Seasonal incursion of Indian Monsoon humidity and precipitation into the southeastern Qinghai-Tibetan Plateau inferred from tree ring $\delta^{18}\text{O}$ values with intra-seasonal resolution

Xiaomin Zeng ^{a, d}, Xiaohong Liu ^{a*}, Michael N. Evans ^b, Wenzhi Wang ^{a, d}, Wenling An ^c, Guobao Xu ^a, Guoju Wu ^{a, d}

Author family names: Zeng, Liu, Evans, Wang, An, Xu, and Wu

a. State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Lanzhou 730000, China

b. Department of Geology and Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA

c. Ministry of the Education, Key Laboratory for Coast and Island Development, School of Geographic and Oceanographic Sciences, Nanjing University, Nanjing 210093, China

d. University of the Chinese Academy of Sciences, Beijing 100049, China

Running title: Intra-seasonal $\delta^{18}\text{O}$ pattern of Smith fir tree rings

*Author for Correspondence:

Dr. Xiaohong LIU

State Key Laboratory of Cryospheric Sciences

Cold and Arid Regions Environmental and Engineering Research Institute

Chinese Academy of Sciences

Donggang West Road No. 320, Lanzhou 730000, China

E-mail: liuxh@lzb.ac.cn

Tel.: 0086-931-496-7342

Fax: 0086-931-827-1124

Abstract

Incursion of the Indian Monsoon flow onto the Qinghai-Tibetan Plateau is an important regional moisture-delivery mechanism, but the causes of intra-seasonal and longer-term variations are poorly understood. We observed a clear intra-seasonal cycle in the oxygen isotope composition ($\delta^{18}\text{O}$) of Smith fir (*Abies forrestii* var. *georgei*) growing at two different altitudes (high-elevation site: 29°39'N, 94°42'E, 4200 m a.s.l.; low-elevation site: 29°39'N, 94°43'E, 3800 m a.s.l.) on a SE-facing slope in the Sygera Mountains, southeastern Qinghai-Tibetan Plateau. Mechanistic modeling suggests that $\delta^{18}\text{O}$ of precipitation, which in turn depends on relative humidity and precipitation amount, is important in controlling the intra-seasonal tree-ring isotopic cycle, and we speculate that the same controls also operate on interannual and longer time scales. If so, multi-century $\delta^{18}\text{O}$ records with intra-seasonal resolution may enable us to infer long-term variations in the incursion of the Indian Monsoon onto the Qinghai-Tibetan Plateau.

Key words: intra-seasonal variation; $\delta^{18}\text{O}$; precipitation; relative humidity; tree rings; Qinghai-Tibetan Plateau

1. Introduction

During the past century, global climate change has exerted an increasingly important influence on water resources and ecosystem services around the world, and this has had important social and economic consequences (IPCC, 2014). The Qinghai-Tibetan Plateau is very sensitive to climate change and is currently experiencing significant warming and hydrological changes (Kang et al., 2010; Tian et al., 2006), placing increasing pressure on biodiversity (Klein et al., 2004). Unfortunately, historical observations are scarce in the region, so placing recent hydroclimatic changes within the context of the longer-term, natural variability is difficult. Consequently, investigations must rely on indirect physical, chemical and stable isotopic observations made in dated geological and biological archives such as tree rings and layered ice sheets (Thompson et al., 2000; Tian et al., 2006; Zhang et al., 2015).

Precipitation on the Qinghai-Tibetan Plateau is highly seasonal. Its oxygen isotopic composition ($\delta^{18}\text{O}$) reflects the influence of mid-latitude westerly and Indian Monsoon moisture sources, and local evaporation, convection, and droplet re-evaporation (Yao et al., 2013). At present, however, the interannual and longer-term drivers of variation of precipitation $\delta^{18}\text{O}$ in records from the southern Qinghai-Tibetan Plateau are controversial (Gao et al., 2013). The proposed controls on recently observed variations in precipitation

$\delta^{18}\text{O}$ include regional temperature (Thompson et al., 2000; Yao et al., 2006), precipitation amount and the intensity of the Indian Monsoon (Kaspari et al., 2007; Tian et al., 2001), and relative humidity (Zhang et al., 2005). It has also been suggested that the response of $\delta^{18}\text{O}$ on the plateau to precipitation amount and temperature may not be stable over time (Johnson and Ingram, 2004). Hence, to accurately reconstruct hydroclimatic variation on the Qinghai-Tibetan Plateau, a better understanding of the intra- to interseasonal timescale environmental controls on precipitation $\delta^{18}\text{O}$ is required.

The extensive forests of the southeastern Qinghai-Tibetan Plateau present an archive of past environmental variations. In particular, observations and simulations indicate that $\delta^{18}\text{O}$ of the α -cellulose component of the wood primarily reflects the isotope composition of the plant's source water, leaf-level evapotranspiration, and thermal and biosynthetic fractionation effects (e.g., Barbour et al., 2004). In temperate humid regions such as those of the southeastern Qinghai-Tibetan Plateau, precipitation is an important component of the plant's source water, especially for shallow-rooted trees; if the local influences of evapotranspiration and temperature are small, variations in the isotope composition of α -cellulose from trees are closely correlated with variations in precipitation $\delta^{18}\text{O}$ (Liu et al., 2013; Shi et al., 2011; Treydte et al., 2014). During the boreal summer, the climate of the southeastern Qinghai-Tibetan Plateau is dominated by the Indian Monsoon, which is driven by thermal contrast of the Tibetan Plateau relative to sea surface temperature in the Bay of Bengal (Gao et al., 2013).

In the present study, we hypothesize that the intra-seasonal variation in $\delta^{18}\text{O}$ of α -cellulose of trees in the southeastern Qinghai-Tibetan Plateau will reflect variation in the $\delta^{18}\text{O}$ of precipitation associated with incursion of the Indian Monsoon, and discuss the potential to use these variations to reconstruct variations in monsoon intensity in the southeastern Qinghai-Tibetan Plateau over the past several centuries. Our study focuses on intra-seasonal variation in $\delta^{18}\text{O}$ in the tree rings of Smith fir (*Abies forrestii* var. *georgei*) from two elevations on a southeast-facing slope in the Sygera Mountains of the southeastern Qinghai-Tibetan Plateau. We use a mechanistic forward model (modified from Evans, 2007) of $\delta^{18}\text{O}$ of the α -cellulose of wood to identify the processes most likely to explain the observations, and then compare our observations to other isotopic records from regions influenced by the Asian Monsoon. Based on these results, we discuss the potential for reconstructing indicators of monsoon incursion onto the plateau using multi-century tree ring records with intra-seasonal resolution.

2. Materials and methods

87 **2.1. Study area**

88 The study was conducted on the eastern side of the Sygera Mountains on the south-eastern Tibetan
 89 Plateau, China (Fig. 1). The site is characterized by a mean annual precipitation that ranges from 514 to 985
 90 mm (of which 80% falls during the growing season), a mean annual temperature that ranges from 7.9 to
 91 10.2 °C, and a mean annual relative humidity that ranges from 58 to 66%; temperatures during the growing
 92 season range from 13.5 to 15.9°C. These conditions allow the widespread development of forests at
 93 elevations of 3600 to 4400 m asl in our study area. In the boreal summer, a moisture flow reaches this area
 94 from the southwest during the onset of the annual Indian Monsoon, resulting in abundant rainfall. A detailed
 95 description of the regional climatology is provided by Zeng et al. (2014), and is summarized in Figure 2a.

97 **Fig. 1.** Wind speeds (May to September; vectors) and total precipitation (May to September) in the study
 98 area affected by the Indian Monsoon. Wind values are provided at the 850-mbar level from the National
 99 Centers for Environmental Prediction and total precipitation is from the Global Precipitation Climatology
 100 Centre over land (1950 to 2011) (data source: <http://www.esrl.noaa.gov/psd/data/>) . Letters represent the
 101 locations of the present study site and of sites in recently published studies on intra-seasonal tree-ring $\delta^{18}\text{O}$
 102 values in the Indian Monsoon region: (a) Present study, (b) Central India (Managave et al., 2010), (c) Kerala

in southern India (Managave et al., 2011), (d) northern Thailand (Zhu et al., 2012a), (e) Cambodia (Zhu et al., 2012b), and (f) Indonesia (Schollaen et al., 2013).

