



## Abstract

The reconstruction of droughts is essential for the understanding of past drought dynamics, and can help evaluate future drought scenarios in a changing climate. This article presents a reconstruction of summer droughts in France based on annually resolved, absolutely dated chronologies of oxygen isotope ratios ( $\delta^{18}\text{O}$ ) in tree ring cellulose from *Quercus* spp. Samples were taken from living trees and timber wood from historic buildings at two sites: Fontainebleau (48° 23' N, 2° 40' E; 1326–2000 AD) and Angoulême (45° 44' N, 0° 18' E; 1360–2004 AD). Cellulose  $\delta^{18}\text{O}$  from these sites proved to be a good proxy of summer climate, as the trees were sensitive to temperature and moisture availability. However, offsets in average  $\delta^{18}\text{O}$  values between tree cohorts necessitated a correction before joining them to the final chronologies.

Using the corrected  $\delta^{18}\text{O}$  chronologies, we developed models based on linear regression to reconstruct drought, expressed by the standardized precipitation evapotranspiration index (SPEI). The significant correlations between the SPEI and cellulose  $\delta^{18}\text{O}$  ( $r \approx -0.70$ ), as well as the verification of the models by independent data support the validity of these reconstructions. At both sites, recent decades are characterized by increasing drought. Fontainebleau displays dominantly wetter conditions during earlier centuries, whereas the current drought intensity is not unprecedented in the Angoulême record.

While the  $\delta^{18}\text{O}$  chronologies at the two studied sites are highly correlated during the 19th and 20th century, there is a significant decrease in the correlation coefficient between 1550 and 1800 AD, which indicates either a weaker climate sensitivity of the tree ring proxies during this period, or a more heterogeneous climate in the north and the south of France. Future studies of tree ring isotope networks might reveal if the seasonality and spatial patterns of past droughts can explain this decoupling.

CPD

11, 5113–5155, 2015

## French summer droughts since 1326 AD

I. Labuhn et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



# 1 Introduction

Droughts can have severe impacts on ecosystems and on human activities (Büntgen et al., 2010; Seneviratne et al., 2012; Diaz and Trouet, 2014), as they influence water availability, groundwater recharge, algal blooms (Paerl et al., 2011), forest productivity (Allen et al., 2010), carbon sink saturation (Nabuurs et al., 2013), crop yields, forest fires, soil degradation, building subsidence and insurance costs (Corti et al., 2011, 2009), as well as human health (Haines et al., 2006; O'Brien et al., 2014). In response to increased greenhouse gas concentrations, climate projections anticipate a marked increase in heat waves and droughts (Dai, 2013; Kovats et al., 2014). More intense and longer meteorological droughts have already been identified in southern Europe (Sousa et al., 2011; Vicente-Serrano et al., 2014) and southern France (Giuntoli et al., 2013), and are projected in France for the 21st century (Vidal et al., 2012), augmenting the pressure on water resources and challenging the sustainability of the current agricultural system (Itier, 2008; Levraut et al., 2010).

Soil moisture feedbacks have shown to play an important role in recent European hot summers (Zampieri et al., 2009) and their seasonal predictability (Quesada et al., 2012). Vidal et al. (2010) have provided a homogenized reference framework for French droughts since the 1950s based on high resolution meteorological reanalyses. However, prior to 1950, little is known about the past intensity, return period and spatial extent of drought events, mostly based on historical sources (Garnier, 2011). The detection and attribution of recent hydroclimate changes and their link with the ongoing warming trend therefore remain an open issue. A reconstruction of the temporal and spatial extent of drought in the past would constitute a valuable basis for expanding the knowledge on past droughts using natural climate archives.

In semi-arid regions, tree ring width chronologies can provide records of past drought periods (e.g. Cook et al., 2004; Li et al., 2006; Esper et al., 2007; Stahle et al., 2007; Linares et al., 2012; Yadav, 2013). Drought, however, can also occur in high-rainfall areas and is a recurrent feature of the European climate (European Environment Agency,

## French summer droughts since 1326 AD

I. Labuhn et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**French summer droughts since 1326 AD**

I. Labuhn et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

2001). A great amount of high-resolution proxy data from Europe exists, but many tree-ring based reconstructions focus on high-altitude or high-latitude sites, where ring width and density show a strong sensitivity to temperature. Pan-European signature years in oak ring width series have been related to soil moisture anomalies (Kelly et al., 2002), but they only give access to extreme events.

