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A MULTI-PROXY APPROACH TO DROUGHT RECONSTRUCTION

■

Inga LABUHN[1,2], Valérie DAUX[1] & Dominique GENTY[1]

ABSTRACT

In palaeoclimate reconstructions, the combination of proxy records measured in different climate archives is challenging because of the uncertainties associated with each proxy, but it can also help reduce some of these uncertainties. Here, we present a novel approach to combine speleothem and tree ring proxies for a drought reconstruction of the last 640 years: a fluid inclusion $\delta^{18}O$ record from a stalagmite from Villars Cave (southwest France) and a tree ring cellulose $\delta^{18}O$ record of *Quercus* spp. from the nearby Angoulême area. The $\delta^{18}O$ of the fluid inclusions is taken as an estimate of the $\delta^{18}O$ of the trees' source water. Then, the cellulose and source water $\delta^{18}O$ are used to calculate the leaf water isotopic enrichment, as well as relative humidity, which is the dominant controlling factor of this enrichment. The reconstructed long-term trends in relative humidity differ from a previously published reconstruction of moisture variability based on the tree ring record alone. Further measurements will be necessary to support either reconstruction. Nevertheless, this investigation demonstrates the great potential for combining isotope proxies from speleothems and tree rings to reconstruct both the low- and high-frequency variability of drought.

Keywords: tree rings, cellulose, speleothems, fluid inclusions, stable isotopes, oxygen ($\delta^{18}O$), palaeoclimate, drought, multi-proxy, France

RÉSUMÉ

RECONSTITUTION DES PÉRIODES DE SÉCHERESSE PAR APPROCHE MULTI-INDICATEUR

En paléoclimatologie, la comparaison entre les différentes archives est complexe à cause des incertitudes associées à chaque indicateur ; elle peut cependant aussi aider à réduire les incertitudes. Nous présentons ici une nouvelle approche pour combiner les indicateurs paléoclimatiques issus des spéléothèmes et des cernes d'arbre pour reconstituer les sécheresses au cours des derniers 640 ans : le $\delta^{18}O$ des inclusions fluides d'une stalagmite de la grotte de Villars (sud-ouest de la France) et le $\delta^{18}O$ de la cellulose des cernes de chênes (*Quercus* spp.) proches d'Angoulême. Le $\delta^{18}O$ des inclusions fluides est considéré comme le $\delta^{18}O$ de l'eau souterraine qui alimente les arbres. Puis le $\delta^{18}O$ de la cellulose et celui de l'eau souterraine sont utilisés pour calculer l'enrichissement isotopique de l'eau de la feuille ainsi que l'humidité relative qui est le facteur dominant contrôlant cet enrichissement. La variation de l'humidité relative reconstituée diffère des reconstitutions publiées basées uniquement sur les cernes d'arbre suggérant la nécessité de faire d'autres reconstitutions pour mieux comprendre ces différences. Ce travail montre tout l'intérêt de comparer deux archives pour tenter de reconstituer les périodes de sécheresse passées.

Mots-clés : cernes d'arbre, cellulose, spéléothèmes, inclusions fluides, isotopes stables, oxygène ($\delta^{18}O$), paléoclimat, sécheresses, multi-indicateur, France

1 - INTRODUCTION

The ever-increasing number of palaeoclimate proxy records deepens our understanding of climate variability in the past on different temporal and spatial scales (Masson-Delmotte *et al*., 2013). At the same time, field and laboratory studies on the formation processes of climate archive lead to a better comprehension of the climatic and non-climatic information recorded in the proxies, and contribute to a better evaluation of the proxies' limitations (e.g. Dreybrodt & Scholz 2011; Offermann *et al*., 2011; Steen-Larsen *et al*., 2011; Gessler *et al*., 2013; Genty *et al*., 2014; Labuhn *et al*., 2014). However, it remains challenging to compare and combine proxies from different climate archives, as all are afflicted with their own uncertainties related to dating, climate sensitivity, and linearity, and they are limited to certain aspects of variations in climate. A multi-proxy approach can give a broader perspective on past climate change, and may help constrain the causes of variability (Mann, 2002; Guiot *et al*., 2005; Li *et al*., 2010).

Tree rings have been the principal source of information for hemispheric-scale temperature reconstructions of the past millennium (Mann *et al*., 1999; Esper *et al*., 2002; Briffa *et al*., 2004; D'Arrigo *et al*., 2006). Their advantage lies in the annual resolution and the precise dating.

