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Reconstruction of past precipitation δ^{18}O using tree-ring cellulose δ^{18}O and δ^{13}C: A calibration study near Lac d'Annecy, France

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Abstract

Two sets of living oaks (*Quercus R.*) growing under different hydrological situations were sampled near Lac d'Annecy, France. The stable isotope composition of the latewood cellulose was analysed in terms of oxygen and carbon isotopic composition for the period 1971–2001 and compared to the nearby monthly meteorological (temperature, relative humidity) and isotopic composition of precipitation records. A linear regression shows that 60% of the cellulose oxygen isotopic composition inter-annual variations are due to changes in precipitation isotopic composition and relative humidity. The small slope between cellulose versus precipitation oxygen isotopic composition suggests a significant contribution of local continental recycling and questions the common assumption that vapour oxygen isotopic composition is at equilibrium with precipitation isotopic composition in Europe during the growing season. Finally, the combined use of tree-ring oxygen and carbon isotopic composition records enables to account for leaf water enrichment due to stomata stress and to provide a reconstruction ($R^2=0.64$) of the summer precipitation isotopic composition.

Keywords: Quercus; tree rings; proxy; oxygen; carbon; stable isotopes; humidity

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1. Introduction

Quantitative reconstructions of recent climatic changes provide a necessary framework to evaluate the natural versus anthropogenic variability and the realism of high resolution climate simulations, increasingly used for predictions and impact studies.

The oxygen isotopic composition of water (δ^{18}O) is classically used to reconstruct past temperature changes from ice cores (e.g.[1]). Precipitation δ^{18}O (hereafter $\delta^{18}O_p$) is an integrated tracer of the hydrological cycle. It is related to local temperature through the air mass distillation, but can also record other features such as evaporation conditions, origin of the air mass, continental recycling [2,3]. It can also be simulated within global [4] or regional [5] atmospheric models. Unfortunately, complex deposition and post-deposition effects preclude the application of this method to Alpine glacier ice. Alternative indirect archives of $\delta^{18}O_p$ with constrained

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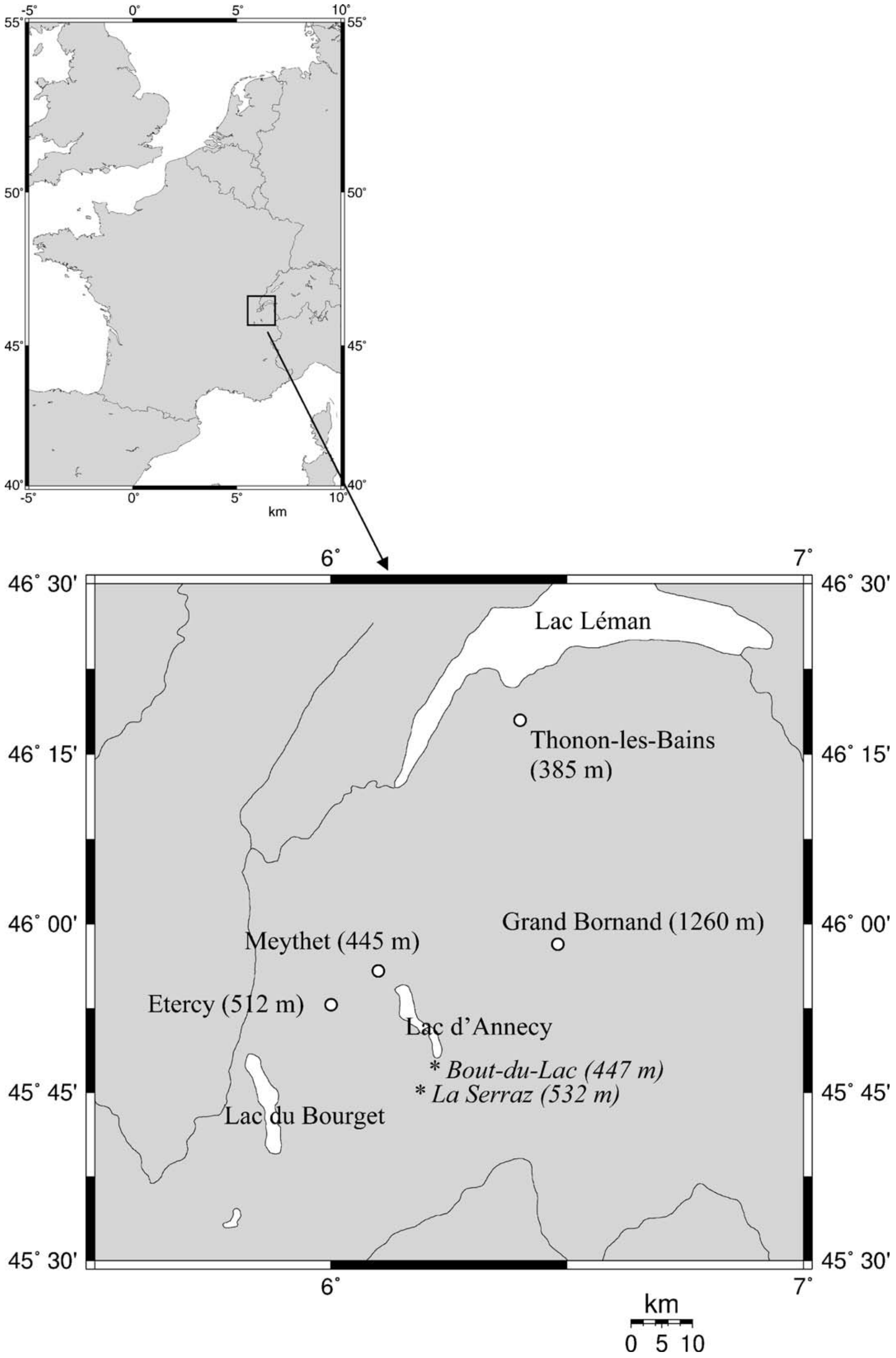