Stable isotopes in tree ring cellulose have proven to be the more reliable proxy in areas where tree growth is not strongly dependent on climate, typically at low elevation, mid-latitude sites (e.g. Loader et al., 2008; Saurer et al., 2008; Young et al., 2012), and can therefore help extend climate reconstructions into regions which are not yet well covered (Leavitt et al., 2010). Several recent studies have revealed the sensitivity of French oak cellulose  $\delta^{18}\text{O}$  to the combined effects of temperature and humidity, and therefore of drought (Raffalli-Delcerce et al., 2004; Masson-Delmotte et al., 2005; Etien et al., 2008, 2009; Labuhn et al., 2014). This influence can be explained by the physical processes and mechanisms, such as the isotopic enrichment of leaf water, which relate the cellulose  $\delta^{18}\text{O}$  signal to climate (Hill et al., 1995; Barbour and Farquhar, 2000; Barbour et al., 2004; Cernusak et al., 2005; Sternberg, 2009; Gessler et al., 2009, 2013).

A complete understanding of past climate variability must include the whole frequency spectrum from inter-annual to multi-centennial scales. A challenge of tree ring based climate reconstructions is the preservation of low-frequency variability in the proxy records. The construction of ring width chronologies necessitates the standardization of individual ring width series to correct non-climatic growth trends (Cook et al., 1990). However, standardization can also eliminate low-frequency climatic trends in the series. Esper et al. (2004) identified the standardization method applied to ring width and density data as the most important cause of differences in low-frequency trends between different hemispheric scale temperature reconstructions of the past millennium. If appropriate data and methods are used, multi-centennial climate variability can be preserved in ring width chronologies (Briffa et al., 2002; Esper et al., 2002), but large numbers of samples are required.

**French summer droughts since 1326 AD**

I. Labuhn et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

For isotope proxies, a strong common signal between trees at a site is usually found, which means that fewer trees are necessary to obtain a robust climate signal (Leavitt, 2010; Daux et al., 2011; Shi et al., 2011). This is especially beneficial if the number of available samples is limited, e.g. when subfossil wood or ancient building material is used. Although stable isotope series have a greater potential to retain long-term climatic trends as they are usually not standardized, a problem can arise when combining different trees or tree cohorts into an isotope chronology, if site-related factors lead to offsets in average isotope values between individual trees or sub-series. However, an offset correction might induce not only a partial loss of low-frequency climate information, but also makes it difficult to relate differences in absolute isotope values between distant sites to climatic gradients, because the effects of these gradients can be superimposed by the influence of the local environment.

In this article, we present annually resolved chronologies of oxygen isotope ratios in latewood cellulose ( $\delta^{18}\text{O}_c$ ) constructed from *Quercus* spp. living trees and timbers at two sites in France: (1) an extension of the previously published series from Fontainebleau (1596–2000) (Etien et al., 2008, 2009) back to 1326; and (2) an extension of the previously published series from Braconne forest near Angoulême (1860–2004) (Labuhn et al., 2014) back to 1360. The previous studies have demonstrated that  $\delta^{18}\text{O}_c$  at these sites responds to summer temperature and moisture availability. Here, we present reconstructions of summer droughts for Angoulême and Fontainebleau based on the  $\delta^{18}\text{O}_c$  chronologies. Furthermore, we investigate the absolute and relative variability between individual trees and between tree cohorts from the same site, and address methodological issues related to the construction of long isotope chronologies from several cohorts. Then, we compare  $\delta^{18}\text{O}_c$  between Fontainebleau and Angoulême at different time scales to evaluate the spatial coherence of the records and the temporal stability of their relationship. As meteorological data are only available for the 20th century, this comparison can give indications if the climatic forcing for northern and southwest France droughts which influences  $\delta^{18}\text{O}_c$  is stable over time.





## French summer droughts since 1326 AD

I. Labuhn et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



origin of the wood can be assumed. The possibility to crossdate timber cores and living trees demonstrates a common climatic influence on interannual ring width variability. A subset of cores was selected for isotope analyses to obtain a sample depth of four to six trees for each year with sufficient overlap between samples; only between 1556 and 1591 is the number of trees  $< 4$ .

The living trees at FON are *Quercus petraea*. At ANG, the species has not been determined in the field, but *Q. petraea* and *Q. robur* are the dominant species in the forest. For all timber wood, the oak species is unknown. Although methods to determine the species based on wood anatomy exist (for a review see Feuillat et al., 1997), an unambiguous discrimination between *Q. petraea* and *Q. robur* is not possible (Schoch et al., 2004). To our knowledge, the oxygen isotopic composition of cellulose in the two oak species has never been compared, but specific differences in the  $\delta^{18}\text{O}$ , as already shown for  $\delta^{13}\text{C}$  due to differences in water use efficiency (Ponton et al., 2001), cannot be ruled out. Even if there is no direct species effect, different species have different site preferences (Lévy et al., 1992), and the site hydrology influences the  $\delta^{18}\text{O}$  (Labuhn et al., 2014). However, site effects can also influence the  $\delta^{18}\text{O}$  of trees within a species. We therefore consider that the site-related uncertainty is more important than the uncertainty due to the ambiguity in species determination.