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Tree ring proxies can be well replicated and quantified by comparing them directly to meteorological variables from the year of ring formation. Their calibration is based on the statistical relationships with climate (e.g. Fritts & Guiot, 1990). Models for climate reconstruction based on these relationships can be verified using independent meteorological data, i.e. data that have not been used in the calibration, and the variance explained by the model can be quantified (e.g. Briffa *et al*., 1992). However, tree ring proxies may be biased towards climate conditions of the time of year that has the strongest influence on tree growth. Tree-ring reconstructed changes in summer climate, for example, might not be representative of the evolution of the annual climate (Jones *et al*., 2003). Furthermore, tree rings, in particular tree ring widths, are limited for reconstructing low-frequency climate variability because of the standardization process and the limited length of individual tree series (Cook *et al*., 1995; Esper *et al*., 2004; Moberg *et al*., 2005).

Speleothems have the potential to provide a low-frequency signal. However, their dating is less precise compared to the trees. Despite the high analytical precision that is now achieved for U-Th dating (Hoffmann *et al*., 2009; Cheng *et al*., 2013), and the possibility to count annual growth layers in some speleothem samples (Genty & Quinif, 1996; Tan *et al*., 2006; Baker *et al*., 2008; Shen *et al*., 2013), slight changes in the growth rate or short hiatuses increase the error in the chronology, making it difficult to compare a stalagmite record to instrumental data or to high-resolution proxy data from tree rings. While adequate samples, which have a high growth rate and a precisely dated lamination, enable a direct calibration by comparison with meteorological data (Genty & Quinif, 1996; Proctor *et al*., 2000), in many cases the calibration of speleothem proxies relies on an understanding of the cave processes, based on monitoring data, laboratory experiments, and modeling exercises (Spötl *et al*., 2005; Genty, 2008; Tremaine *et al*., 2011; Wackerbarth *et al*., 2012; Treble *et al*., 2013). Lastly, an environmental signal can be lagged and/or attenuated before it is transmitted to the cave interior (Fairchild & Baker, 2012), whereas tree ring proxies often reflect the environmental signal more directly, i.e. during the current growing season.

Few previous studies have attempted to directly compare tree rings and speleothems. Berkelhammer *et al*. (2014) and Trouet *et al*. (2009) used tree ring and speleothem proxy records from remote regions to study teleconnections and atmospheric circulation indices. Betancourt *et al*. (2002) compared annual band widths in tree rings and a stalagmite from the same site and found no correspondence, but their approach has been criticized because even if the banding in both archives is annual, the band width in each proxy might not depend on the same influences (Baker & Genty 2003). However, when tree ring and speleothem proxies from the same region respond to the same dominant factors, e.g. droughts, they can show similar patterns (Sinha *et al*., 2011; Wassenburg *et al*., 2013). Managave (2014) used a model to investigate to what extent the oxygen isotopic composition of tree ring cellulose and speleothem calcite can be correlated if they have the same source water. The author determined that a correspondence between these proxies is likely when the variation in the $\delta^{18}O$ of precipitation is high compared to the variation induced by the influences on each single proxy, i.e. the cave temperature and equilibrium conditions during precipitation for calcite $\delta^{18}O$, and relative humidity, leaf temperature and the isotopic composition of atmospheric water vapor for cellulose $\delta^{18}O$.

This article explores the potentials and limits of a multi-proxy climate reconstruction based on speleothem and tree ring proxy records from the southwest of France, a region characterized by recurrent drought periods that might prove to be particularly vulnerable to the consequences of global warming (Moisselin *et al*., 2002; Itier 2008; Lemaire *et al*., 2010; Levrault *et al*., 2010). Identifying the patterns of moisture variability in the past may help evaluate the possible future extent of droughts in a changing climate. Both archives have in common that we can measure oxygen isotope ratios in their components: in cellulose from the wood of tree rings ($\delta^{18}O_c$), and in water that is incorporated in speleothem calcite, the so-called fluid inclusions ($\delta^{18}O_{fi}$). Here, we combine a $\delta^{18}O_{fi}$ record from a speleothem from Villars Cave (Labuhn *et al*., 2015) and a $\delta^{18}O_c$ chronology from the nearby Angoulême (Labuhn *et al*., 2016) in order to reconstruct both low and high frequency drought variability during the last 640 years. The oxygen in both proxies originates from the precipitation feeding the soil water reservoir, which subsequently infiltrates into the cave, or is tapped by the trees. We therefore hypothesize that it is possible to use the $\delta^{18}O_{fi}$ as an independent estimate of the source water $\delta^{18}O$ for the trees. In a first step, we investigate the co-variation of the fluid inclusion and the cellulose $\delta^{18}O$ time series. In a second step, we assume that the $\delta^{18}O_{fi}$ represents the $\delta^{18}O$ of the tree source water, and, using $\delta^{18}O_c$ and $\delta^{18}O_{fi}$, we calculate the isotopic enrichment of the leaf water above the source water, as well as relative humidity (RH), which is the dominant controlling factor of this enrichment. Lastly, we compare this reconstruction of relative humidity with a previous drought reconstruction based only on tree rings (Labuhn *et al*., 2016).