Fig. 2. (a) Monthly mean temperature, total precipitation and relative humidity from 1960 to 2011 at the Nyingchi meteorological station and monthly mean precipitation $\delta^{18}\text{O}$ from 2007 to 2008 at Lulang town. (b) Mean 15-day temperature, precipitation and relative humidity at the Nyingchi meteorological station (2007 to 2011) and precipitation $\delta^{18}\text{O}$ at Lulang town (2007 to 2008) during the growing season (Yang et al., 2012).

The study site is located on a southeast-facing 15° slope. The forest canopy coverage is approximately 60% (Li et al., 2013). The dominant tree species, Smith fir (*Abies forrestii* var. *georgei*), grows along an altitudinal gradient from 3550 to 4400 m a.s.l. (Liang et al., 2010). Growth of Smith fir begins at the end of May and ends in late August to early October; cell wall thickening begins in June and ends by late September to early October (Li et al., 2013).

2.2. Tree-ring sampling and cross-dating

We sampled Smith fir from two different attitudes (site A1, at $29^{\circ}39'\text{N}$, $94^{\circ}42'\text{E}$, 4200 m a.s.l., referred

to as the high-elevation site hereafter; site A2, at 29°39'N, 94°43'E, 3800 m a.s.l., referred to as the low-elevation site hereafter) in May 2012 (Zeng et al., 2014). At both sites, we selected 20 mature trees (about 100 years old), and obtained two cores at approximately 1.3 m above the ground from each tree using a 12-mm increment borer; the samples were taken at right angles to each other. After surface preparation, tree-ring widths were measured (with 0.01-mm resolution) and cross-dated (Stokes and Smiley, 1968) against the local master chronology (Liang et al., 2010). We used the COFECHA software to verify this cross-dating (Holmes, 1983), and created the ring-width chronologies by detrending the individual cross-dated ring width series using a fitted negative exponential model, and then modeling their common autoregression characteristics using the ARSTAN software (Cook, 1985).

We selected two trees per site, with one core per tree (Table S1). The selected cores contained no false or missing rings, had similar tree ages, and had wide rings (>1 mm) during the study period from 2007 to 2011. Sub-annual samples of each ring were obtained by carefully creating discrete slices throughout the width of an annual ring using a rotary microtome (HM340E, Thermo Scientific, Waltham, MA, USA) at a resolution of 100 μm for tree H1 at the high-elevation site and 140 μm for trees L1 and L2 at the low-elevation site and trees H2 at the high high-elevation site.

2.3. Modeling of timing of cell formation and seasonal tree growth

We estimated the timing of cell formation from 2007 to 2008, and therefore the beginning and end of the growing season, using a model derived from the growth rates of other representative trees at the sampling site, for which the number of cells in the enlarging, wall thickening, and mature phases was determined by taking micro-scale cores on a weekly basis throughout the growing season (Li et al., 2013). A Gompertz function, relating the cell position in the tree ring to its time of formation, was calculated for the weekly cumulative sum of tracheids (E. Liang, pers. comm.):

$$y = A \exp[-e^{(\beta - \kappa t)}] \quad (1)$$

where y is the cumulative weekly sum of the number of tracheids, t is the day of the year (DOY), A is the upper asymptote for the minimum number of tracheids, β is the x -axis placement parameter, and k is the rate of increase in the tracheid number (no./week). A , β , and k were estimated from site data to be 23.73, 5.78, and 0.03, respectively. Following the methods of Li et al. (2013), we determined that the mean growing season extended from 20 May to 7 October.

2.4. Cellulose extraction and oxygen isotope measurements

We extracted α -cellulose from the microtomed raw wood samples following the methods of Leavitt and Danzer (1993). Briefly, the samples were sealed in permeable filter bags (ANKOM Technology, Macedon, NY, USA) and placed in a Soxhlet apparatus that recirculated a 2:1 v/v toluene–ethanol solution (95%) through the sample bags for 24 h at 70°C. Samples were air dried for 6 h, then placed again in the Soxhlet apparatus for 24 h with 95% ethanol. The sample was then bleached using a mixture solution of 20% v/v sodium chlorite and 20% v/v acetic acid (3:2 v/v), yielding holocellulose. Conversion to α -cellulose was achieved by treatment with 17% w/v NaOH, followed by rinsing with deionized water and final drying of the samples. To better homogenize the resulting product, we used an ultrasound machine (JY92-2D, Scientz Industry, Ningbo, China) to break the cellulose fibers.

We loaded 0.14 to 0.16 mg of α -cellulose into silver capsules and determined the isotope composition using a high-temperature-conversion elemental analyzer coupled to a gas stable-isotope mass spectrometer (TC/EA, MAT-253; Thermo Electron Corporation, Bremen, Germany) at the State Key Laboratory of Cryospheric Sciences, Chinese Academy of Sciences. To estimate the internal reproducibility of the isotopic analyses, we performed four separate analyses of CO converted from four separate subsamples of each sample. After excluding outliers (values more than three standard deviations from the mean), we calculated the mean value for each sample. Replicated analyses of a benzoic acid working standard, itself calibrated to the IAEA-601 benzoic acid standard ($\delta^{18}\text{O} = 23.3\text{‰}$, VSMOW), were measured once per seven sample analyses to monitor the analytical precision and accuracy. The IAEA-C₃ cellulose standard ($\delta^{18}\text{O} = 32.2\text{‰}$, VSMOW) was then used to calibrate the tree-ring oxygen isotope measurements against an international reference material with a chemical structure similar to that of the samples. The analytical precision, based on repeated measurements of IAEA-601 and IAEA-C₃, was 0.25‰ (1 σ) or lower for $\delta^{18}\text{O}$.

2.5. Forward modeling of the oxygen isotope composition of wood

We modified the Evans (2007) model, which was derived from the Barbour et al. (2004) model, by forcing the model with daily mean local meteorological data (from Nyingchi meteorological station), including the observed daily mean isotope composition of precipitation (from Lulang town, see section 2.6), to simulate the intra-seasonal $\delta^{18}\text{O}$ time series. There are 14 parameters in the model, for which we used default values from Barbour et al. (2004) and Evans (2007) for 12, and estimated the values of the 2 remaining parameters (for the regression of stomatal conductance on the leaf-to-air saturation vapor-pressure deficit) using observed data from our study site (Ren et al., 2011; Table S2). We used a Monte Carlo

procedure (with 1000 simulations) and randomized adjustments ($c_5 = 20\%$) of the model parameters (Evans, 2007) to estimate the sensitivity of the annual patterns of variability to the parameter estimates.

Following the method of Evans (2007), we parameterized leaf temperature as a function of air temperature. Because the altitude of condensation (which determines the condensation temperature) is poorly observed at this site, we estimated the temperature of condensing precipitation (T_c) as a linear function of air temperature and relative humidity according to the method of Lawrence (2005):

$$T_c = T - (100 - RH)/5 + 273.15 \quad (2)$$

where T_c is in Kelvins (K), T is the air temperature ($^{\circ}\text{C}$), and RH is the relative humidity (%). Measured stomatal conductance and vapor-pressure deficit data for Smith fir growing in the Sygera Mountains (Ren et al., 2011) were used to estimate the values of parameters c_3 and c_4 (Table S2). Consistent with the method of Evans (2007), we calculated evapotranspiration (E) according to the method of Jarvis and McNaughton (1986). Because the average surface atmospheric pressure (P_{atm}) is stable at the Nyingchi meteorological station during the growing season, we set it to be constant at 709 mbar, which is the site average value from May to September, within the formulation for E .