Fig. 1. Location map of sampling sites: Lac d'Annecy (5.16°E, 45.88°N, 447 m elevation), forests of Bout-du-Lac and La Serraz, water stable isotope sampling sites of Etercy (6°E, 45.88°N, 512 m elevation), Grand Bornand (6.48°E, 45.97°N, 1260 m elevation) and Thonon-les-Bains (6.4°E, 46.3°N, 385 m elevation), meteorological station of Meythet (45°55′45″N, 6°5′56″E, 445 m elevation). Elevations above sea level are also displayed on the map.

hydrological effects have to be used over the continents such as speleothems [6] or lake sediments. For instance, [7] demonstrated that the oxygen isotopic composition of the calcite of selected species of benthic ostracods valves from Ammersee (S. Germany) can be a proxy for $\delta^{18}O_p$ equivalent to Greenland deep ice cores.

In order to obtain a second European record of similar decadal resolution, a similar effort has been implemented at Lac d'Annecy, south-eastern France (Fig. 1). Local monthly $\delta^{18}O_p$ have been monitored during ~3 years in order to refine the knowledge of regional $\delta^{18}O_p$ variability, available from the long-term monitoring of Thonon-Les-Bains established in 1963. The lake sediments will offer a ~decadal resolution, because of the water turn over in the lake basin [8]. In order to develop a multi-archive approach to reconstruct past $\delta^{18}O_p$ changes, we have explored the climatic potential of another archive, the tree-ring cellulose. Owing to the development of continuous flow mass spectrometry techniques [9], a wealth of recent studies has been dedicated to tree-ring isotopic composition, and highlighted the climatic potential of $\delta^{18}O$ records from several tree species at mid-latitudes, in Switzerland [10–14], northern Eurasia [15], Canada [16], Great-Britain [17,18], and France [19,20].

The latewood tree-ring cellulose $\delta^{18}O_{lwc}$ is indirectly related to precipitation $\delta^{18}O_p$ [18,22,21]. The trees use soil water through their roots, without fractionation. The xylem water is then transported to the leaves. In the leaves, stomata water vapour exchanges with the atmospheric water vapour [23] including the Péclet effect [24] that leads to leaf water enrichment. Photosynthesis imprints an additional fractionation of oxygen in the organic molecules with respect to leaf water isotopic composition. During their transport towards the wood cell and the formation of cellulose and other organic compounds of the wood, these photosynthesis products exchange about 40% of their oxygen atoms with the xylem water [24–27]. In contrast with the fractionation processes associated with carbon assimilation more directly linked with the stomata and photosynthesis effects, the overall processes leading to the $\delta^{18}O_{lwc}$ include a return spring towards soil moisture isotopic signal. The selection of one component (cellulose) from one growing season (latewood) should enable to avoid supplementary sources of uncertainties related to the relative proportion of different compounds of the wood (e.g. lignin versus cellulose) and the use of previous season photosynthetic products mostly used to form the early wood. The relationship between the soil water available for the trees and $\delta^{18}O_p$ itself is not necessary straightforward, as it is expected to depend on soil water renewal time at root depths.

In order to evaluate the climate potential of $\delta^{18}O_{lwc}$, we have chosen to sample living oaks (*Quercus R.*) from two forests growing in different hydrological conditions. La Serraz is located on a ridge about 85 m above the lake level, while the second site, Bout-du-Lac, is in the flood plain of the Ire river, a lake tributary. In this paper, we discuss the observed relationships between $\delta^{18}O_{lwc}$ records and the nearby meteorological and $\delta^{18}O_p$ records (Figs. 2 and 3) for the time period from 1971 to 2002. We propose a method to estimate past changes in $\delta^{18}O_p$ taking advantage of combined $\delta^{18}O_{lwc}$ and $\delta^{13}C_{lwc}$ measurements.