Tree ring width was measured under a binocular microscope using a LINTAB measuring table (Rinntech) with a precision of 0.01 mm, and cores were crossdated. The crossdating was verified visually and statistically with the program COFECHA (Holmes, 1983; Grissino-Mayer, 2001).

### 2.3 $\delta^{18}\text{O}$ measurements, pooling strategy and corrections

For isotope analysis, the selected cores were cut ring by ring with a scalpel and earlywood was separated from latewood. Only the latewood was analyzed. Corresponding rings of multiple cores taken from the same tree were pooled. The wood samples were homogenized and cellulose was extracted according to Green (1963) and Leavitt and Danzer (1993). The  $\delta^{18}\text{O}$  of cellulose was measured using a thermal combustion el-

emental analyzer (Finnigan Thermo TC-EA) coupled with a Finnigan MAT252 mass spectrometer at LSCE in Gif-sur-Yvette, France. The measurements were corrected using the cellulose reference Whatman CC31. Each sample was measured at least twice. The analytical uncertainty was 0.20‰.  $\delta^{18}\text{O}$  values are reported with reference to VSMOW (Coplen, 1994). A total of 1371 samples (787 ANG, 584 FON) was measured for this study, excluding replicates.

For the previously published FON  $\delta^{18}\text{O}_c$  chronology, wood from all living tree and timber cores had been pooled for each year prior to analysis. In this study, the new FON samples were pooled by building, thereby grouping together trees of approximately the same age. Although the inter-tree variability of  $\delta^{18}\text{O}_c$  at a site was generally low, a systematic offset had been observed between the old (ANG-GR) and the young (ANG-B) trees at Braconne forest, which is likely due to differences in the site hydrology (Labuhn et al., 2014). This observation raises concerns about a possible site-related increased variability in timber samples. To address this question, we performed an inter-tree comparison for the ANG timber wood by analyzing individual rings at a 5 year interval. For the remaining years, the rings of all timber cores were pooled prior to cellulose extraction.

A juvenile effect of increasing  $\delta^{18}\text{O}_c$  during the first 20 years of a tree's life had been observed in the trees from site ANG-B (Labuhn et al., 2014). In the ANG data and the new FON data (1326–1595), the juvenile effect was taken into account by omitting the first 20 years of each tree core from the analysis. For the previously published series from FON (1596–2000), several trees had been pooled and a correction was not possible anymore. Furthermore, for these samples, only the calendar year of each ring was known but not their cambial age. It was therefore not possible to verify whether the trees had been cored to the pith, and we do not know whether the innermost rings of a core actually correspond to a period of juvenile growth.

Both the FON and ANG chronologies are composed of several sub-series (cohorts), which have been analyzed separately. The cohorts showed differences in the mean isotope values for their periods of overlap of up to 1‰ (see Sect. 3.2). As all trees

## CPD

11, 5113–5155, 2015

### French summer droughts since 1326 AD

I. Labuhn et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



have been exposed to the same climatic influences, these offsets are likely due to the local conditions (competition, microclimate, rooting depth, soil hydrology). We tested different methods to merge the overlapping series (following Hangartner et al., 2012) in order to investigate the effects of such offsets on the final chronology: (1) no correction was applied; (2) the mean  $\delta^{18}\text{O}_c$  values of the older cohorts were adjusted to match the mean of the corresponding younger cohorts in their period of overlap; (3) all cohorts were normalized to have the same mean ( $\mu = 0$ ) before merging them. In all cases, the averages of two cohorts were calculated weighting each cohort by the number of trees.

## 2.4 Statistical analyses

Statistical analyses were performed using the R software (R Development Core Team, 2015). The site chronologies were decomposed to high-pass and low-pass filtered data using a cubic smoothing spline with a 50% variance cutoff at a period of 10 years, which enables a comparison of the inter-annual and decadal variability between series. Running correlations between sites and running standard deviations (SD) for each site were calculated using a window of 51 years. Correlation coefficients were calculated between  $\delta^{18}\text{O}_c$  and the meteorological variables at a monthly and seasonal time scale, in order to investigate the climate response of the trees and to identify the climate parameters which can be reconstructed from the tree ring proxy.

A model for reconstruction of the drought index SPEI was developed based on a linear regression between the index and  $\delta^{18}\text{O}_c$ . The validity of the model was tested by dividing the SPEI data into a calibration (two-thirds of the values) and a verification data set (one-third of the values). This enables a quantitative comparison of the reconstructed drought index with independent data not used in the calibration. The subsets of data were selected randomly and the procedure was repeated 1000 times. To evaluate the skill of the model in estimating the SPEI, we calculated the correlation coefficient ( $r$ ), the reduction of error statistic (RE), and the coefficient of efficiency (CE) (see Briffa et al., 1988) for each iteration.