2.6. Climate data

In our study, the linear regression equation for the relationship between the growing season precipitation $\delta^{18}\text{O}$ and the precipitation amount was significant but weak ($r = 0.44$, $n = 41$, $P < 0.001$ for 2007; $r = 0.44$, $n = 78$, $P < 0.001$ for 2008; Fig. S1), as might be expected from a site that is not only influenced by two monsoon branches, but also influenced by the westerlies (Mölg et al., 2014). In addition, we suspect the distant observing station may not be representative of the study site, nor the mesoscale and microscale variability of the area. To avoid this problem, we used observed precipitation $\delta^{18}\text{O}$ data as input to the model, instead of precipitation amount. Precipitation $\delta^{18}\text{O}$ data was gathered by Yang et al. (2012) at the Southeast Tibet Observation and Research Station for the Alpine Environment (<http://www.tpe.ac.cn/obs>) in the Lulang town ($29^{\circ}46'\text{N}$, $94^{\circ}44'\text{E}$, 3330 m asl, about 12 km from the study site). According to isotopic criteria, date of the start of summer monsoon is 22 Apr in 2007 and 28 Apr in 2008 (Yang et al., 2012). Liang et al. (2011) reported that the variation of climate variables on the valley bottom (Nyingchi meteorological station) was highly consistent with the measurements at the upper timberline. Therefore, we used temperature and relative humidity data (Fig. 2b) from Nyingchi meteorological station ($29^{\circ}34'\text{N}$, $94^{\circ}28'\text{E}$, 2991 m a.s.l., about 23 km from the study site) as model input variables. However, because the

precipitation $\delta^{18}\text{O}$ data were available only for the periods from 22 January to 21 November 2007 and from 20 February to 22 November 2008, we only modeled intra-seasonal tree-ring $\delta^{18}\text{O}$ for the 2007 and 2008 growing seasons.

2.7. Data analysis

To facilitate comparison between observed and simulated climatic and isotopic data, it is necessary to place all data on a common time scale. We used the Gompertz function with empirically derived coefficients (section 2.3) to convert incremental growth to calendar times (Fig. S2). To create a composite intra-seasonal climatology at both sites for comparison with the simulated tree-ring $\delta^{18}\text{O}$ series, we created a normalized intra-annual ring-fraction age model.

To facilitate comparison of isotopic patterns among the four tree cores at the two sites, the intra-seasonal time-series for each ring was linearly interpolated at increments of 0.0833 (i.e., 1/12th) of a ring; we then calculated the root-mean-square difference (RMSD) across all observations at each site to estimate the observational uncertainty. We used paired *t*-tests to assess whether intra-seasonal amplitudes of the difference between the maximum and minimum $\delta^{18}\text{O}$ values differed significantly between the two sites.

To compare the climate-driven intra-seasonal variation in cellulose $\delta^{18}\text{O}$ and source water $\delta^{18}\text{O}$, we standardized all tree-ring $\delta^{18}\text{O}$ values within each ring for all trees and for all precipitation $\delta^{18}\text{O}$ values using Z-scores, and then fitted a third-order polynomial to each of the data series as an estimate of the variation over the course of the growing season.

To remove the influence of the annual cycle, and focus on interannual variations in the intra-annual cellulose $\delta^{18}\text{O}$ isotope composition, we fitted sinusoidal models to the composite intra-annual tree-ring $\delta^{18}\text{O}$ time-series and to climate variables using version 3.04 of the PAST software (Table S3). We then performed forward stepwise regression between the tree-ring $\delta^{18}\text{O}$ residuals time series (H1, H2, L1 and Mean series) and the climate residuals time series (temperature, precipitation and relative humidity), using regression significance at $p < 0.05$ to decide whether to include a variable.

Finally, to independently compare the simulated and observed amplitudes of the intra-seasonal cycle, we compared the simulated and observed intra-seasonal tree-ring $\delta^{18}\text{O}$ time-series, and calculated their RMSD. We analyzed the observed tree-ring $\delta^{18}\text{O}$, modeled enrichment of ^{18}O in leaf water and the climatic simulation inputs (relative humidity, precipitation, and precipitation $\delta^{18}\text{O}$), to identify the plant-related processes that best explained the variation in the intra-seasonal oxygen isotope composition of tree-ring

234 α -cellulose in the observations. We calculate the explained variance (R^2) between different variables based
 235 on linear regression analysis:

236
$$\delta^{18}\text{O}_p = a_1P + b_1 \quad (3)$$

237
$$\delta^{18}\text{O}_p = a_2RH + b_2 \quad (4)$$

238
$$\Delta^{18}\text{O}_{\text{leaf}} = a_3RH + b_3 \quad (5)$$

239
$$\delta^{18}\text{O}_c = a_4\delta^{18}\text{O}_p + b_4 \quad (6)$$

240
$$\delta^{18}\text{O}_c = a_5\Delta^{18}\text{O}_{\text{leaf}} + b_5 \quad (7)$$

241 where $\delta^{18}\text{O}_p$ and $\delta^{18}\text{O}_c$ represent $\delta^{18}\text{O}$ values of precipitation and tree-ring cellulose, respectively; P and RH
 242 represent precipitation and relative humidity, respectively; $\Delta^{18}\text{O}_{\text{leaf}}$ indicates modeled enrichment of ^{18}O in
 243 leaf water ($\Delta^{18}\text{O}_{\text{leaf}} = \text{Leaf water } \delta^{18}\text{O} - \text{Precipitation } \delta^{18}\text{O}$); a_1 to a_5 and b_1 to b_5 indicate the slope and
 244 intercept of Eq. 3 to Eq. 7, respectively.

245 3. Results

246 3.1. Intra-seasonal $\delta^{18}\text{O}$ of tree rings

247
 248 **Fig. 3.** Intra-seasonal variations in the tree-ring $\delta^{18}\text{O}$ of Smith fir over a 5-year period for trees collected at
 249 two elevations on a southeast-facing slope in the Sygera Mountains. H1 and H2 represent trees at the
 250 high-elevation site; L1 and L2 represent trees at the low-elevation site.

251 Fig. 3 shows the intra-seasonal tree-ring $\delta^{18}\text{O}$ series from trees H1, H2, L1, and L2, and Table S1 shows
 252 their statistical characteristics for the period from 2007 to 2011. We observe a clear intra-seasonal cycle in
 253 all $\delta^{18}\text{O}$ profiles (all trees and all years), with the most enriched values (higher in ^{18}O) found at the
 254 beginning of the growing season, followed by a mostly steady decrease until late in the growing season (Fig.
 255 3). A second period of ^{18}O enrichment occurred at the ends of the 2008, 2009, and 2011 growing seasons,

but it was small relative to the decrease that occurred during the preceding parts of the growing season. In general, there was an abrupt transition from the $\delta^{18}\text{O}$ minima at the end of one growing season to the $\delta^{18}\text{O}$ maxima at the beginning of the next growing season, with the exception of the transition between the 2009 and 2010 growing seasons for tree H1. The $\delta^{18}\text{O}$ values decreased by up to 12.4‰ within a single growing season, with average intra-annual amplitude of 7.1‰. However, the amplitude of the intra-seasonal $\delta^{18}\text{O}$ variation at the high-elevation site was significantly lower than that observed at the low-elevation site (mean difference = -0.37, $P < 0.01$), and this difference mainly resulted from differences in the maximum values observed at the beginning of the growing season; by the end of the growing season, the values were generally similar at the two elevations. The largest mean amplitude of the annual cycle (8.6‰) was observed in 2010; the smallest (5.5‰) was observed in 2011. The tree-ring $\delta^{18}\text{O}$ values and trends in these values were remarkably coherent among trees at a given site (Fig. 3; Table S4), which is consistent with the results of Treydte et al. (2014)'s investigation in the Swiss Alps. The observational error between the series was < 0.05 except in 2011 at the high-elevation site, and the observation error at the high-elevation site (a mean of 0.06) was much higher than that (0.02) at the low-elevation site (Table S4).

The amplitude of the intra-seasonal cycle was greater at the low-elevation site (mean amplitude: 9.36‰) than at the high-elevation site (mean amplitude: 4.81‰) (Fig. S3; Table S1). This offset might result from altitudinal gradient of source water $\delta^{18}\text{O}$ and climate variable (temperature, relative humidity and precipitation) differences between two sites (Zeng et al., 2014).