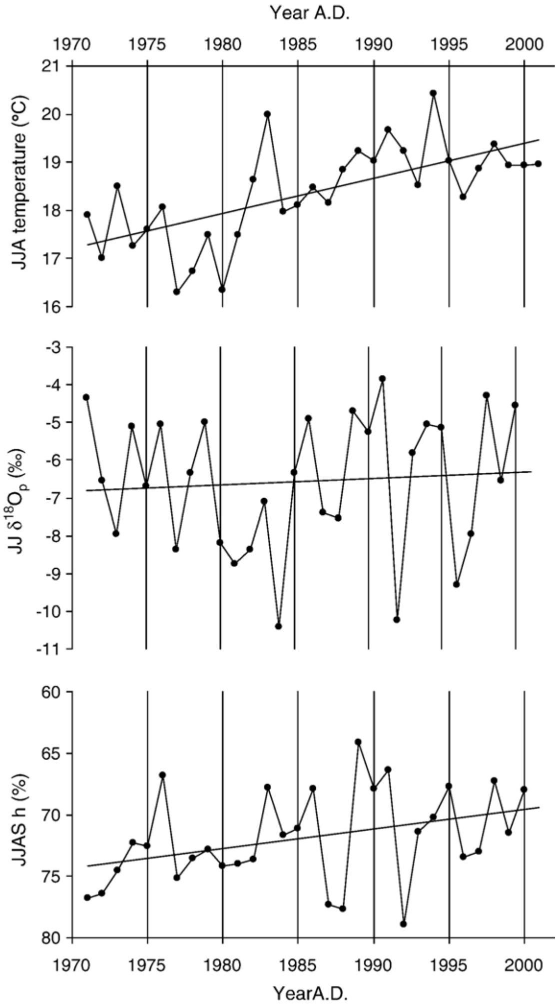

Fig. 2. Temporal evolutions of Meythet June–July–August mean temperature (°C), Thonon-les-Bains June–July–August precipitation $\delta^{18}O$, and Meythet June–July–August–September relative humidity (inversed vertical axis, in %) from 1971 to 2002.

2. Materials and methods

2.1. Sampling and dating

At La Serraz (Fig. 1), thirteen oak trees of homogeneous appearance (dominant, healthy trees showing the physiological characteristics of Quercus R., with similar diameters and heights) were sampled. For each tree, three cores regularly spaced on the circumference were taken at ca. 1.30 m height. The annual tree-ring widths (earlywood and latewood widths) were measured at LSCE. The trees were estimated to be 50 to 80 years old. The possible effect of tree aging on their growth is discussed in Section 3.1. Four outliers with anomalous growth patterns were discarded according to 1) the comparison of the ring width to the mean ring width of the whole set, ii) the age of the tree, iii) the inter-tree and inter-annual variabilities. The latewood rings of the time period 1971–2001 from the nine selected trees were cut and yearly samples from the individual selected trees were pooled.

At Bout-du-Lac (Fig. 1), 15 trees were sampled with the same selection criteria and methodology. A set of 6 trees of homogeneous growth patterns was selected and yearly latewood samples were pooled.

The average ring widths of the selected sets are displayed on Fig. 4 and the different mean tree growths are discussed in Section 3.1.

2.2. Isotopic measurements

For each core of each tree of the selected sets, latewood rings were cut and pooled. The pooled samples were milled (<80 μm). The α-cellulose was extracted following the procedure developed by [28] and modified by [29]. $\delta^{18}O_{lwc,}$ and $\delta^{13}C_{lwc}$ were measured with an elemental analyser (NC 2500, Carbo Elba) connected to a continuous flow mass spectrometer (Finnigan® MAT 252) at LSCE [9]. $\delta^{18}O_{lwc}$ and $\delta^{13}C_{lwc}$ are quoted in standard δ notation relative to V-SMOW and PDB, respectively. Our internal standard is a pure α-cellulose (CC31 from Whatman®). We measured its absolute values ($\delta^{18}O = 31.85$‰/SMOW and $\delta^{13}C = -25.43$‰/PDB) relatively to IAEA C3 standard. The reproducibility of measurements carried out on CC31 is better than 0.3‰ for $\delta^{18}O$ and 0.1‰ for $\delta^{13}C$. The samples were systematically analysed several times (2