2 - STUDY SITES AND DATA

The study sites Villars Cave and Angoulême are situated in the southwest of France at 50 km distance, in similar geological and climatological settings (fig. 1). As both are located at approximately the same altitude (100-175 m a.s.l.) and distance from the coast (~150 km), and no important relief separates them, they experience similar variations in temperature, moisture conditions (Météo-France, 2009), and in the isotopic composition of precipitation (Millot *et al*., 2010). The bedrock in the region is a Jurassic limestone, and karstic features such as dolines, caves, and surface collapses characterize the landscape.

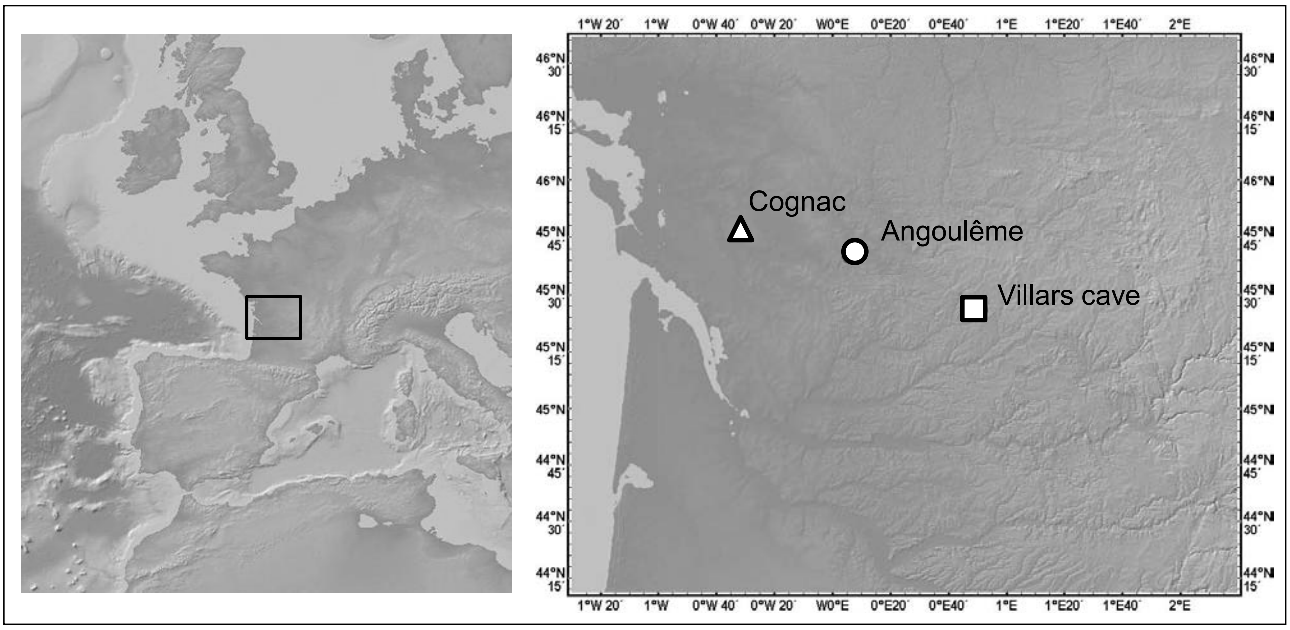

Fig. 1: Study site locations.
The square indicates the location of Villars Cave, where the stalagmite was sampled, the circle indicates the location of the tree ring chronology from Angoulême, and the triangle indicates the location of the meteorological station in Cognac.
*Fig. 1 : Localisation des sites d'*étude. *Le carré indique la localisation de la grotte de Villars, le cercle indique la localisation de la chronologie des cernes d'arbre* à *Angoulême, et le triangle indique la localisation de la station météorologique de Cognac.*

The crossdated, annually resolved chronology of tree ring cellulose $\delta^{18}O$ from Angoulême (45°44'N, 0°18'E) has been constructed using living trees and building timbers of oak (*Quercus* spp.), and covers the period from 1360 to 2004 (Labuhn *et al*., 2014; 2016). Inter-annual variations in $\delta^{18}O_c$ at this site are dominated by the atmospheric conditions that influence leaf water enrichment (Labuhn *et al*., 2014), but the underlying low-frequency variability are likely linked to variations in the source water $\delta^{18}O$.