3.2. Stepwise linear regression analysis between the intra-seasonal $\delta^{18}\text{O}$ and local climate variables

Table 1 presents the model coefficients selected by stepwise linear regression of the cellulose $\delta^{18}\text{O}$ on temperature, precipitation and relative humidity for the two sites from 2007 to 2011 ($n = 60$). The strongest relationship for the raw data was obtained for tree L1 (Table 1);. The regression equations explained an average of 25% of the mean tree-ring $\delta^{18}\text{O}$ residual variance. Of the three climate variables (temperature, precipitation, and relative humidity), relative humidity was selected as a significant variable in all regressions, suggesting it was the most important environmental control on cellulose $\delta^{18}\text{O}$.

Table 1. Stepwise linear regression modeling of tree isotope data. H1 and H2 represent trees at the high-elevation site; L1 and L2 represent trees at the low-elevation site. T , P , and RH represent temperature, precipitation and relative humidity, respectively. Z represents the normalized series for the environmental variables.

Tree		Equation	R^2	RMSE	P	df
H1	Raw data	$y = -0.083 RH$	0.13	1.20	<0.01	58
	Normalized	$Z_y = -0.36 Z_{RH}$				
H2	Raw data	$y = -0.059 RH$	0.07	1.20	<0.05	58
	Normalized	$Z_y = -0.27 Z_{RH}$				
L1	Raw data	$y = -0.37 RH - 0.73 T + 0.03 P$	0.40	1.61	<0.001	56
	Normalized	$Z_y = -1 Z_{RH} - 0.37 Z_T + 0.34 Z_P$				
L2	Raw data	$y = -0.13 RH$	0.15	1.78	0.002	58
	Normalized	$y = -0.38 Z_{RH}$				
Mean	Raw data	$y = -0.17 RH - 0.47 T$	0.25	1.31	<0.001	57
	Normalized	$Z_y = -0.67 Z_{RH} - 0.34 Z_T$				

3.3. Comparison with precipitation $\delta^{18}\text{O}$

The pattern of intra-annual climatological variation in the standardized anomaly (Z-scores) of cellulose $\delta^{18}\text{O}$ as a function of the distance from the ring boundary is consistent with the pattern of variation in the standardized anomaly (Z-scores) of precipitation $\delta^{18}\text{O}$, with the values most enriched in ^{18}O occurring early in the growing season, followed by a steady decrease during the growing season to reach a minimum late in the growing season (Fig. 4). Moreover, the RMSE value for precipitation $\delta^{18}\text{O}$ was higher than that for tree-ring $\delta^{18}\text{O}$ (Fig. 4).

Fig. 4. Scatter plot of the standardized intra-seasonal tree-ring and precipitation $\delta^{18}\text{O}$ anomalies (Z-scores). The bottom horizontal axis represents the fractional distance from the previous year's ring boundary and the top horizontal axis represents the day of year (DOY).

Correlation analysis (Table 2) indicated that the variation in precipitation $\delta^{18}\text{O}$ was significantly negatively related to the variation in daily mean relative humidity ($r = -0.61$, $P < 0.001$, $n = 166$) and precipitation ($r = -0.43$, $P < 0.001$, $n = 166$) throughout the growing season (May to September), but not outside the growing season (January to April). In contrast, temperature was only significantly correlated to this variation in May, July, and August ($r \leq 0.55$) and for the period from January to April ($r = 0.63$, $P < 0.001$). We interpret the strong correlation of precipitation $\delta^{18}\text{O}$ with temperature in the early growing season and with relative humidity in the mid-to-late growing season (Table 2), as evidence that the air mass source region is an important control on intra-seasonal variation in precipitation $\delta^{18}\text{O}$.

317 **Table 2** Pearson's correlation coefficient (r) for the relationship between event-based daily precipitation
318 $\delta^{18}\text{O}$ and climate variables at the Nyingchi meteorological station in 2007 and 2008. MJJAS represents the
319 season from May to September. JFMA represents the season from January to April. Significance: *, $P < 0.05$;
320 **, $P < 0.01$; ***, $P < 0.001$.

Month	Correlation coefficient (r)			n
	Temperature	Precipitation	Relative humidity	
May	0.55**	-0.74***	-0.60***	31
June	0.02	-0.42*	-0.38*	35
July	0.49**	-0.38*	-0.37*	40
Aug.	0.38*	-0.50**	-0.48**	36
Sept.	0.20	-0.57**	-0.67***	24
MJJAS	0.05	-0.43***	-0.61***	166
JFMA	0.63***	0.06	0.13	72

321 3.4. Modeling results

322 Figures 5a and 5b compare the simulated and observed tree-ring $\delta^{18}\text{O}$ values in the 2007 and 2008
323 growing seasons. The simulated pattern of variation within the growing season, from high values at the onset
324 of growth to lower values at the end of the growing season, agreed with the observations. The mean
325 simulated value was significantly ($P < 0.001$) higher than the mean in the observed series, with mean offsets
326 of 4.72‰ (2007) and 5.75‰ (2008). Moreover, the offset between the simulated and observed series
327 decreased during the growing season (Fig. 5a, b), which agrees with the trends shown in Figure 3. The
328 simulations showed larger intra-seasonal fluctuations than the observed values, but in both the observations
329 and the simulations, the intra-seasonal variations were small compared to the total decrease over the course of
330 the growing season (Fig. 5a, b). It is also possible that the precipitation $\delta^{18}\text{O}$ at the study site differs from the
331 precipitation $\delta^{18}\text{O}$ at the meteorological station.

Fig. 5. Comparison between the observed and simulated intra-seasonal patterns of cellulose $\delta^{18}\text{O}$. Simulation of tree-ring $\delta^{18}\text{O}$, and of the difference in $\delta^{18}\text{O}$ between the simulated and observed values (the simulated value minus the observed value) for (a) 2007 and (b) 2008. (c) Scatterplots of the simulations with temperature (T) or relative humidity (RH) held constant at the mean 2007 to 2008 values, versus the full model simulation. The diagonal line represents $y = x$. (d) as in (c), except that the comparison is for simulations with precipitation $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_{\text{pre}}$) held constant at the mean 2007 to 2008 value versus the full model simulation. The horizontal line represents $\delta^{18}\text{O}$ of α -cellulose = 22.1‰, which represents mean value of the simulated series.

We assessed the simulated response to the input variables by repeating the same simulations, but with either temperature and relative humidity (Fig. 5c) or precipitation $\delta^{18}\text{O}$ (Fig. 5d) held constant at their mean 2007 to 2008 values. With temperature and relative humidity held constant, the scatterplot of the full vs. constrained (mean value) simulations showed values along the 1:1 line on the plot, indicating that the result was not sensitive to variations in temperature and relative humidity (Fig. 5c). However, if we held the precipitation $\delta^{18}\text{O}$ constant, the simulated variation is much reduced (Fig. 5d), suggesting that the observed variations are strongly sensitive to variations in the $\delta^{18}\text{O}$ of precipitation.

4. Discussion

4.1 Tree-ring $\delta^{18}\text{O}$ as a proxy for the seasonal incursion of the Indian Monsoon moisture

Plant physiological modeling suggests that tree-ring $\delta^{18}\text{O}$ is primarily controlled by the $\delta^{18}\text{O}$ of the source water, which itself depends on the precipitation amount, relative humidity, temperature, $\delta^{18}\text{O}$ of water vapor, and large-scale atmospheric circulation (Breitenbach et al., 2010; Kaspari et al., 2007; Yao et al., 2006, 2013; Zhang et al., 2005). Consistent with recent studies (Schubert and Jahren, 2015; Treydte et al., 2014; Yu et al., 2014), we found that source water $\delta^{18}\text{O}$ is the most important factor controlling tree-ring $\delta^{18}\text{O}$. The results from the mechanistic forward model from our study suggest that the intra-seasonal pattern of variation of tree-ring $\delta^{18}\text{O}$ was sensitive to variations in precipitation $\delta^{18}\text{O}$, but not to variations in relative humidity and temperature which contribute to evaporative enrichment of ^{18}O leaf water (Fig. 5c, d).