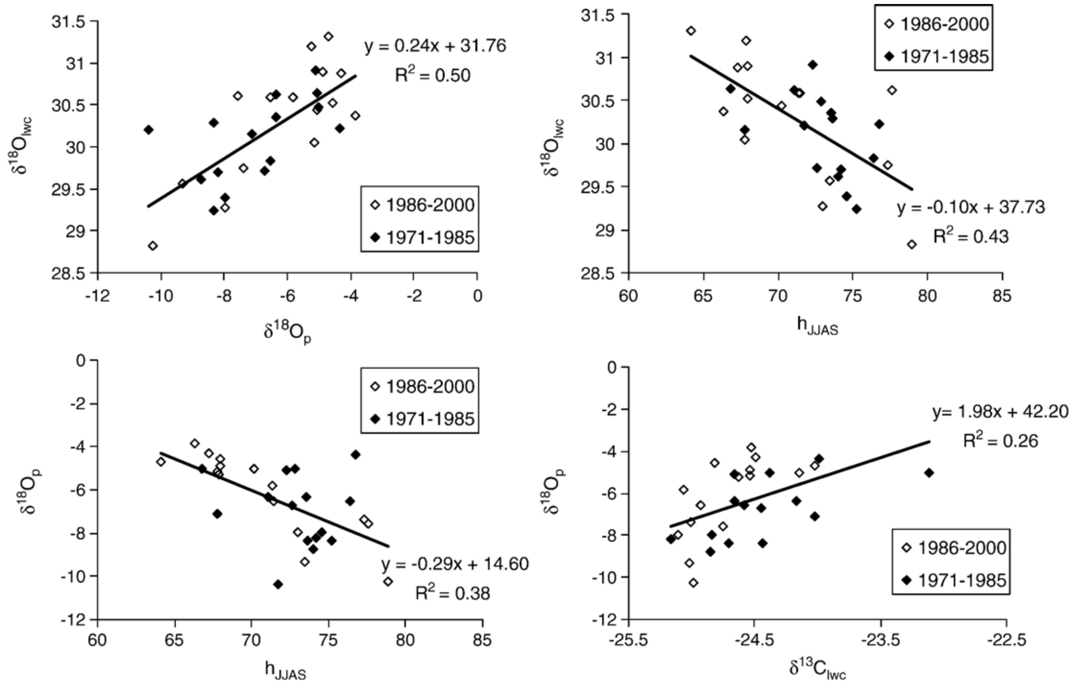

Fig. 3. Top panels: Correlations between the average Annecy latewood cellulose $\delta^{18}O$ (‰) and observations of (top left) June–July Thonon-les-Bains June–July precipitation $\delta^{18}O$ (‰) and (top right) June–July–August–September relative humidity (%). Linear regressions are displayed for the full records but the first and second half of the datasets are displayed with different colours to show the changes between the first and second half of the records. Bottom panels: Correlations between the June–July Thonon-les-Bains June–July precipitation $\delta^{18}O$ (‰) and (left) average Annecy latewood cellulose $\delta^{13}C$ (‰), (right) June–July–August–September relative humidity (%).