The fluid inclusion $\delta^{18}O$ measurements were acquired from a stalagmite from Villars Cave (45°26'N, 0°47'E; Labuhn *et al*., 2015). The record covers the last 2,300 years, and the fluid inclusion samples have a resolution of approximately 25 years. The stalagmite was dated by the U-Th and ^{14}C methods, as well as by laminae counting. Long-term monitoring series of precipitation and cave drip water $\delta^{18}O$ demonstrated that drip water corresponds to a weighted mean of pluri-annual precipitation at this site, without any evaporative enrichment or seasonal bias due to plant transpiration (Genty *et al*., 2014). An investigation of corresponding modern fluid inclusion samples indicated that the isotopic composition of the infiltrating water was preserved in the fluid inclusions (Labuhn *et al*., 2015).

Monthly relative humidity (RH) data was obtained from Météo-France for Cognac (1961-2012, station no. 16089001), which is the longest available RH record from the study area. The standardized precipitation evapotranspiration index (SPEI; Beguería *et al*., 2010; Vicente-Serrano *et al*., 2010) was obtained from http://sac.csic.es/spei/database.html, and the time series for the Angoulême grid cell (1901-2011) was extracted.

3 - METHODOLOGY

3.1 - COMPARISON OF THE FLUID INCLUSION AND CELLULOSE RECORDS

For the comparison of fluid inclusions and cellulose, the $\delta^{18}O_c$ time series was smoothed by a 25-year running mean. This interval was chosen because it likely corresponds to the time period integrated in a fluid inclusion sample, as deduced from sample size, stalagmite growth rate and the infiltration time of the water from the surface to the cave (Labuhn *et al*., 2015). Both time series were transformed to z-scores (i.e. the differences of each value and the mean value of the time series, divided by the standard deviation) to make their variations more comparable.

3.2 - CALCULATION OF LEAF WATER ENRICHMENT AND RELATIVE HUMIDITY

In order to calculate the leaf water isotopic composition and RH using the speleothem and tree ring isotope proxies, we suppose that the $\delta^{18}O_{fi}$ represents the tree source water. The $\delta^{18}O_{fi}$ values were linearly interpolated in order to obtain a time series of annual resolution. Then, this time series was smoothed using a 25-year running mean. The resulting interpolated and smoothed fluid inclusion $\delta^{18}O$ values were supposed to be the source water $\delta^{18}O$ for the trees each year. The cellulose $\delta^{18}O$ time series, which had been normalized to a mean of zero (as published in Labuhn *et al*., 2016), was adjusted to the mean $\delta^{18}O$ value of recent cellulose (31 ‰).

The oxygen isotopic composition of cellulose can be related to the isotopic composition of source water

($\delta^{18}O_{sw}$) and leaf water ($\delta^{18}O_{lw}$) (Sternberg *et al.*, 1986; Yakir & DeNiro, 1990):

$$\delta^{18}O_c = 0.42 \times (\delta^{18}O_{sw} + \varepsilon_{wc}) + 0.58 \times (\delta^{18}O_{lw} + \varepsilon_{wc}) \quad \text{(Eq. 1)}$$

where ε_{wc}, the fractionation factor between water and carbonyl oxygen, is approximately equal to 27 ‰. Thus, using our $\delta^{18}O_c$ record and the interpolated fluid inclusion time series as an estimate of $\delta^{18}O_{sw}$, we can calculate $\delta^{18}O_{lw}$.

The $\delta^{18}O_{lw}$ is related to relative humidity (RH) as follows (Dongman *et al.*, 1974):

$$\delta^{18}O_{lw} = \delta^{18}O_{sw} \times (1 - RH) + \delta^{18}O_v \times RH + \varepsilon^* + \varepsilon_k \times (1 - RH) \quad \text{(Eq. 2)}$$

where $\delta^{18}O_v$ is the oxygen isotopic composition of atmospheric water vapor, and ε^* and ε_k are the equilibrium and kinetic fractionation factors. At 20°C, ε^* is equal to 9.7 ‰ (Horita & Wesolowski, 1994); ε_k is equal to 16 ‰ / 21 ‰ / 32 ‰ for turbulent/laminar/static boundary conditions respectively (Burk & Stuiver, 1981). Under normal European summer conditions, the water vapor is, on average, approximately in isotopic equilibrium with soil water (Förstel & Hutzen, 1982). Thus:

$$\delta^{18}O_v = \delta^{18}O_{sw} - \varepsilon^* \quad \text{(Eq. 3)}$$

Combining Equations (2) and (3) gives the equation to calculate RH:

$$RH = 1 - \frac{\delta^{18}O_{lw} - \delta^{18}O_{sw}}{\varepsilon^* + \varepsilon_k} \quad \text{(Eq. 4)}$$

4 - RESULTS AND DISCUSSION

4.1 - COMPARISON OF THE FLUID INCLUSION AND CELLULOSE RECORDS

The $\delta^{18}O$ records in tree ring cellulose from Angoulême and in speleothem fluid inclusions from Villars Cave display some common trends: a decrease from 1500 to 1700, an increase from 1750 to present, and a marked peak around 1720 (fig. 2). However, there is also a period where the two series show opposing trends, between 1360 and 1500. Furthermore, even if the general increasing trend in the most recent period is apparent in both records, the large increase in the cellulose time series from 1750 to 1850 and the subsequent rapid decrease are not seen in the fluid inclusions. The range of $\delta^{18}O$ values in both the fluid inclusions and the smoothed cellulose $\delta^{18}O$ time series is about 2 ‰ (not shown). However, the common peak at 1720 is about twice as large in the fluid inclusions.