Combining results from forward modeling (Section 3.4) with the linear regression analysis (Section 3.2), we found that variations in precipitation $\delta^{18}\text{O}$ appear to explain 70% of intra-seasonal variations in cellulose $\delta^{18}\text{O}$ (Fig. 6). Variance in relative humidity does not explain any variance in forward-modeled evaporative enrichment of ^{18}O in leaf water (equation 5; Barbour et al., 2004; Evans, 2007). Evaporative enrichment of ^{18}O in the leaf water explains only 2% of the overall variance of tree-ring $\delta^{18}\text{O}$ (Eq. 7; Fig. 6; Table 3). Treydte et al. (2014) suggested that seasonal variations in evaporative enrichment of leaf water ^{18}O have a weaker influence on tree-ring $\delta^{18}\text{O}$ tree-ring variations than source water $\delta^{18}\text{O}$ in temperate and humid regions. Our study site is also humid, with a mean annual relative humidity of 78.8%, and is cool, with a mean annual temperature of $-0.73\text{ }^{\circ}\text{C}$ (Fig. 2); as a result of these factors, the evaporative demand is low (a total mean annual evaporation of 544 mm). Furthermore, Yu et al. (2014) conducted a monitoring study on the woody plant *Quercus aquifolioides* on the southeastern Tibetan Plateau, which also suggested leaf water stable isotopes values more closely tracked those observed in the monsoon precipitation, which was assumed to be source water during the rainy season. We consequently hypothesize that the low proportion of the additional variance explained by evaporative enrichment of ^{18}O in needle water in our study might have been influenced by low evaporation rates at our study site. In addition, Treydte et al. (2014) also suggested that a large part of the leaf water ^{18}O enrichment signal in tree-ring α -cellulose might be lost due to complicated fractionation processes between needles and the xylem; if uncorrelated with humidity and/or temperature variations, this loss of signal would increase the relative strength of the source water $\delta^{18}\text{O}$ signal in tree-ring $\delta^{18}\text{O}$ compared with that associated with evaporative enrichment of ^{18}O in leaf water.

377 However, previous studies of inter-annual resolution tree-ring $\delta^{18}\text{O}$ have suggested that the source water
378 $\delta^{18}\text{O}$ and evaporative enrichment of ^{18}O in leaf water both controlled tree-ring $\delta^{18}\text{O}$ in our study region (Liu
379 et al., 2013; Shi et al., 2011; Zeng et al., 2014). For instance, Shi et al. (2011) suggested that variations in
380 soil water $\delta^{18}\text{O}$ and leaf water ^{18}O enrichment could explain 44% and 51%, respectively, of the amplitude of
381 inter-annual tree-ring $\delta^{18}\text{O}$ variations simulated by the ORCHIDEE-iso model. Furthermore, these studies
382 have shown the importance of relative humidity in controlling inter-annual variations in tree ring $\delta^{18}\text{O}$. They
383 suggested the relative humidity could influence the leaf water enrichment of $\delta^{18}\text{O}$, and this signal may be
384 reflect in tree-ring $\delta^{18}\text{O}$. However, these studies neglected the covariation between relative humidity and the
385 precipitation $\delta^{18}\text{O}$ and source water $\delta^{18}\text{O}$, via dew-point deficit (ΔT_d), re-evaporation and isotopic exchange
386 between ambient water vapor and precipitation $\delta^{18}\text{O}$ in Asian monsoon regions (Zhang et al., 2005). Treydte
387 et al. (2014) also suggested that week-to-week variations in leaf-water $\delta^{18}\text{O}$ enrichment were strongly
388 controlled by weather conditions during the growing season; these short-term variations were, however, not
389 observed in intra-seasonal tree-ring $\delta^{18}\text{O}$.

390

391 **Table 3** Parameters (slope, intercept and R^2) of linear regression analysis for the relationship between
392 tree-ring $\delta^{18}\text{O}$, modeled enrichment of ^{18}O in leaf water and the climatic simulation inputs (relative humidity,
393 precipitation, and precipitation $\delta^{18}\text{O}$). Significance of slopes: *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

394

Dependent variable vs. Independent variable	Slope	Intercept	R^2	Equation
$\delta^{18}\text{O}_p$ vs. P	$a_1: -1.76^*$	$b_1: 14.18$	0.18	(3)
$\delta^{18}\text{O}_p$ vs. RH	$a_2: -0.76^{***}$	$b_2: 59.88$	0.42	(4)
$\Delta^{18}\text{O}_{\text{leaf}}$ vs. RH	$a_3: -0.15$	$b_3: 71.85$	0.01	(5)
$\delta^{18}\text{O}_c$ vs. $\delta^{18}\text{O}_p$	$a_4: 0.45^{***}$	$b_4: 27.96$	0.70	(6)
$\delta^{18}\text{O}_c$ vs. $\Delta^{18}\text{O}_{\text{leaf}}$	$a_5: 0.18$	$b_5: 21.15$	0.02	(7)

395

Fig. 6. Summary of the plant-mediated variables that potentially influence the intra-seasonal tree-ring $\delta^{18}\text{O}$ at our study sites from 2007 to 2008. The percentages along arrow lines and thickness of arrow lines represent the explained variance calculated from linear regression analysis (Table 3). Percentages in red are estimated from Eq. (5) and (7). Percentages in blue are estimated from Eq. (3), (4), and (6); note that these regressions are nonindependent. The proportion of the variance unexplained by precipitation amount and relative humidity = $1 - (\text{variance explained by precipitation} + \text{variance explained by relative humidity})$ and the unexplained variance in tree ring $\delta^{18}\text{O} = 1 - (\text{variance explained by precipitation } \delta^{18}\text{O} + \text{variance explained by leaf water enrichment of } ^{18}\text{O})$.

Precipitation $\delta^{18}\text{O}$ is an integrated tracer of water cycle fractionation associated with local phase changes and phase changes that cause variations in the $\delta^{18}\text{O}$ of source waters. Therefore, variations in precipitation $\delta^{18}\text{O}$ could reflect changes in the intensity of Indian Monsoon precipitation, if we may assume that the moisture source itself is not changing (Kaspari et al., 2007; Tian et al., 2001). Previous studies of the $\delta^{18}\text{O}$ in precipitation on the Tibetan Plateau have shown a coincidence of $\delta^{18}\text{O}$ decrease with the timing of monsoon onset, and a negative correlation between $\delta^{18}\text{O}$ and monsoon intensity (Tian et al. 2001). We interpret these results to suggest that incursion of Indian Monsoon moisture is responsible for the variation of tree-ring $\delta^{18}\text{O}$ over the course of the growing season in the data reported here. At the onset of the Indian monsoon (May to June), the monsoon activities begin transporting oceanic moisture from the Indian Ocean toward the southeastern Qinghai-Tibetan Plateau (Yu et al., 2014). However, precipitation amount at this time is still

low and soil evaporation capacity is very high (Gao et al., 2013; Yang et al., 2012), resulting in relatively enriched source water and tree-ring $\delta^{18}\text{O}$ (Figs 4, 5). Previous studies also demonstrated that tree-ring $\delta^{18}\text{O}$ in the early growing season may be affected by oxygen in stored reserves (starch and water) from the previous year (Jäggi et al., 2003; Roden et al., 2002; Treydte et al., 2014). Roden et al. (2002) proposed that the storage of photosynthates enriched in ^{18}O could result in higher tree-ring $\delta^{18}\text{O}$ in the early growing season. However, if trees at our study sites used photosynthate from the previous year to support early-season incremental growth, we would expect to observe lower $\delta^{18}\text{O}$ values (Fig. 4); this is inconsistent with the abrupt shift in $\delta^{18}\text{O}$ that we observed between the end of the previous growing season and beginning of the next season (Fig. 3). This suggests that even though trees require stored photosynthate for their early growth, oxygen from current precipitation dominated the signal. Further analysis of storage effects will be required to resolve this inconsistency based on analyses of pre-growing season and early growing season soil water $\delta^{18}\text{O}$ and needle $\delta^{18}\text{O}$ measurements.