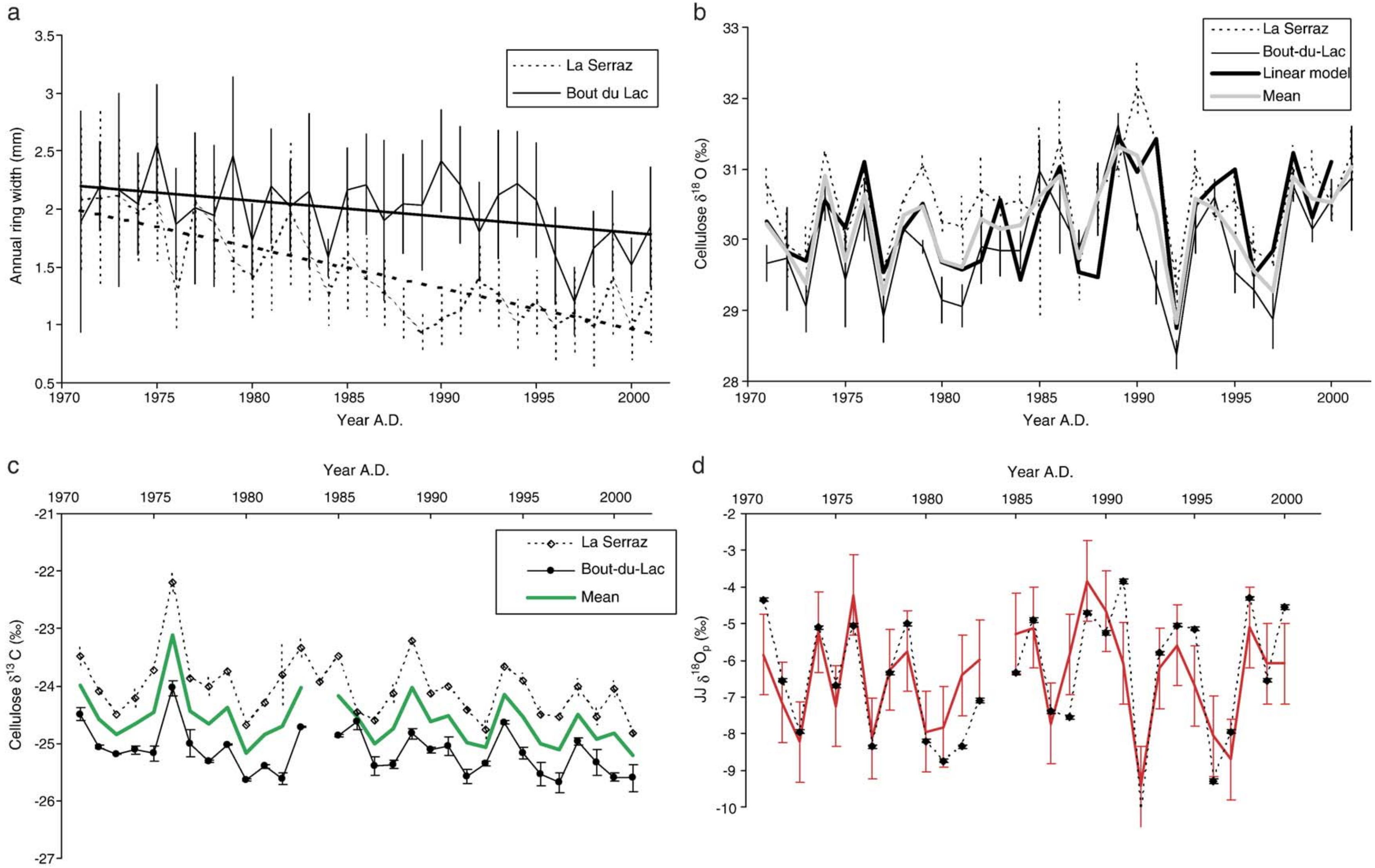

Fig. 4. (a) Inter-annual fluctuations of mean ring width of selected trees from La Serraz (dashed line) and from Bout-du-Lac (solid line). Error bars correspond to the inter-tree annual ring width standard deviation. (b) Inter-annual fluctuations of cellulose δ^{18}O (‰) from La Serraz (dashed line) and Bout-Du-Lac (solid line). Error bars correspond to the analytical reproducibility estimated from 2 to 3 measurements conducted on the same cellulose samples. The signal averaged from the 2 sites is displayed in grey. The cellulose δ^{18}O estimated from a linear model depending on Thonon-les-Bains June–July δ^{18}O and Thonon-les-Bains June–July–August–September relative humidity is displayed as a thick black line. (c) Inter-annual fluctuations of cellulose δ^{13}C (‰) from La Serraz (dashed line) and Bout-du-Lac (solid line). Error bars correspond to the analytical reproducibility estimated from 2 to 3 measurements conducted on the same cellulose samples. The signal averaged from the 2 sites is displayed in thick line. (d) Observed and reconstructed Thonon-les-Bains June–July precipitation δ^{18}O (‰). The uncertainty on the reconstruction (1.1‰) is estimated using Eq. (2) (see text) and the mean analytical uncertainties on cellulose isotopic measurements.

or 3 times). The error bars reported on Fig. 4b correspond to the standard deviation calculated for each sample from these replicated measurements (in average 0.33‰ for δ^{18}O and 0.12‰ for δ^{13}C).

3. Results and discussion

3.1. Tree growth

At La Serraz, the average tree−ring width is ~55% larger for the first half of the record compared to the second half of the record, mainly to a step-like increase between 1980 and 1983 (Fig. 4a). This trend may result from the combination of aging and changing climatic conditions. Indeed, the Thonon-les-Bains station shows a 1.3 °C temperature increase from 1971–1986 to 1987–2001, both for summer and annual mean temperatures (and mainly due to the increase of temperature minima) (Fig. 2), and a 3.5% decrease of the amount of summer precipitation, which could result in a larger summer water stress. Due to this common shift between the first and second half of the records, an anti-correlation is observed between ring width and temperature. Determination coefficients of $R^2=0.35$ with June July August mean temperature and $R^2=0.49$ with annual mean temperature are calculated together with a slope of −0.23 to −0.35 mm of growth per °C ($n=29$). We did not have enough local constraints regarding soil texture and root depths to run a soil hydrology model to quantify the water stress [30]. The only quantitative information on summer water balance variations arises from the monitoring of the Eau Morte flow, a river which feeds the lake. For the period when the measurements are available (from 1977 onwards), the correlation between La Serraz ring width and the Eau Morte flow is $R^2=0.34$ ($n=23$). This correlation and the soil properties considerations confirm that trees growing at La Serraz have a growth which seems significantly limited by summer moisture availability.

At Bout-du-Lac, the mean growth of the selected set of trees is ~35% larger and more stable than at La Serraz, without any decreasing trend (in average 1.99 ±0.29 mm/year at Bout-du-Lac versus 1.47±0.39 mm/year at La Serraz). The Bout-du-Lac tree-ring width is not significantly correlated with any climatic or hydrological parameter tested here ($R^2<0.15$). As it was expected from the location and the soil characteristics of the sites, the ring width series confirm that the Bout-du-Lac trees undergo less water limitation than at La Serraz.