The co-variation in both records can be ascribed to a common source water $\delta^{18}O$, which is controlled by the average $\delta^{18}O$ of precipitation in the region. Although the $\delta^{18}O_c$ is strongly influenced by leaf water enrichment on an inter-annual scale, the underlying low-frequency component can be attributed to the variability of the source water (Labuhn *et al.*, 2014). Furthermore, enhanced evaporation and transpiration during dry periods might cause an increase of $\delta^{18}O$ in both proxies (e.g. Bar-Matthews *et al.*, 1996; Denniston *et al.*, 1999; Sternberg, 2009; Gessler *et al.*, 2013). Several factors may contribute to the disagreement between cellulose and fluid inclusions:

(1) - The isotopic composition of the source water can be modified before it becomes preserved in the proxies. The modern calibration indicates that speleothem fluid inclusions from Villars cave correspond to a weighted mean of pluri-annual precipitation, without any significant modification (Genty *et al.*, 2014), but this might not hold true for the past. The $\delta^{18}O_c$, on the other hand, reflects partly the isotopic composition of the source water, and partly the isotopic composition of enriched leaf water (eq. 1). Their relative contribution to the $\delta^{18}O_c$ has been estimated (Roden *et al.*, 2000; Cernusak *et al.*, 2005), but is likely to vary over the growing season, as well as over longer time periods (Gessler *et al.*, 2009; Offermann *et al.*, 2011);

(2) - The $\delta^{18}O_c$ time series might not capture well the low frequency variability in precipitation/source water $\delta^{18}O$. A correction had to be applied for offsets in average

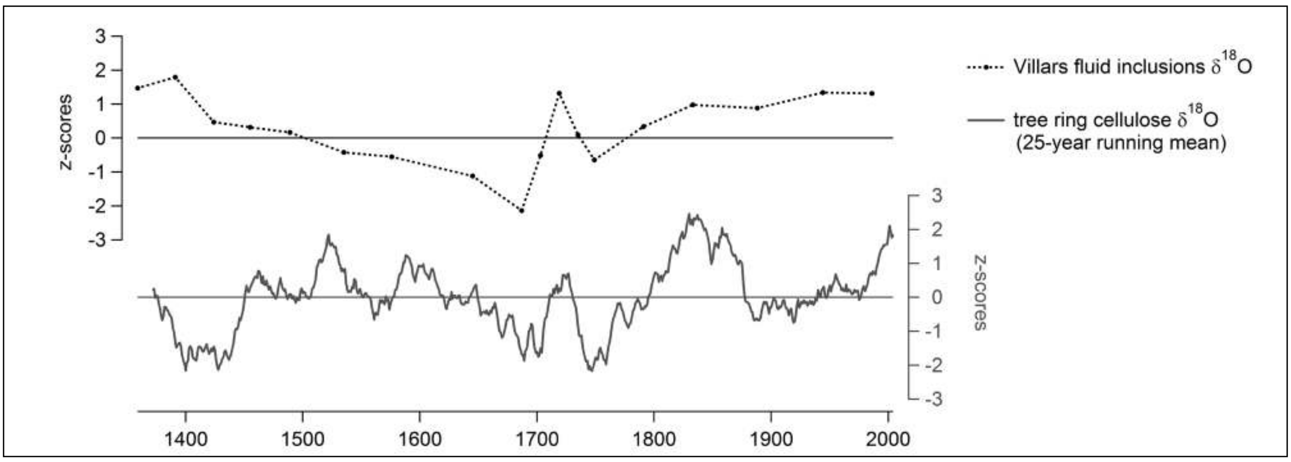

Fig. 2: Comparison of the speleothem fluid inclusion and tree ring cellulose $\delta^{18}O$ time series (z-scores).
The cellulose $\delta^{18}O$ chronology has been smoothed by a 25-year running mean.
Fig. 2 : Comparaison des séries temporelles du $\delta^{18}O$ des inclusions fluides des spéléothèmes et de la cellulose des cernes d'arbre (z-scores). La chronologie de $\delta^{18}O$ de la cellulose a été lissée par une moyenne glissante de 25 ans.