During the active monsoon period (July to September), the Indian monsoon prevails at our study site. Water vapor flux is high, and intense precipitation events frequently occur (Yu et al., 2014), such that relative humidity and precipitation amount become the primary factors that determine variations in precipitation $\delta^{18}\text{O}$, and are thereafter reflected in the tree-ring $\delta^{18}\text{O}$, causing minimum $\delta^{18}\text{O}$ values to be observed toward the end of the growing season (Fig 4). Previous studies of the precipitation $\delta^{18}\text{O}$ on the Qinghai-Tibetan Plateau have shown a $\delta^{18}\text{O}$ decrease with onset of the monsoon and a strong negative correlation between $\delta^{18}\text{O}$ and monsoon intensity (Gao et al., 2013; Tian et al., 2001; Yang et al., 2012). In the present study, the intra-seasonal tree-ring $\delta^{18}\text{O}$ data suggests a similar pattern. Therefore, variations in tree-ring $\delta^{18}\text{O}$ might provide a useful indicator of interannual variations in the intra-seasonal intensity of the Indian Monsoon. For example, the intra-seasonal tree-ring $\delta^{18}\text{O}$ in 2011 reached a minimum 1 month earlier than in other years (Fig. 3), which might be interpreted to indicate the early onset of the monsoon during 2011 (Fig. S4). However, additional intra-seasonally resolved data for years in which Indian Monsoon intensity varied are necessary to support this conjecture.

4.2 Comparison with earlier studies from monsoon regions

Previous studies have suggested that intra-seasonal variation in tree-ring $\delta^{18}\text{O}$ reflects seasonal variation of the monsoon rainfall amount and relative humidity in the Indian Monsoon region (Fig. 1; Managave et al., 2010, 2011; Schollaen et al., 2013, 2014; Zhu et al., 2012a, 2012b). Previous studies of the isotope

composition of wood from monsoon-affected regions found intra-seasonal cycles and seasonal amplitudes (a range of 3 to 6‰) smaller than those observed in the present study (Fig. 7). Figure 7 shows that most previous studies found higher tree-ring $\delta^{18}\text{O}$ in the early and late growing seasons, and lower tree-ring $\delta^{18}\text{O}$ in the middle, from August to September (Managave et al., 2010; Schollaen et al., 2013, 2014; Zhu et al., 2012a, 2012b); however, Managave et al. (2011) found that tree rings have lower $\delta^{18}\text{O}$ values in the early and late growing seasons and higher values in the middle. Our results showed more of a sinusoidal pattern, with a relatively continuous decrease in tree-ring $\delta^{18}\text{O}$ throughout the growing season, but with a slight increase towards the end of the growing season, in September. This is not consistent with the observed intra-seasonal tree-ring $\delta^{18}\text{O}$ pattern for the other study areas, which are tropical Asian monsoon locations (Fig. 1). Because our study site lies far from the tropics, we infer that the greater influence of relative humidity relative to precipitation amount is affected by the different climatic conditions. In general, northward movement of the region of atmospheric convergence during the growing season brings moisture-laden southwest winds from the Indian Ocean region into our study area, which results in high rainfall and relative humidity from June to September, accompanied by lower tree-ring $\delta^{18}\text{O}$; southward movement of the atmospheric convergence after September brings mostly dry northwest continental winds onto the southeastern Qinghai-Tibetan Plateau, producing less rainfall, lower relative humidity, and higher tree-ring $\delta^{18}\text{O}$ (Managave et al., 2010; Zhu et al., 2012a). The same pattern is observed during the onset of rainy season conditions in the southern hemisphere (Schollaen et al., 2013, 2014). Because of the short growing season at our study sites, tree-ring $\delta^{18}\text{O}$ shows only a slight increase toward the end of the growing season despite the return of the westerly wind regime.

Fig. 7. Comparison of the observed intra-seasonal tree-ring $\delta^{18}\text{O}$ patterns between the present study and other sites. The grey shading represents periods with similar patterns of tree-ring $\delta^{18}\text{O}$ variation at several sites. (a) The present study. (b) Central India (Managave et al., 2010), (c) Kerala India (Managave et al., 2011), (d) northern Thailand (Zhu et al., 2012a), (e) Cambodia (Zhu et al., 2012b), and (f) Indonesia (Schollaen et al., 2013).

4.3 Uncertainty in the forward simulations

Although the simulations agreed qualitatively with the observed patterns, differences in the actual values may have arisen from observational uncertainties, poorly constrained model parameters, uncertainty in the model's forcing inputs, and uncertainty arising from the simplifications of modeling. First, the Péclet effect on leaf water enrichment and the proportion of isotopic exchange between xylem water and carbohydrate oxygen (f) may differ among species, leaf morphologies, and stomatal activity (Song et al., 2014; Treydte et al., 2014). If the Péclet effect or oxygen atom exchange during wood (α -cellulose) synthesis is not constant over the year, then f is not constant either (Treydte et al., 2014). Consequently, the physiology of Smith fir at the study location should be observed during the growing season to obtain more accurate f values for use in future research.

Second, we assumed that $\delta^{18}\text{O}$ in the source water (soil water) can be represented by the unmodified precipitation $\delta^{18}\text{O}$, but soil water $\delta^{18}\text{O}$ may be evaporatively enriched in ^{18}O compared with precipitation, with the enrichment in proportion to changes in the evapotranspirational demand over the course of the growing season (Moreno-Gutiérrez et al., 2012). The variation in modeled tree-ring $\delta^{18}\text{O}$ at an intra-seasonal

resolution may arise from neglecting to model the mixing of water from different rain events with different precipitation $\delta^{18}\text{O}$ signatures in the soil water pool from which the trees pull their source water (Jäggi et al., 2003; Fig. 4).

Third, $\delta^{18}\text{O}$ in different precursors to α -cellulose may be significantly correlated on daily to weekly timescales, and this correlation may be relevant for intra-seasonal studies (Barnard et al., 2007; Gessler et al., 2009). For example, Barnard et al. (2007) found that the time-lag from $\delta^{18}\text{O}$ in needle water to phloem sap is about 1 to 2 days. Furthermore, a certain residence time of xylem water in the tracheids (Brandes et al., 2007) and considerable time lags for water at the base of the trunk of coniferous species to reach the crown (2.5 to 21 d; Meinzer et al., 2006) could decouple temporal tree-ring $\delta^{18}\text{O}$ patterns from source water $\delta^{18}\text{O}$ patterns during the growing season. In our study, there was also a time lag of 2 to 3 days between precipitation $\delta^{18}\text{O}$ and tree-ring $\delta^{18}\text{O}$ (data not shown). Consequently, time-lag effects should also be considered in future tree-ring $\delta^{18}\text{O}$ modeling.

Beyond the uncertainty in plant physiological factors and modeling, the use, and quality and representativity of our meteorological station datasets can also cause offset between observed and modeled intra-seasonal tree-ring $\delta^{18}\text{O}$. The input meteorological dataset is not co-located with the investigation sites. This is a common problem for calibration of palaeoclimatic observations, but is exacerbated for high (intra-annual) resolution studies because short timescale variations in precipitation and humidity are expected to be less correlated across distance than long timescale processes (Wallace, 1996a,1996b), perhaps especially in topographically variable climates and ecosystems as found in high Asia.

4.4 Other potential sources of disagreement between the observed and simulated values

Schollaen et al. (2014) found that the ability of trees to integrate environmental information depends on the rate of wood formation and the longevity of cells relative to the timescale of the environmental forcing. Although thin-walled earlywood cells form rapidly, they may only live for days. In contrast, thick-walled latewood cells are built slowly, but may live for few weeks (during the process of lignification) and may therefore integrate environmental information over a much longer period of time; this might also lead to smoothing of the tree-ring $\delta^{18}\text{O}$ series at intra-seasonal resolution (Fig. 3, 4). In addition, the model we used does not account for other seasonally varying tree physiological processes, such as the kind and size of the carbohydrate pools (amounts of C and O), partitioning between catabolic and anabolic metabolism, and metabolic flux rates (Gessler et al., 2009; Werner et al., 2012). It is still unclear whether oxygen exchange

between organic compounds and water occurs during phloem loading and transport (Gessler et al., 2009, 2014). For example, Gessler et al. (2013) studied the transfer of oxygen isotopes from leaf water via leaf sugars to phloem sugars in five tree species; though they found that leaf sugars showed the expected ^{18}O enrichment in all five species, they found that the expected enrichment in phloem sugars was lower than expected based on the leaf water enrichment in two coniferous gymnosperms (*Pinus sylvestris* and *Larix decidua*) and a broadleaf evergreen angiosperm (*Eucalyptus delegatensis*).