3.2. Local water δ^{18}O and meteorological situation

During the years 2001–2002, monthly mean temperatures and $\delta^{18}O_p$ have been monitored at Etercy, 12 km westwards of Lac d'Annecy and about 100 m above the lake level [30]. Meteorological data are also available at the weather station of Meythet (3 km north of the lake) and a long-term monitoring of monthly $\delta^{18}O_p$ has been performed at the IAEA station of Thonon-les-Bains (Fig. 1) since 1963.

The monthly mean surface air temperature and precipitation amounts at these three locations are consistent over the monitoring period (not shown). There is an excellent correlation between monthly Etercy and Thonon-les-Bains meteorological and isotopic records over 2001–2002 ($R^2=0.99$, 0.81 and 0.86, respectively, for surface temperature, precipitation and $\delta^{18}O_p$). Monthly mean $\delta^{18}O_p$ were in average 0.4‰ lower at Etercy, with the largest deviations reaching 1.3‰. These correlations testify the regional validity of the data. The long meteorological and isotopic records from Meythet and Thonon-les-Bains can thus be considered as representative of Lac d'Annecy climatic and $\delta^{18}O_p$ inter-annual variations before 2001. From 1971 to 2001, mean temperatures are slightly cooler at Meythet than at Thonon-les-Bains (−0.6 °C in annual mean, −0.4 °C during summer months) and precipitation amounts are significantly larger (+22% in annual mean, +19% in the summer months). Our tree-ring signals will be compared to Thonon-les-Bains $\delta^{18}O_p$ and with Meythet temperature, precipitation and relative humidity data, more representative of the lake surroundings local climate.

The Lac d'Annecy climatic conditions are typically semi-continental with a mean temperature of 10 °C, a seasonal temperature amplitude of 18 °C and an inter-annual standard deviation of summer temperatures of 1.5 °C. The mean monthly precipitation reaches 100 mm/month, with relative maxima in spring (May–June) and autumn (October) and a large inter-annual variability (the inter-annual monthly standard deviation is for most months above 50% of the mean monthly precipitation amount). The mean relative humidity level is 76% with rather stable levels around 70% from April to August, and a summer relative humidity inter-annual standard deviation around 5%. The mean precipitation $\delta^{18}O_p$ cycle follows the local temperature seasonal cycle, with a mean value of −9.4‰, summer maxima around −6‰ in July–August and summer inter-annual standard deviations around 2‰ (not shown).

When the trees were cored (25th and 26th of June 2002), the xylem of one oak tree of Bout-du-Lac and two oak trees of La Serraz were sampled for δ^{18}O water analysis every hour during about 8 h. Soil moisture isotopic composition was also sampled in a pit at each site (40 cm depth at La Serraz; 140 cm at Bout du Lac). The xylem water δ^{18}O was −8.74±011‰ for tree Q11 of Bout-du-Lac, −8.55±0.22 and −8.21±0.24, respectively, for trees P1 and P13 of La Serraz. The soil water δ^{18}O decreased significantly in the upper section (first 7.5 cm, where the soil ponderal humidity decreased from about 0.7 to 0.25) and was rather stable from 7.5 cm below the surface to the bottom of the pit. The average soil water δ^{18}O was −8.92±0.87‰ at La Serraz and −8.65±0.97‰ at Bout-du-Lac. These values are very close to the usual May–June isotopic levels (−8.7‰ after correction for the observed Thonon–Etercy gradient). We therefore suggest that most of the source water is provided by the growing season precipitation.

Using Thonon-les-Bains meteorological and $\delta^{18}O_p$ records, the temporal $\delta^{18}O_p$-temperature slopes can be estimated on different time scales: the largest correlation is obtained for the seasonal cycle ($R^2=0.9$, slope of 0.35‰ per °C using averages from 1966 to 2001), and the largest slope from the inter-annual June–July–August variations from 1971 to 2001 ($R^2=0.22$, slope of 0.7‰ per °C); the 30-year-long trends exhibit a slope close to the one obtained from the mean seasonal cycle (slope of 0.3.‰ per °C) (Figs. 2 and 3). At the inter-annual scale, the summer $\delta^{18}O_p$ is also anti-correlated to summer relative humidity ($R^2=0.28$, slope of −0.3‰ per %). This could be explained by a significant contribution of soil moisture and/or droplet reevaporation to the atmospheric water vapour, leading to an apparent enrichment of $\delta^{18}O_p$.