$\delta^{18}O_c$ values between the tree cohorts that were combined in this chronology, which might have removed some of the low-frequency trends (Labuhn *et al*., 2016). Offsets occur because the source water $\delta^{18}O$ can be different for individual trees, due to local soil hydrology or rooting depth (Phillips & Ehleringer, 1995; Tang & Feng, 2001; Labuhn *et al*., 2014). Moreover, the oak species had not been determined and both *Quercus petraea* and *Q. robur* could have contributed to the chronology. To date, however, no study has shown a difference in $\delta^{18}O_c$ between these two species;

(3) - The resolution of the fluid inclusion record is much lower than the resolution of the tree rings. Therefore, the peaks in the smoothed cellulose time series are not all seen in the fluid inclusions, e.g. around 1540 or 1850;

(4) - The dating of the stalagmite is less precise than the dating of the tree rings. Although there is generally a good agreement between growth layer counting, ^{14}C and U-Th dates, the uncertainty of the stalagmite age model is up to 100 years (Labuhn *et al*., 2015);

(5) - The seasonality of the proxies is different. The speleothem fluid inclusions represent the mean annual precipitation $\delta^{18}O$, which is dominated by the $\delta^{18}O$ of winter precipitation because most precipitation falls during the winter months (Genty *et al*., 2014). Tree ring cellulose $\delta^{18}O$ could be biased towards growing season precipitation. However, it is possible that trees use water stored in the soil from the previous winter, especially during dry summers (Phillips & Ehleringer, 1995; Daux *et al*., 2011), so their source water $\delta^{18}O$ may still reflect annual precipitation.

4.2 - CALCULATED LEAF WATER ENRICHMENT AND RELATIVE HUMIDITY

4.2.1 - Leaf water enrichment

The assumption that $\delta^{18}O_{fi}$ represents the tree source water is supported by the fact that, at Villars Cave, there is no seasonal bias in the isotopic composition of the drip water due to the transpiration of the vegetation (Genty *et al*., 2014). This indicates that plants take up a mixed water, and not only growing season water, and this water consequently must have the same $\delta^{18}O$ as the drip water. The calculated leaf water is enriched compared to the source water by 13 to 23 ‰, which is in the range of values found for trees (Saurer *et al*., 1998a,b; Gessler *et al*., 2013) and other plants (Sheshshayee *et al*., 2005; Ferrio *et al*., 2012).

4.2.2 - Observed vs. reconstructed relative humidity

We compare the reconstructed RH to the observed summer (JJA) RH, as June to August are the months that give the highest significant correlations between RH and $\delta^{18}O_c$ (Labuhn *et al*., 2014). The inter-annual variability of RH is well captured by the reconstruction, but average reconstructed RH values are too low (fig. 3). Our calculation is likely too simplistic for the following reasons.

It assumes the kinetic isotope fractionation as water diffuses through stomata and through the boundary layer (ε_k in eq. 2) to be constant; but ε_k varies with the boundary layer conditions, which in turn depend on wind speed (Dongman *et al*., 1974; Burk & Stuiver, 1981). The fractionation factor significantly influences the reconstructed RH. Applying the values given by Burk and Stuiver (1981) for the period 1961-2004 yields an average RH of 36 % (ε_k = 16), 46 % (ε_k = 21), and 60 % (ε_k = 32) respectively. The average of the observed RH during this period is 71 %. The calculation using static leaf boundary layer conditions (ε_k = 32) therefore yields the best estimate. However, turbulent conditions are more realistic in nature (Gonfiantini, 1986).

As we do not have an independent temperature reconstruction covering the time period of the proxy records, we also suppose that the temperature, and consequently the temperature-dependent equilibrium isotope fractionation (ε_k* in eq. 2), are constant, which is not realistic. However, according to the fractionation factors given by Barbour *et al*. (2004) for 20°C and 25°C, the reconstructed RH would only vary by 1 % for a 5°C temperature change.

Furthermore, our calculation ignores the influence of a Péclet effect, which leads to a leaf water that is less enriched than predicted by the equations. If the calculated leaf water enrichment is too high, the reconstructed RH is too low. The Péclet effect could lower the leaf water $\delta^{18}O$ by 2 ‰ (Barbour *et al*., 2004). This would translate into a 7 % increase in reconstructed RH according to our calculation.

Likewise, the calculation neglects that trees can take water from different soil depths (Bréda *et al*., 1995). Superficial soil water is more enriched than deeper soil water, and its isotopic composition is more variable as it is influenced by evaporation and rainfall events (Tang & Feng, 2001). The average summer precipitation $\delta^{18}O$ is 3 ‰ higher than average annual precipitation in the study area (Genty *et al*., 2014). This difference in the $\delta^{18}O$ of the source water results in a 10 % change in the reconstructed RH.

Lastly, it is also supposed that the atmospheric water vapor is in isotopic equilibrium with the soil water.