CPD

11, 5113–5155, 2015

## French summer droughts since 1326 AD

I. Labuhn et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





lower on average than the raw values before 1640, and higher on average after this year.

The uncorrected chronologies of FON and ANG differ in long-term trends and  $\delta^{18}\text{O}_c$  values diverge prior to 1620, although the decadal trends are largely synchronous. The corrected chronologies, on the contrary, show a good agreement for the centennial trends (Fig. 5). The subsequent analyses are based on the chronologies which are corrected by subtracting the mean from each cohort before merging them.

### 3.3 Comparison of $\delta^{18}\text{O}$ site chronologies

The  $\delta^{18}\text{O}_c$  chronologies from FON and ANG are significantly correlated during the 20th century ( $r = 0.71$  for high-pass and  $r = 0.69$  for low-pass filtered data). The correlation shows a marked decrease between 1600 and 1800. These patterns are similar for the inter-annual variability and the decadal smoothed chronologies (Figs. 6 and 7).

The standard deviation calculated for a 51 year moving window illustrates common patterns of changes in the magnitude of inter-annual variability, e.g. periods of low inter-annual variability around 1470, 1620 and 1800, and increased variability before 1400 and around 1700. In general, the variability is slightly lower at FON (mean SD = 0.52) than at ANG (mean SD = 0.60).

### 3.4 Correlations with meteorological variables

The strength and direction of the correlations of  $\delta^{18}\text{O}_c$  with different meteorological variables are generally similar for FON and ANG (2).  $\delta^{18}\text{O}_c$  is positively correlated to temperature during the summer months, with stronger correlations for maximum temperature than for mean temperature. The strongest correlations are obtained with maximum temperature averaged over June–August. Negative correlations are found with precipitation and the drought index SPEI during the summer months. Again, correlations are improved when considering the integral of the summer months.

## French summer droughts since 1326 AD

I. Labuhn et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The relationship between  $\delta^{18}\text{O}_c$  and the climate variables is relatively stable throughout the 20th century, as correlation coefficients ( $r$ ) calculated for a 31 year moving window vary only slightly (standard deviation of  $r$  between 0.04 and 0.08 for different pairs of variables; not shown).

### 3.5 Drought reconstructions

For these reconstructions, we selected the SPEI drought index at a 3 month resolution, which integrates drought conditions during the summer months (June–August). The correlation between SPEI and  $\delta^{18}\text{O}_c$  is  $r = -0.69$  ( $p < 0.001$ ,  $N = 100$ ) for FON and  $r = -0.68$  ( $p < 0.001$ ,  $N = 104$ ) for ANG. The equations describing the linear regression line between the two variables are used to estimate the SPEI from  $\delta^{18}\text{O}_c$  for each site (Fig. 8). The  $r$ , RE and CE statistics confirm the validity of the models (high  $r$ , positive RE and CE; see Briffa et al., 1988). The squared correlations are  $R^2 = 0.48$  for FON and  $R^2 = 0.46$  for ANG, which means that almost 50 % of the variability in the drought index is accounted for by the respective models. The standard deviation of the differences between modeled and observed SPEI (0.72 for FON; 0.70 for ANG) defines the confidence interval for the respective reconstructions (Fig. 9).

For ANG, the oldest part of the reconstruction is characterized by a prolonged period of relatively wet conditions (1360–1450), followed by a period of drier conditions until 1600 (Fig. 10). Another wet period until 1760 follows, with a short increase to relatively drier conditions around 1720. The most marked trend in the reconstruction is the shift to dry conditions from 1760 to 1850. The late 20th century is characterized by increasingly dry summers, but these SPEI values are not unprecedented in the record.

The reconstructed SPEI at FON indicates relatively wet conditions for large parts of the record prior to 1800, except two drier intervals in the 14th century and in the earlier half of the 16th century. Like for ANG, there is a marked step to drier conditions around 1800, and the late 20th century is characterized by increasing drought.

CPD

11, 5113–5155, 2015

## French summer droughts since 1326 AD

I. Labuhn et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





## French summer droughts since 1326 AD

I. Labuhn et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



5 fined confidence interval. When such site-related offsets exist, it is not appropriate to compare absolute isotope values at distant sites, e.g. to infer climatic gradients. When averaging uncorrected series, there is a risk of introducing artificial shifts or trends in the final chronology that are not climatic. Applying a normalization, however, implies a partial loss of the low-frequency variability, as the variability which exceed the length of the cohorts may not be preserved.