3.3. Cellulose $\delta^{18}O$ records

We observe a systematic offset between the Bout-du-Lac and La Serraz $\delta^{18}O_{lwc}$ series of 0.59‰ (Fig. 4b), in fair agreement with similar systematic offsets between different trees near Rennes, Brittany, western France (typically 0.5‰ offsets both for different living trees of the same planting [19] and for trees and beams for the early 20th century [20]). La Serraz $\delta^{18}O_{lwc}$ is systematically higher than Bout-du-Lac $\delta^{18}O_{lwc}$, which cannot be explained by the elevation effect (locally −0.29‰ per 100 m for $\delta^{18}O_p$) [30]. We suggest that the systematic offset could be related to a lower relative humidity [31] and a ~1‰ larger leaf water enrichment at La Serraz.

The two $\delta^{18}O_{lwc}$ profiles are significantly correlated ($R^2=0.37$; $n=29$). Although only 6 and 9 trees were combined to produce these records, they do capture a common signal, which is much clearer than for ring width ($R^2=0.13$ between the two locations). The mean cellulose $\delta^{18}O_{lwc}$ therefore represents a regional scale signal, independently of local soil hydrology effects. Significant correlations are observed with June, July and August $\delta^{18}O_p$ and relative humidity.

At both sites, $\delta^{18}O_{lwc}$ records exhibit a small increasing trend during the last 30 years (+0.53‰ at Bout-du-Lac and +0.35‰ at La Serraz). This could partly be related to the small trend in Thonon June–July–August $\delta^{18}O_p$, although with a 50% to 80% smaller amplitude (Figs. 2, 4b). There is no marked $\delta^{18}O_{lwc}$ change between the 1970–1986 and 1987–2001 periods, in contrast with the local temperature record.

Single linear regressions performed between inter-annual fluctuations of $\delta^{18}O_{lwc}$, Thonon-les-Bains $\delta^{18}O_p$ and Meythet meteorological data have been calculated for each month and each season. The best correlations are obtained for La Serraz and Bout-du-Lac $\delta^{18}O_{lwc}$, respectively, with June–July $\delta^{18}O_p$ ($R^2=0.40$, slope of 0.23‰ per ‰, $P<0.01$), and June $\delta^{18}O_p$ ($R^2=0.33$, slope of 0.22‰ per ‰, $P<0.01$). Both records show similar dependencies on June–July–August–September relative humidity ($R^2=0.38$ for La Serraz, $P<0.01$; $R^2=0.30$ for Bout-du-Lac, $P<0.05$, same slope of −0.11‰ per %). Poorer correlations are obtained with maxima temperatures ($R^2=0.17$, slope of 0.8‰ per °C, $P<0.05$). We have assessed the stability of these relationships by comparing the same regressions obtained for the full dataset (29 or 30 years) and for the first and second halves of this dataset (15 years). The R^2 correlations are 0.1 to 0.2 systematically higher during the most recent 15 years than earlier 15 years but the slopes remain within 20% of the slopes obtained for the full records.

Based on multiple regression analyses, we propose a simple linear model to estimate the inter-annual fluctuations in the average Annecy $\delta^{18}O_{lwc}$ signal, using:

$$\Delta\delta^{18}O_{\mathrm{lwc,\,model}} = (0.16\pm0.05)\Delta\delta^{18}O_{\mathrm{p,JJ}} - (0.06\pm0.02)\Delta h_{\mathrm{JJAS}}, \quad (1)$$

with h_{JJAS} the June to September relative humidity in percent and $\delta^{18}O_{p,JJ}$ the Thonon June–July $\delta^{18}O_p$. The slopes obtained here are slightly different from the slopes discussed in the previous paragraph and obtained from single linear regressions, which is due to a partial correlation between $\Delta\delta^{18}O_{p,,JJ}$ and $\Delta h_{JJAS,}$ particularly strong during the last 15 years. The multiple regression analysis has been repeated on the first and second half of the records with robust results.

The correlation coefficient between $\Delta\delta^{18}O_{model}$ and $\Delta\delta^{18}O_{lwc}$ is $R^2=0.58$ ($P<0.001$) (Fig. 4), consistent with the current views of processes leading to the tree-ring $\delta^{18}O$ signal acquisition. In this linear model, inter-annual changes in $\Delta\delta^{8}O_{p,,JJ}$ and Δh_{JJAS} account, respectively, for 60.7% and 39.3% of the $\Delta\delta^{18}O_{lwc,\ model}$ variance. Compared to other similar studies conducted in England [32], the dependency of $\delta^{18}O_{lwc}$ on $\delta^{18}O_p$ is three times lower at Annecy (here ~0.2‰ per ‰ to be compared with 0.6 for Sandringham Park, England). The main uncertainties in the present study are the local relative humidity above the leaves and the soil hydrology. It seems however that most of the latewood is formed during summer, when soil moisture and its isotopic composition mainly originate from precipitation of June and July. There is an apparent contradiction between the good correlation between summer $\delta^{18}O_p$ and $\delta^{18}O_{lwc}$ (suggesting at least common processes without inertia), and the small slope (suggesting a 20% contribution of summer rainfall to source water following the approach of [33]. This slope is however consistent with recent findings suggesting that the combined effects of Péclet and subsequent exchange at the sites of cellulose synthesis could diminish the initial enrichment at the sites of evaporation by ~80% [34].