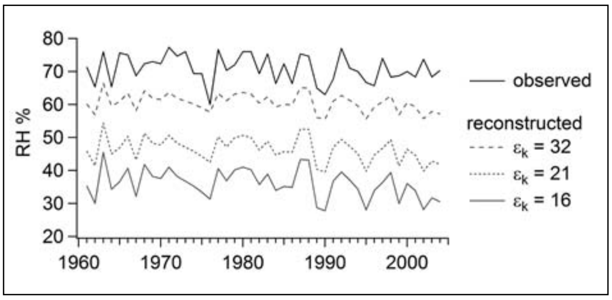

Fig. 3: Observed vs. reconstructed relative humidity (RH).
The reconstructions are based on different fractionation factors ε_k for static (32 ‰), laminar (21 ‰), and turbulent (16 ‰) leaf boundary layer conditions. The values are given by Burk and Stuiver (1981).
Fig. 3 : Humidité relative (RH) observée et reconstruite. Les reconstructions sont basées sur des facteurs de fractionnement ε_k pour différents états *de la couche limite : statique (32 ‰), laminaire (21 ‰), et turbulent (16 ‰). Les valeurs sont données par Burk et Stuiver (1981).*

Although this might be a good approximation for a growing-season average (Förstel & Hutzen, 1982), the isotopic composition of the vapor varies significantly on shorter time scales (Berkelhammer *et al*., 2013).

The average RH is significantly underestimated by the reconstructions, and none of the factors discussed here are sufficient to explain the differences with the observations, unless we suppose unrealistic boundary layer conditions. A more complex model would be needed to adequately represent RH values, e.g. by taking into account the Péclet effect, as well variations in the depth of the water supply, in the $\delta^{18}O$ of atmospheric water vapor, and in temperature. However, even if some of these parameters could be adjusted to present-day observations, they are unknown in the past and are likely to have varied over time.

Nevertheless, the inter-annual variability in RH is well represented by the reconstruction. Despite the offset, we can compare relative variations in reconstructed SPEI (based on $\delta^{18}O_c$) and reconstructed RH (based on a combination of $\delta^{18}O_c$ and $\delta^{18}O_{fi}$).

4.3 - DROUGHT RECONSTRUCTION WITH AND WITHOUT A SOURCE WATER $\delta^{18}O$ ESTIMATE

The observed summer drought index SPEI (JJA) and summer RH (JJA) are highly correlated during the period of observations (1961-2011) and are comparable to represent summer moisture conditions in the study area (fig. 4). The inter-annual variability in the RH reconstruction based on fluid inclusion and cellulose $\delta^{18}O$ and the SPEI reconstruction based only on cellulose $\delta^{18}O$ (Labuhn *et al*., 2016) is the same as they both depend linearly on the inter-annual variability in the cellulose $\delta^{18}O$ time series. However, the two reconstructions give a different picture of the long-term moisture changes in the past (fig. 5). The marked $\delta^{18}O$ peak at 1720, for example, disappears in the RH reconstruction, because it is ascribed to changes in the source water isotopic composition, and not to increased drought. Moreover, the RH reconstruction indicates drier conditions during the 16th and 17th century, and wetter conditions during the 19th and 20th century compared to the SPEI reconstruction.

The model for the tree-ring based drought reconstruction is well-verified with independent data, and correlations between the proxy and the reconstructed drought index are highly significant and stable throughout the 20th century, all of which gives strong indications for the validity of this reconstruction (Labuhn *et al*., 2016). However, the low-frequency drought variability may not be well represented in this record. The RH reconstruction supposedly captures better the low frequency. However, it must be interpreted with caution because of the dating uncertainties in the stalagmite and the low resolution of fluid inclusion measurements compared to the tree rings, as well as the simplicity of the model used to calculate RH. Most importantly, a replication of the fluid inclusion record is needed to confirm whether it represents average regional precipitation $\delta^{18}O$, and therefore can serve as an estimate of the source water of the trees.

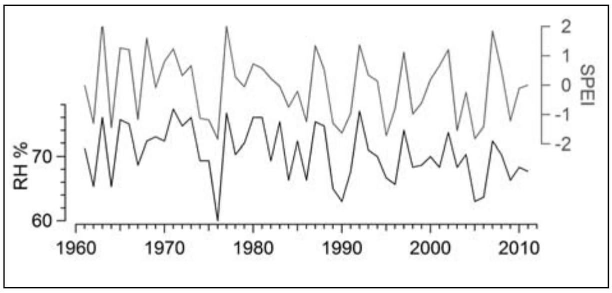

Fig. 4: Time series of relative humidity (RH) and the drought index SPEI during the summer months (JJA).
The correlation between RH and SPEI is $r = 0.85$ ($p < 0.001$).
Fig. 4 : Séries temporelles de l'humidité relative (RH) et de l'indice de sécheresse SPEI pour les mois d'été (JJA). La corrélation entre RH et SPEI est r = 0.85 (p < 0.001).