4.5 Summary

We detected an intra-seasonal cycle of tree-ring $\delta^{18}\text{O}$ from several annual growth rings of Smith fir growing in a mountainous region of the southeastern Qinghai-Tibetan Plateau. The pattern of intra-seasonal variation observed in the tree-ring $\delta^{18}\text{O}$ was consistent with the intra-seasonal pattern of precipitation $\delta^{18}\text{O}$, despite large uncertainties that led to differences between the observed and simulated values. Mechanistic modeling and linear regression analysis both suggested that the decrease in tree-ring $\delta^{18}\text{O}$ from the early to late growing season was mainly controlled by monsoon precipitation $\delta^{18}\text{O}$, which was in turn controlled by variations in relative humidity and precipitation amount, particularly during the late growing season. Consistent with previous studies of tree-ring $\delta^{18}\text{O}$, the observed intra-seasonal variation of the tree-ring $\delta^{18}\text{O}$ of can reflect the seasonal evolve of the Indian Monsoon. Our results suggest that anomalies in tree-ring $\delta^{18}\text{O}$ during the mid- to late parts of the growing season may reveal inter-annual variations in Indian Monsoon intensity and, in combination with wood anatomical measurements, might be used to infer changes in the timing and intensity of the monsoon in the southeastern Qinghai-Tibetan Plateau. Further tree physiological measurements and additional intra-annually resolved datasets for periods spanning recent variations in the intensity of the Indian Monsoon will be required to improve our understanding of the processes involved in isotopic fractionation and facilitate interpretation of longer, intra-seasonal-resolution $\delta^{18}\text{O}$ data series to study natural variability in monsoon moisture transport into the study region on interannual to multi-century time scales.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (41571196 & 41121001), by the Major State Basic Research Development Program of China (973 Program) (2013CBA01808). M.N. Evans is grateful for support from the United States National Science Foundation award (ATM-0902794) and from the University of Maryland. We thank Prof. Eryuan Liang and Dr. Xiaoxin Yang from the Institute

of Tibetan Plateau Research, Chinese Academy of Sciences, for providing the Gompertz function and precipitation $\delta^{18}\text{O}$ data. We also thank Dr. Xiaoxia Li and Dr. Xiaoming Lu from the Institute of Tibetan Plateau Research, Chinese Academy of Sciences, for their help during our field work. We thank the editor and three anonymous reviewers, whose comments and suggestion are very helpful in improving the quality of the manuscript.

References

- Barbour, M.M., Roden, J.S., Farquhar, G.D., Ehleringer, J.R., 2004. Expressing leaf water and cellulose oxygen isotope ratios as enrichment above source water reveals evidence of a Péclet effect. *Oecologia* 138(3), 426-435.
- Barnard, R.L., Salmon, Y., Kodama, N., Sorgel, K., Holst, J., Rennenberg, H., Gessler, A., Buchmann, N., 2007. Evaporative enrichment and time lags between delta O-18 of leaf water and organic pools in a pine stand. *Plant Cell Environ.* 30, 539-550.
- Cook, E.R., 1985. A time series analysis approach to tree-ring standardization, PhD dissertation. University of Arizona, Tucson, AZ, USA. Software available at: <http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software>
- Evans, M.N., 2007. Toward forward modeling for paleoclimatic proxy signal calibration: a case study with oxygen isotopic composition of tropical woods. *Geochem. Geophys. Geosys.* 8(7), 1-13.
- Gao, J., Masson-Delmotte, V., Risi, C., He, Y., Yao, T., 2013. What controls precipitation $\delta^{18}\text{O}$ in the southern Tibetan Plateau at seasonal and intra-seasonal scales? A case study at Lhasa and Nyalam. *Tellus B* 65, 21043. <http://dx.doi.org/10.3402/tellusb.v65i0.21043>.
- Gessler, A., Brandes, E., Buchmann, N., Helle, G., Rennenberg, H., Barnard, R.L., 2009. Tracing carbon and oxygen isotope signals from newly assimilated sugars in the leaves to the tree-ring archive. *Plant Cell Environ.* 32, 780-795.
- Gessler, A., Brandes, E., Keitel, C., Boda, S., Kayler, Z., Granier, A., Barbour, M., Farquhar, G.D., Treydte, K., 2013. The oxygen isotope enrichment of leaf-exported assimilates—does it always reflect lamina leaf water enrichment? *New Phytol.* 200, 144–157.
- Holmes, R.L., 1983. Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bull.* 43, 69-75.
- IPCC, 2014. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral*

Aspects, in: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E.,
Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N.,
MacCracken, S., Mastrandrea, P.R., White L.L. (Eds.), Cambridge University Press, Cambridge, United
Kingdom, pp. 1-1132.

Jäggi, M., Saurer, M., Fuhrer, J., Siegwolf, R., 2003. Seasonality of $\delta^{18}\text{O}$ in needles and wood of *Picea*
abies. New Phytol. 158, 51-59.

Jarvis, P.G., McNaughton, K.G., 1986. Stomatal control of transpiration: scaling up from leaf to region. Adv.
Ecol. Res. 15, 1-19.

Johnson, K.R., Ingram, B.L., 2004. Spatial and temporal variability in the stable isotope systematics of
modern precipitation in China: implications for paleoclimate reconstructions. Earth Planet Sci. Lett. 220,
365-377.

Kang, S., Xu, Y., You, Q., Flügel, W.A., Pepin, N., Yao, T., 2010. Review of climate and cryospheric change
in the Tibetan Plateau. Environ. Res. Lett. 5, 015101. doi:10.1088/1748-9326/5/1/015101.

Kaspari, S., Mayewski, P., Kang, S., Sneed, S., Hou, S., Hooke, R., Kreutz, K., Introne, D., Handley,
M., Maasch, K., Qin, D., Ren, J., 2007. Reduction in northward incursions of the South Asian monsoon
since 1400 AD inferred from a Mt. Everest ice core. Geophys. Res. Lett. 34, 16, 948276.

Klein, J.A., Harte, J., Zhao, X.Q., 2004. Experimental warming causes large and rapid species loss,
dampened by simulated grazing, on the Tibetan Plateau. Ecol. Lett. 7(12), 1170–1179.

Lawrence, M.G., 2005. The relationship between relative humidity and the dew point temperature in moist
air: a simple conversion and applications. Bull. Am. Meteorol. Soc. 86, 225-233.

Leavitt, S.W., Danzer, S.R., 1993. Method for batch processing small wood samples to holocellulose for
stable-carbon isotope analysis. Anal. Chem. 65, 87-89.

Li, X., Liang, E., Gricar, J., Prislan, P., Rossi, S., Cufar, K., 2013. Age dependence of xylogenesis and its
climatic sensitivity in Smith fir on the south-eastern Tibetan Plateau. Tree Physiol. 33(1), 48-56.

Liang, E., Liu, B., Zhu L., Yin Z-Y. 2011. A short note on linkage of climatic records between a river valley
and the upper timberline in the Sygera Mountains, southeastern Tibetan Plateau. Global Planet.
Change 77(1-2, 97-102.

Liang, E., Wang, Y., Xu, Y., Liu, B., Shao, X., 2010. Growth variation in *Abies georgei* var. *smithii* along
altitudinal gradients in the Sygera Mountains, southeastern Tibetan Plateau. Trees 24(2), 363-373.

601 Liu, X., Zeng, X., Leavitt, S. W., Wang, W., An, W., Xu, G., Sun, W., Wang, Y., Qin, D., Ren, J., 2013. A
 602 400-year tree-ring $\delta^{18}\text{O}$ chronology for the southeastern Tibetan Plateau: implications for inferring
 603 variations of the regional hydroclimate. *Global Planet. Change* 104, 23–33.