We suggest that in the Annecy and Thonon-les-Bains area, where large lakes can provide significant amount of vapour in summer, the often made assumption that the $\delta^{18}O$ of vapour, source and precipitation are in equilibrium [35] may not be verified. The models of $\delta^{18}O_{lwc}$ relying on this assumption indeed have a 1 per 1‰ slope with respect to soil water $\delta^{18}O$, five times larger than obtained here. Unfortunately, only few atmospheric vapour $\delta^{18}O$ measurements are available. Data from seven growing seasons at Heidelberg [36] suggest a ~20% error when assuming equilibrium between vapour and precipitation. The effect of nearby lakes (Lac d'Annecy, Lac Léman) might induce an even larger bias for our sites, however damped by about 30% by the tree isotopic exchange processes.

3.4. $\delta^{13}C_{lwc}$ and methodology to reconstruct past $\delta^{18}O_p$

The inter-annual $\delta^{13}C_{lwc}$ of La Serraz and Bout-du-Lac trees are highly correlated ($R^2=0.59$). $\delta^{13}C_{lwc}$ levels are systematically less depleted at La Serraz by 1.1‰. This is also consistent with the hypothesis that the site of La Serraz is systematically drier.

The average $\delta^{13}C_{lwc}$ is converted to carbon discrimination $\Delta^{13}C_{lwc}$ after correction for observed changes in atmospheric CO_2 $\delta^{13}C$ (which amounts to ~0.77‰ between 1971 and 2001). Linear regressions show that $\Delta^{13}C_{lwc}$ is significantly influenced by June–July–August temperature ($R^2=0.52$, slope of −0.25‰ per °C) and by June–July–August–September relative humidity ($R^2=0.45$, slope of 0.07‰ per °C). The correction for atmospheric CO_2 $\delta^{13}C$ has no significant effect on the linear regressions discussed hereafter.

We now have two different isotopic parameters measured on the same tree rings ($\Delta^{13}C_{lwc}$ and $\delta^{18}O_{lwc}$) related to stomata processes and soil water $\delta^{18}O$, almost not linearly correlated ($R^2=0.1$). Because leaf processes are strongly influenced by water stress and relative humidity changes, we use a multiple linear regression to combine these isotopic parameters and propose a methodology to reconstruct past fluctuations in $\delta^{18}O_p$:

$$\Delta\delta^{18}O_{p,JJ,rec} = (0.92\pm0.50)\Delta\delta^{13}C_{lwc} + (1.87\pm0.35)\delta^{18}O_{lwc}. \quad (2)$$

This statistical linear model accounts for 64% of the inter-annual variance of $\delta^{18}O_p$. ($P<0.001$). $\delta^{18}O_{lwc}$ and $\delta^{13}C_{lwc}$ account, respectively, for 82% ($P<0.001$) and 18% ($P<0.1$) of the reconstructed $\delta^{18}O_{p,\ JJ}$ inter-annual variance (Fig. 4d). Due to the analytical uncertainties (here 0.33‰ for $\delta^{18}O_{lwc}$ and 0.12 for $\delta^{13}C_{lwc}$), we estimate the error on the reconstructed $\delta^{18}O_p$ to be about 1.1‰ by taking into account the analytical errors on each measurement and the uncertainties on the determination of the slopes. This error remains limited when compared with the total amplitude of June–July $\delta^{18}O_p$ inter-annual fluctuations (6.4‰). The mean deviation between the reconstructed signal and the original signal is within this uncertainty (0.8‰). The improvement of the $\Delta\delta^{18}O_{p,\ JJ,\ rec}$ reconstruction due to the use of $\Delta\delta^{13}C_{lwc}$ compared to the use of $\Delta\delta^{18}O_{lwc}$ only is of secondary importance.

The search for non-linear models such as Generalized Addictive Models did not provide any improvement over simple linear models such as outlined by Eqs. [(1) and (2).

4. Conclusions and perspectives

This calibration study shows that, rather independently of the very specific sampling place, the $\delta^{18}O$ of the cellulose of oaks latewood grown near Lac d'Annecy should enable a reconstruction of past summer precipitation $\delta^{18}O$ changes. The significant correlation ($R^2=0.37$) between nearby sites with different elevations, distance to the lake, and soil settings suggests that the combination of woods of different local origins is feasible.

Obtaining longer chronologies should be a challenge with oaks at this place where building wood was traditionally provided by coniferous species. This calibration however offers the potential for multi-proxy δ^{18}O reconstructions by combining the multi-year Lac d'Annecy benthic ostracod δ^{18}O, lake isotopic modelling [8] and tree-ring δ^{18}O fluctuations near Thonon-les-Bains, the only place in France with long-term precipitation δ^{18}O monitoring.

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