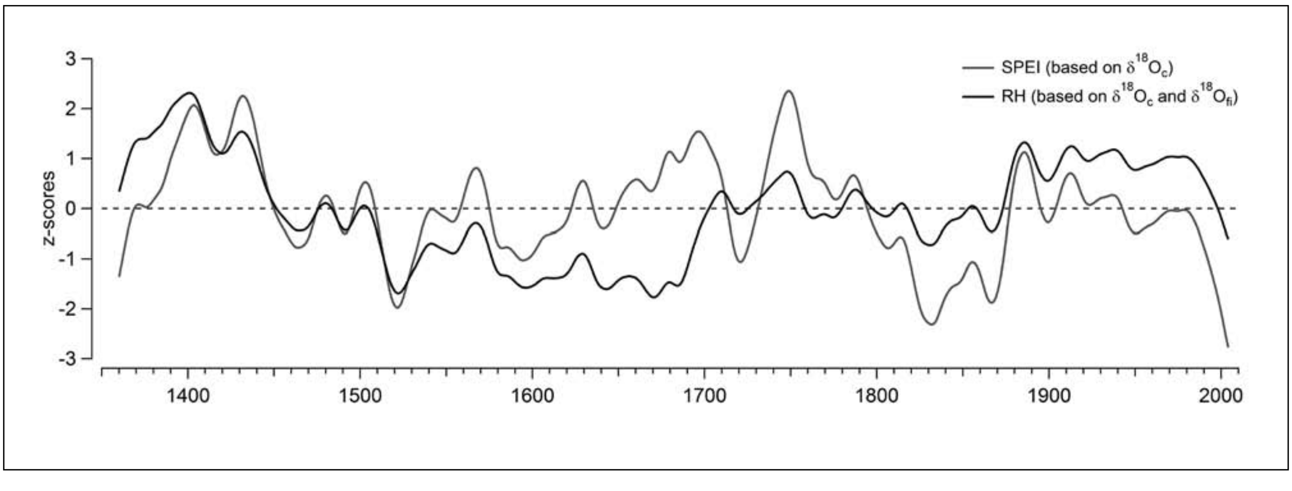

Fig. 5: The drought index (SPEI) and relative humidity (RH).
The SPEI was reconstructed using tree ring cellulose $\delta^{18}O$, and RH was reconstructed using the calculation of leaf water enrichment from cellulose $\delta^{18}O$ and speleothem fluid inclusion $\delta^{18}O$ (as an estimate of the source water isotopic composition). Both curves were smoothed using a 30-year spline and transformed to z-scores. Positive values indicate wet conditions, negative values indicate dry conditions.
Fig. 5 : L'indice de sécheresse (SPEI) et l'humidité relative (RH). Le SPEI est reconstitué sur la base du $\delta^{18}O$ de la cellulose des cernes d'arbre, et la RH est reconstituée sur la base du calcul de l'enrichissement de l'eau des feuilles utilisant le $\delta^{18}O$ de la cellulose et le $\delta^{18}O$ des inclusions fluides des spéléothèmes. Les deux courbes ont été lissées avec une spline de 30 ans et transformées en z-scores. Les valeurs positives indiquent des conditions humides, les valeurs négatives indiquent des conditions sèches.

5 - CONCLUDING REMARKS

These investigations demonstrate the great potential in combining oxygen isotope ratios in speleothem fluid inclusions and tree ring cellulose to reconstruct moisture conditions, and the theoretical approach is established here. The combination of proxies might provide an estimate of past droughts that comprises both the low- and high-frequency variability, combining the strengths of the two climate archives while compensating their weaknesses when used alone. However, further investigation will be necessary to better understand the differences between this multi-proxy reconstruction and the reconstruction based only on tree rings. In particular, the reconstructed low frequency trends in moisture conditions could be supported by a replication of the speleothem fluid inclusion record using another stalagmite from the same region to confirm their utility to estimate the isotopic composition of precipitation and subsequently the trees' source water. Likewise, a larger sample depth of the tree ring chronology could reduce the uncertainty due to cohort offsets and better capture low frequency climate variability.

An improved replication of both speleothem and tree ring records could not only increase our confidence in such multi-proxy climate reconstructions, but also reveal spatial patterns of past droughts in France. This is important because drought severity depends on both the duration of a drought and on its spatial extent. In a future research perspective, there is a potential to find other cave sites in France with forests and historic buildings nearby. These might provide additional oxygen isotope data from speleothem fluid inclusions and tree ring cellulose, which can be used to reconstruct drought patterns in the past and to test the validity of the approach demonstrated in this study.

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