604 Managave, S.R., Sheshshayee, M.S., Borgaonkar, H.P., Ramesh, R., 2010. Past break-monsoon conditions
 605 detectable by high resolution intra-seasonal $\delta^{18}\text{O}$ analysis of teak rings. *Geophys. Res. Lett.* 37, L05702.
 606 doi:10.1029/2009GL041172

607 Managave, S.R., Sheshshayee, M.S., Bhattacharyya, A., Ramesh, R., 2011. Intra-seasonal variations of teak
 608 cellulose $\delta^{18}\text{O}$ in Kerala, India: implications to the reconstruction of past summer and winter monsoon
 609 rains. *Clim. Dynam.* 37(3-4), 555-567.

610 Meinzer, F.C., Brooks, J.R., Domec, J.C., Gartner, B.L., Warren, J.M., Woodruff, D.R., Bible, K., Shaw,
 611 D.C., 2006. Dynamics of water transport and storage in conifers studied with deuterium and heat tracing
 612 techniques. *Plant Cell Environ.* 29, 105-114.

613 Mölg, T., Maussion, F., Scherer, D., 2014. Mid-latitude westerlies as a driver of glacier variability in
 614 monsoonal High Asia. *Nature Clim. Change* 4, 68–73.

615 Moreno-Gutiérrez, C., Dawson, T.E., Nicolás, E., Querejeta, J.I., 2012. Isotopes reveal contrasting water use
 616 strategies among coexisting plant species in a Mediterranean ecosystem. *New Phytol.* 196, 489-496.

617 Ren Q., Zhao, J., Wang, J., Yang, X., Pu, Q., Sun, Y., Chen, B., 2011. Photosynthetic physiological
 618 characteristics of alpine timberline Smith fir (*A. georgei* var. *smithii*) in on southeastern Tibetan Plateau.
 619 *Journal of Northeast Forestry University* 39(1), 17-19. (In Chinese with English abstract)

620 Roden, J.S., Lin, G., Ehleringer, J.R., 2002. Response to the comment of V. J. Terwilliger on “A mechanistic
 621 model for interpretation of hydrogen and oxygen isotope ratios in tree-ring cellulose”. *Geochim.*
 622 *Cosmochim. Acta* 66, 733-734.

623 Schollaen, K., Heinrich, I., Neuwirth, B., Krusic, P.J., D'Arrigo, R.D., Karyanto, O., Helle, G., 2013.
 624 Multiple tree-ring chronologies (ring width, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) reveal dry and rainy season signals of
 625 rainfall in Indonesia. *Quat. Sci. Rev.* 73, 170-181.

626 Schollaen, K., Heinrich, I., Helle, G., 2014. UV-laser-based microscopic dissection of tree rings—a novel
 627 sampling tool for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ studies. *New Phytol.* 201(3), 1045-1055.

628 Schubert, B. A., Jahren A.H., 2015. Seasonal temperature and precipitation recorded in the intra-annual
 629 oxygen isotope pattern of meteoric water and tree-ring cellulose. *Quat. Sci. Rev.* 125, 1-14.

Shi, C., Masson-Delmott, V., Risi, C., Eglin, T., Stievenard, M., Pierre, M., Wang, X., Gao, J., Breon, F.M.,
 Zhang, Q.B., Daux, V., 2011. Sampling strategy and climatic implications of tree-ring stable isotopes on
 the southeast Tibet Plateau. *Earth Planet. Sci. Lett.* 301, 307–316.

Song, X., Clark, K.S., Helliker, B.R., 2014. Interpreting species-specific variation in tree-ring oxygen
 isotope ratios among three temperate forest trees. *Plant Cell Environ.* 37, 2169-2182.

Stokes, M.A., Smiley, T.L., 1968. *An Introduction to Tree-Ring Dating*. University of Chicago Press,
 Chicago.

Thompson, L.G., Yao, T., Mosley-Thompson, E., Davis, M.E., Henderson, K.A., Lin, P.N., 2000. A
 high-resolution millennial record of the South Asian Monsoon from Himalayan ice cores. *Science* 289,
 1916-1919.

Tian, L., Masson-Delmotte, V., Stievenard, M., Yao, T., Jouzel, J., 2001. Tibetan Plateau summer monsoon
 northward extent revealed by measurements of water stable isotopes. *J. Geophys. Res.* 106(D22),
 28081–28088.

Tian, L., Yao, T., Li, Z., MacClune, K., Wu, G., Xu, B., Li, Y., Lu, A., Shen, Y., 2006. Recent rapid warming
 trend revealed from the isotopic record in Muztagata ice core, eastern Pamirs. *J. Geophys. Res.* 111,
 D13103.

Treydte, K., Boda, S., Pannatier, E.G., Fonti, P., Frank, D., Ullrich, B., Saurer, M., Siegwolf, R., Battipaglia,
 G., Werner, W., Gessler, A., 2014. Seasonal transfer of oxygen isotopes from precipitation and soil to the
 tree ring: source water versus needle water enrichment. *New Phytol.* 202(3), 772-783.

Wallace, J., 1996a. Observed Climatic Variability: Time Dependence, in: Anderson, D.T., Willebrand, J.
 (Eds.), *Decadal Climate Variability*. Springer, Berlin Heidelberg, 44: 1-30.

Wallace, J., 1996b. Observed Climatic Variability: Spatial Structure, in: Anderson, D.T., Willebrand, J.
 (Eds.), *Decadal Climate Variability*. Springer, Berlin Heidelberg, 44: 1-30.

Werner, C., Schnyder, H., Cuntz, M., Keitel, C., Zeeman, M.J., Dawson, T.E., Badeck, F.W., Brugnoli, E.,
 Ghashghaie, J., Grams, T.E.E. et al., 2012. Progress and challenges in using stable isotopes to trace plant
 carbon and water relations across scales. *Biogeosciences* 9, 3083–3111.

Yang, X., Yao, T., Yang, W., Xu, B., He, Y., Qu, D., 2012. Isotopic signal of earlier summer monsoon onset
 in the Bay of Bengal. *J. Clim.* 25(7), 2509-2516.

Yao, T., Guo, X., Thompson, L.G., Duan, K., Wang, N., Pu, J., Xu, B., Yang, X., Sun, W., 2006. $\delta^{18}\text{O}$ record

and temperature change over the past 100 years in ice cores on the Tibetan Plateau. *Sci. China Ser. D* 49, 1-9.

Yao, T., Masson-Delmotte, V., Gao, J., Yu, W., Yang, X., Risi, C., Sturm, C., Werner, M., Zhao, H., He, Y., Ren, W., Tian, L., Shi, C., Hou, S., 2013. A review of climatic controls on $\delta^{18}\text{O}$ in precipitation over the Tibetan Plateau: observations and simulations. *Rev. Geophys.* 51, 525-548.

Yu, W., Xu, B., Lai, C., Ma, Y., Tian, L., Qu, D., Zhu, Z., 2014. Influences of relative humidity and Indian monsoon precipitation on leaf water stable isotopes from the southeastern Tibetan Plateau. *Geophys. Res. Lett.* 41: 7746-7753.

Zeng, X., Liu, X., Wang, W., Xu, G., An, W., Wu, G., 2014. No altitude-dependent effects of climatic signals are recorded in Smith fir tree-ring $\delta^{18}\text{O}$ on the southeastern Tibetan Plateau, despite a shift in tree growth. *Boreas* 43, 588–599.

Zhang, Q., Evans, M.N., Lyu, L., 2015. Moisture dipole over the Tibetan Plateau during the past five and a half centuries. *Nat. Commun.* 6, 8062. doi:10.1038/ncomms9062.

Zhang, X., Liu, J., He, Y., Tian, L., Yao, T., 2005. Humidity effect and its influence on the seasonal distribution of precipitation $\delta^{18}\text{O}$ in monsoon regions. *Adv. Atmos. Sci.* 22(2), 271-277.

Zhu, M., Stott, L., Buckley, B., Yoshimura, K., 2012a. 20th century seasonal moisture balance in Southeast Asian montane forests from tree cellulose $\delta^{18}\text{O}$. *Clim. Change* 115(3-4), 505-517.

Zhu, M., Stott, L., Buckley, B., Yoshimura, K., Ra, K., 2012b. Indo-Pacific Warm Pool convection and ENSO since 1867 derived from Cambodian pine tree cellulose oxygen isotopes. *J. Geophys. Res.* 117, D11307. doi:10.1029/2011JD017198.