10 A solution to this problem would be to increase the sample size and to measure trees individually, possibly at the expense of the temporal resolution, which would allow identifying outliers and calculating a confidence interval around the mean  $\delta^{18}\text{O}_c$  value. Several recent studies propose methods to deal with offsets (Esper et al., 2010; Gagen et al., 2012; Hangartner et al., 2012; Naulier et al., 2015). However, it could be problematic to find appropriate samples for periods where no living tree material is available. This investigation demonstrates the importance of assessing  $\delta^{18}\text{O}_c$  variations between individual trees, and of correcting offsets when combining different sets of trees, in order to carry out meaningful inter-site comparisons and reliable identifica-  
15 tions of multi-centennial trends.

### 4.2 The coherence between site chronologies and its temporal stability

20 The  $\delta^{18}\text{O}$  chronologies from FON and ANG reveal common patterns of variability on different time scales, but their relationship is not stable over time. High correlations between the two isotope chronologies, e.g. during the 19th and 20th century, indicate common forcing factors on  $\delta^{18}\text{O}_c$  variability. The only possible forcing acting on this spatial scale is climate. The changes in correlation strength are likely not linked to the construction of the chronologies, as high correlations occur both with small and large numbers of sampled trees (e.g. during the 15th and 20th century), and a possible  
25 juvenile effect has been accounted for. We propose two hypotheses to explain the periods of decreased correlation between sites: (1) a changing climate response of the trees; and (2) changing climate patterns over France.

## French summer droughts since 1326 AD

I. Labuhn et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Proxies often show a non-linear response to climate (Schleser et al., 1999). The climate sensitivity of trees is known to change with time (e.g. Reynolds-Henne et al., 2007; Friedrichs et al., 2009; Dorado Liñán et al., 2011; Mérian et al., 2011; Voelker, 2011; Linares et al., 2012; Rozas and Olano, 2013; Candela-Galván et al., 2015), due to tree age, changes in the timing and length of the growing season or in the atmospheric CO<sub>2</sub> concentration. In addition, the response of trees to climate changes may depend on their local environment, e.g. soil conditions. The periods of low correlation between sites could be explained by a weaker sensitivity of the proxy to climate when some climate factors are below a certain threshold. For example, during relatively humid periods,  $\delta^{18}\text{O}_c$  would not strongly depend on humidity and it would not exhibit large inter-annual variations. However, the amplitude of inter-annual variability at both sites (illustrated by the running SD; Fig. 7d) does not support this hypothesis, as SD and the site-to-site correlation do not show common patterns. The SD is certainly influenced by the number of trees, but even when the number of trees is constant (e.g. in ANG 1680–1880), large changes in the SD occur. If the climate response of the trees changes, this has implications for our climate reconstruction, which is based on the climate-proxy relationship during the 20th century, where instrumental measurements of meteorological variables are available.

The second explanation for the temporal instability of the correlations between the FON and ANG oxygen isotope chronologies could be a change in the regional homogeneity of the climate. The 20th century is characterized by coherent patterns in meteorological variables at FON and ANG (Fig. 2), and during this period we observe high correlation between the  $\delta^{18}\text{O}_c$  chronologies. However, the climate in France might have been more heterogeneous in the past. Changes in seasonal aspects of climate or in the relationship between temperature and humidity can alter the way these variables act on  $\delta^{18}\text{O}_c$  (Barbour et al., 2002; Masson-Delmotte et al., 2005; Reynolds-Henne et al., 2007). While temperature variations are likely to be coherent between the sites at a time scale which is relevant for the proxy, precipitation patterns are generally more variable in space. The season of the trees water supply (e.g. winter or growing season

precipitation), depends on soil properties, root depth, and precipitation seasonality, and can vary over time and between sites (Bréda et al., 1995; Schulze et al., 1996; Hruska et al., 1999; Hanson et al., 2001).

Correlations with ring width show that FON trees are more sensitive to precipitation, and the site receives less winter precipitation than ANG. The periods of decoupling between the sites could be characterized by changes in winter precipitation, which would influence the drought signal at FON, whereas at ANG, where summer evaporative enrichment dominates the  $\delta^{18}\text{O}_c$  signal (Labuhn et al., 2014), winter precipitation would not have a strong influence. According to our reconstruction, the period of low correlation coincides with a prolonged wet period at FON. Changes in the spatial and seasonal distribution of precipitation could therefore be responsible for the temporal instability of the relationship between the FON and ANG  $\delta^{18}\text{O}_c$  chronologies.

