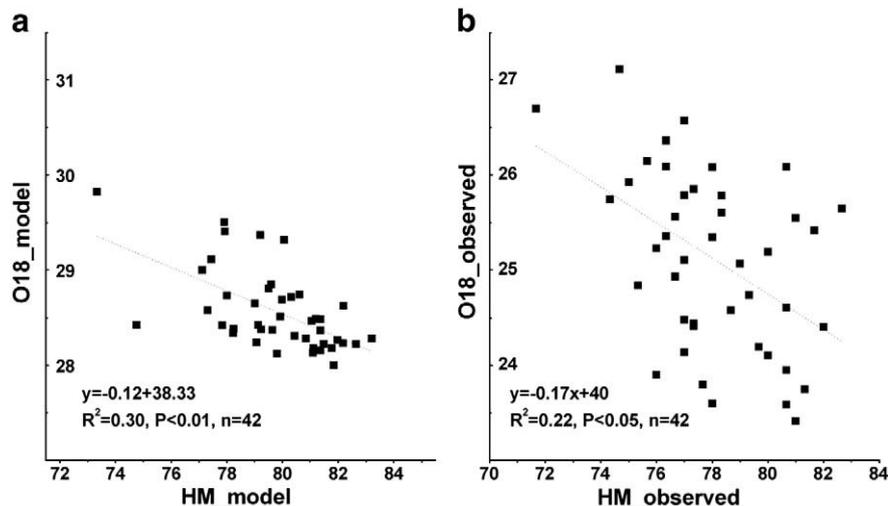
Fig. 8. Modeled versus and observed tree-ring $\delta^{18}O$ (in ‰; a and b respectively), versus relative humidity (in %). Note that observed tree-ring isotopes are compared to observed relative humidity (1961–2002), while simulated isotopes are compared to the relative humidity derived from the ORCHIDEE-iso model, which is slightly different from observed data (1961–2002).

considered in the model. The dependency of cellulose production on meteorological conditions damps the sensitivity of cellulose $\delta^{18}O$ to relative humidity, which would be 11% larger if cellulose $\delta^{18}O$ was not weighted by cellulose production. This is due to cellulose production occurring preferentially in wet conditions during the driest years.

To summarize, the ORCHIDEE-iso model shows that moisture conditions are theoretically strongly imprinted in Bomi tree-ring cellulose $\delta^{18}O$, due to the links between precipitation $\delta^{18}O$, precipitation amount and relative humidity, and to the impact of relative humidity on soil and leaf water enrichments.

3.8. Results and discussion of tree-ring $\delta^{13}C$

The intra-tree and inter-tree $\delta^{13}C$ variability was analyzed for young trees (Y1–Y4), showing similar level with those of $\delta^{18}O$ (Supplementary materials, Suppl. Table 2, Suppl. Fig. 2). The discrimination factor ($\Delta^{13}C = \delta^{13}C_{air} - \delta^{13}C_{cellulose}$) displays a significant decreasing trend (Suppl. Fig. 3). This trend differs from typical increasing $\delta^{13}C$ for juvenile trees and could be due to the physiological response of WUE (Water Use Efficiency) to increasing atmospheric CO_2 concentration (Gagen et al., 2007; McCarroll et al., 2009; Treydte et al., 2009). The detrended young tree $\delta^{13}C$ (subtracted by its own trend) exhibits nearly no significant correlation with monthly mean climate parameters (Suppl. Fig. 4). This is why we have decided not to measure $\delta^{13}C$ on the old tree samples. Theoretical simulations conducted with ORCHIDEE-iso depict a positive correlation with modeled June–August relative humidity (Supplementary materials and Suppl. Fig. 5), due to the parameterization of the stomatal conductance (Krinner et al., 2005). The modeled impact of relative humidity is much stronger than observed. The direct influence of climate on tree-ring $\delta^{13}C$ may be masked by the intermittency of productivity and post-photosynthetic processes (Badeck et al., 2005; Cernusak et al., 2009; Eglin et al., 2010).

4. Conclusion and perspectives

In this study, we have explored the intra-tree and inter-tree $\delta^{18}O$ dispersions. Our results demonstrate i) a very limited effect of intra-tree variability and ii) a high inter-tree coherence. We show that a robust tree-ring $\delta^{18}O$ record can be produced by analyzing only four trees. The comparison of the two groups of trees with different ages shows that there is no age-related offset or response difference for tree-ring cellulose $\delta^{18}O$. We have developed an empirical equation to calibrate tree-ring cellulose $\delta^{18}O$ measurements conducted with EA and TCEA methods.

Systematic inter-comparisons are needed to establish protocols ensuring the inter-calibration of absolute $\delta^{18}O$ values and variability (Boettger et al., 2007).

In the SE Tibetan Plateau, under wet and warm conditions and under the influence of summer monsoon, the inter-annual variations of TRW and young trees $\delta^{13}C$ are not responding clearly to any climate parameter. TRW and $\delta^{13}C$ are characterized by a significant one year lag auto-correlation, which may reflect the effect of tree physiology.

The inter-annual variability of Bomi tree-ring cellulose $\delta^{18}O$ is driven by the inter-annual variability of local to regional moisture conditions, in terms of relative humidity, precipitation amount, and cloud cover. Surprisingly, the strongest anti-correlation is obtained with the regional cloud cover, accounting for up to 41% of the tree-ring cellulose $\delta^{18}O$ inter-annual variance. This correlation arises from the close link between tree-ring $\delta^{18}O$ and moisture conditions, and the strong correlations between various climate parameters (i.e. cloud cover, drought index, and relative humidity).

The anti-correlation between tree-ring $\delta^{18}O$ and local precipitation results from the "amount effect" in southeast Tibetan Plateau precipitation. The processes relating tree-ring cellulose $\delta^{18}O$ with moisture conditions have been investigated using a land surface model equipped with the representation of oxygen stable isotopes, ORCHIDEE-iso. The anti-correlation with relative humidity is suggested to arise from the correlation between relative humidity and precipitation amount (and possibly isotopic composition), but also from the impact of relative humidity on soil and leaf water enrichment. The ORCHIDEE model suggests that photosynthesis occurs preferentially during wet conditions. The integration of the initial leaf signal into the tree-ring cellulose signal could be affected by the intermittency of productivity which dampens the correlations with monthly mean climate variables. In comparison to our data, the ORCHIDEE model seems to over-estimate the impact of relative humidity on cellulose $\delta^{13}C$.

A better process-based understanding of the climatic controls on tree-ring cellulose $\delta^{18}O$ requires documenting the processes at play along the soil–plant–atmosphere continuum. This could be achieved by a continuous monitoring of precipitation, soil, stem water, vapor and leaf water $\delta^{18}O$. Such data sets are necessary to develop isotope-enabled land surface models and to improve the understanding of the drivers of intra and inter-annual $\delta^{18}O$ variability of tree-ring cellulose.

Our study shows the potential of Bomi tree-ring cellulose $\delta^{18}O$ for reconstructing past variations of regional monsoon moisture transport, including humidity, precipitation and cloud cover. Therefore, the production of long tree-ring $\delta^{18}O$ series from old trees, would be very

valuable to further understand the spatiotemporal impact of monsoon variability in southeast TP.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.epsl.2010.11.014.

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