### 4.3 Comparison of the drought reconstructions with grape harvest dates

Historical records of grape harvest dates (GHD) have been interpreted as proxies of summer temperature, and GHD records are available from the Burgundy (near FON) and Bordeaux (near ANG) wine regions (Daux et al., 2012). Tree ring  $\delta^{18}\text{O}_c$  at ANG is significantly correlated with GHD from Bordeaux ( $r = -0.50$ ,  $p < 0.001$ ,  $N = 272$ ). The correlation with a French composite GHD record is only moderate at the inter-annual scale ( $r = -0.27$ ,  $p < 0.001$ ,  $N = 623$ ), but the long-term variability in both records displays common trends, e.g. an increase from 1500 to 1750 AD, followed by a decrease in the mid-18th and 19th century. Warm and dry summers therefore seem to lead to high  $\delta^{18}\text{O}_c$  values and early grape harvest.

At FON, on the contrary,  $\delta^{18}\text{O}_c$  and GHD from Burgundy are not well correlated ( $r = -0.22$ ,  $p < 0.001$ ,  $N = 621$ ). It is possible that FON  $\delta^{18}\text{O}_c$  is less dependent on temperature (weaker correlations than ANG) but more on precipitation (slightly higher correlations than ANG for summer and growing season averages). This is in line with our previous hypothesis (Sect. 4.2): trees at FON respond to droughts caused pri-

## French summer droughts since 1326 AD

I. Labuhn et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion







## French summer droughts since 1326 AD

I. Labuhn et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



- Beguera, S., Vicente-Serrano, S. M., and Angulo-Martínez, M.: A multiscalar global drought dataset: the SPEIbase: a new gridded product for the analysis of drought variability and impacts, *B. Am. Meteorol. Soc.*, 91, 1351–1356, doi:10.1175/2010BAMS2988.1, 2010. 5118
- Bréda, N., Granier, A., Barataud, F., and Moyne, C.: Soil water dynamics in an oak stand. I. Soil moisture, water potentials and water uptake by roots, *Plant Soil*, 172, 17–27, doi:10.1007/BF00020856, 1995. 5129
- Briffa, K. R., Jones, P. D., Pilcher, J. R., and Hughes, M. K.: Reconstructing summer temperatures in northern Fennoscandia back to AD 1700 using tree-ring data from Scots pine, *Arctic Alpine Res.*, 20, 385–394, doi:10.2307/1551336, 1988. 5122, 5125
- Briffa, K. R. K., Osborn, T. T. J., Schweingruber, F. H., Jones, P. D., Shiyatov, S. G., and Vaganov, E. A.: Tree-ring width and density data around the Northern Hemisphere: Part 2, spatio-temporal variability and associated climate patterns, *Holocene*, 12, 759–789, doi:10.1191/0959683602h1587rp, 2002. 5116
- Büntgen, U., Trouet, V., Frank, D., Leuschner, H. H., Friedrichs, D., Luterbacher, J., and Esper, J.: Tree-ring indicators of German summer drought over the last millennium, *Quaternary Sci. Rev.*, 29, 1005–1016, doi:10.1016/j.quascirev.2010.01.003, 2010. 5115
- Candela-Galván, J. D., Büntgen, U., Ginzler, C., Grudd, H. k., Gutiérrez, E., Labuhn, I., and Camarero, J. J.: Drought-induced weakening of growth-temperature associations in Mediterranean high-elevation forests, *Global Planet. Change*, 124, 95–106, doi:10.1016/j.gloplacha.2014.11.011, 2015. 5128
- Cernusak, L. A., Farquhar, G. D., and Pate, J. S.: Environmental and physiological controls over oxygen and carbon isotope composition of Tasmanian blue gum, *Eucalyptus globulus*, *Tree Physiol.*, 25, 129–146, doi:10.1093/treephys/25.2.129, 2005. 5116
- Cook, E. R., Briffa, K. R., Shiyatov, S., and Mazepa, V.: Tree-ring standardization and growth-trend estimation, in: *Methods of Dendrochronology – Applications in the Environmental Sciences*, edited by: Cook, E. R. and Kairiukstis, L. A., Kluwer Academic Publishers, Dordrecht, 104–123, 1990. 5116
- Cook, E. R., Woodhouse, C. A., Eakin, C. M., Meko, D. M., and Stahle, D. W.: Long-term aridity changes in the western United States, *Science*, 306, 1015–1018, doi:10.1126/science.1102586, 2004. 5115
- Coplen, T. B.: Reporting of stable hydrogen, carbon, and oxygen isotopic abundances, *Pure Appl. Chem.*, 66, 273–276, doi:10.1351/pac199466020273, 1994. 5121

**French summer  
droughts since  
1326 AD**

I. Labuhn et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

- Corti, T., Muccione, V., Köllner-Heck, P., Bresch, D., and Seneviratne, S. I.: Simulating past droughts and associated building damages in France, *Hydrol. Earth Syst. Sci.*, 13, 1739–1747, doi:10.5194/hess-13-1739-2009, 2009. 5115
- Corti, T., Wüest, M., Bresch, D., and Seneviratne, S. I.: Drought-induced building damages from simulations at regional scale, *Nat. Hazards Earth Syst. Sci.*, 11, 3335–3342, doi:10.5194/nhess-11-3335-2011, 2011. 5115
- Dai, A.: Increasing drought under global warming in observations and models, *Nature Climate Change*, 3, 52–58, doi:10.1038/nclimate1633, 2013. 5115
- Daux, V., Edouard, J., Masson-Delmotte, V., Stievenard, M., Hoffmann, G., Pierre, M., Mestre, O., Danis, P., and Guibal, F.: Can climate variations be inferred from tree-ring parameters and stable isotopes from *Larix decidua*? Juvenile effects, budmoth outbreaks, and divergence issue, *Earth Planet. Sc. Lett.*, 309, 221–233, doi:10.1016/j.epsl.2011.07.003, 2011. 5117
- Daux, V., Garcia de Cortazar-Atauri, I., Yiou, P., Chuine, I., Garnier, E., Le Roy Ladurie, E., Mestre, O., and Tardaguila, J.: An open-access database of grape harvest dates for climate research: data description and quality assessment, *Clim. Past*, 8, 1403–1418, doi:10.5194/cp-8-1403-2012, 2012. 5129, 5155
- Diaz, H. and Trouet, V.: Some perspectives on societal impacts of past climatic changes, *History Compass*, 12, 160–177, doi:10.1111/hic3.12140, 2014. 5115
- Dorado Liñán, I., Gutiérrez, E., Heinrich, I., Andreu-Hayles, L., Muntán, E., Campelo, F., and Helle, G.: Age effects and climate response in trees: a multi-proxy tree-ring test in old-growth life stages, *Eur. J. Forest Res.*, 131, 933–944, doi:10.1007/s10342-011-0566-5, 2011. 5128
- Esper, J., Cook, E. R., and Schweingruber, F. H.: Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability, *Science*, 295, 2250–2253, doi:10.1126/science.1066208, 2002. 5116
- Esper, J., Frank, D., and Wilson, R.: Climate reconstructions: low-frequency ambition and high-frequency ratification, *Eos*, 85, 113–120, doi:10.1029/2004EO120002, 2004. 5116
- Esper, J., Frank, D., Büntgen, U., Verstege, A., Luterbacher, J., and Xoplaki, E.: Long-term drought severity variations in Morocco, *Geophys. Res. Lett.*, 34, 1–5, 2007. 5115
- Esper, J., Frank, D. C., Battipaglia, G., Büntgen, U., Holert, C., Treydte, K., Siegwolf, R., and Saurer, M.: Low-frequency noise in delta C-13 and delta O-18 tree ring data: a case study of *Pinus uncinata* in the Spanish Pyrenees, *Global Biogeochem. Cy.*, 24, 1–11, doi:10.1029/2010GB003772, 2010. 5127

## French summer droughts since 1326 AD

I. Labuhn et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



- Etien, N., Daux, V., Masson-Delmotte, V., Stievenard, M., Bernard, V., Durost, S., Guillemin, M. T., Mestre, O., and Pierre, M.: A bi-proxy reconstruction of Fontainebleau (France) growing season temperature from A.D. 1596 to 2000, *Clim. Past*, 4, 91–106, doi:10.5194/cp-4-91-2008, 2008. 5116, 5117, 5119, 5142
- 5 Etien, N., Daux, V., Masson-Delmotte, V., Mestre, O., Stievenard, M., Guillemin, M. T., Boettger, T., Bréda, N., Haupt, M., and Perraud, P. P.: Summer maximum temperature in northern France over the past century: instrumental data versus multiple proxies (tree-ring isotopes, grape harvest dates and forest fires), *Climatic Change*, 94, 429–456, doi:10.1007/s10584-008-9516-8, 2009. 5116, 5117, 5119
- 10 European Environment Agency: Sustainable Water Use in Europe, Part 3: Extreme Hydrological Events: Floods and Droughts, Environmental issue report No 21, EEA, Copenhagen, 2001. 5115
- Feuillat, F., Dupouey, J.-L., Sciamia, D., and Keller, R.: A new attempt at discrimination between *Quercus petraea* and *Quercus robur* based on wood anatomy, *Can. J. Forest Res.*, 27, 343–351, doi:10.1139/x96-174, 1997. 5120
- 15 Friedrichs, D. A., Büntgen, U., Frank, D. C., Esper, J., Neuwirth, B., and Löffler, J.: Complex climate controls on 20th century oak growth in Central-West Germany, *Tree Physiol.*, 29, 39–51, doi:10.1093/treephys/tpn003, 2009. 5128
- Gagen, M., McCarroll, D., Jalkanen, R., Loader, N., Robertson, I., and Young, G.: A rapid method for the production of robust millennial length stable isotope tree ring series for climate reconstruction, *Global Planet. Change*, 82–83, 96–103, doi:10.1016/j.gloplacha.2011.11.006, 2012. 5127
- 20 Garnier, E.: Climat de la France : apport de l'histoire, in: *Le climat à découvert. Outils et méthodes en recherche climatique*, edited by: Jeandel, C. and Mossery, R., CNRS Editions, Paris, 111–113, 2011. 5115
- 25 Gat, J. R.: Oxygen and hydrogen isotopes in the hydrologic cycle, *Annu. Rev. Earth Pl. Sc.*, 24, 225–262, doi:10.1146/annurev.earth.24.1.225, 1996. 5126
- Gessler, A., Brandes, E., Buchmann, N., Helle, G., Rennenberg, H., and Barnard, R. L.: Tracing carbon and oxygen isotope signals from newly assimilated sugars in the leaves to the tree-ring archive, *Plant Cell Environ.*, 32, 780–795, doi:10.1111/j.1365-3040.2009.01957.x, 2009. 5116
- 30 Gessler, A., Brandes, E., Keitel, C., Boda, S., Kayler, Z. E., Granier, A., Barbour, M., Farquhar, G. D., and Treydte, K.: The oxygen isotope enrichment of leaf-exported assimi-

**French summer  
droughts since  
1326 AD**

I. Labuhn et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

lates – does it always reflect lamina leaf water enrichment?, *New Phytol.*, 200, 144–157, doi:10.1111/nph.12359, 2013. 5116, 5126

Giuntoli, I., Renard, B., Vidal, J.-P., and Bard, A.: Low flows in France and their relationship to large-scale climate indices, *J. Hydrol.*, 482, 105–118, doi:10.1016/j.jhydrol.2012.12.038, 2013. 5115

Green, J. W.: Wood cellulose, in: *Methods of Carbohydrate Chemistry*, edited by: Whistler, R. L., Academic Press, New York, 9–21, 1963. 5120

Grissino-Mayer, H. D.: Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA, *Tree-Ring Res.*, 57, 205–221, 2001. 5120

Haines, A., Kovats, R. S., Campbell-Lendrum, D., and Corvalan, C.: Climate change and human health: impacts, vulnerability and public health, *Public Health*, 120, 585–596, doi:10.1016/j.puhe.2006.01.002, 2006. 5115

Hangartner, S., Kress, A., Saurer, M., Frank, D., and Leuenberger, M.: Methods to merge overlapping tree-ring isotope series to generate multi-centennial chronologies, *Chem. Geol.*, 294, 127–134, doi:10.1016/j.chemgeo.2011.11.032, 2012. 5122, 5127

Hanson, P. J., Todd, D. E., and Amthor, J. S.: A six-year study of sapling and large-tree growth and mortality responses to natural and induced variability in precipitation and throughfall, *Tree Physiol.*, 21, 345–358, doi:10.1093/treephys/21.6.345, 2001. 5129

Harris, I., Jones, P., Osborn, T., and Lister, D.: Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset, *Int. J. Climatol.*, 34, 623–642, doi:10.1002/joc.3711, 2013. 5118

Haupt, M., Weigl, M., Grabner, M., and Boettger, T.: A 400-year reconstruction of July relative air humidity for the Vienna region (eastern Austria) based on carbon and oxygen stable isotope ratios in tree-ring latewood cellulose of oaks (*Quercus petraea* Matt. Liebl.), *Climatic Change*, 105, 243–262, doi:10.1007/s10584-010-9862-1, 2011. 5126

Hilasvuori, E. and Berninger, F.: Dependence of tree ring stable isotope abundances and ring width on climate in Finnish oak, *Tree Physiol.*, 30, 636–647, doi:10.1093/treephys/tpq019, 2010. 5126

Hill, S. A., Waterhouse, J. S., Field, E. M., Switsur, V. R., and Ap Rees, T.: Rapid recycling of triose phosphates in oak stem tissue, *Plant Cell Environ.*, 18, 931–936, doi:10.1111/j.1365-3040.1995.tb00603.x, 1995. 5116

Holmes, R. L.: Computer-assisted quality control in tree-ring dating and measurement, *Tree-Ring Bulletin*, 43, 69–78, 1983. 5120

## French summer droughts since 1326 AD

I. Labuhn et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



- Hruska, J., Cermák, J., and Sustek, S.: Mapping tree root systems with ground-penetrating radar, *Tree Physiol.*, 19, 125–130, doi:10.1093/treephys/19.2.125, 1999. 5129
- Itier, B.: Agriculture et sécheresse: le contexte et les enjeux (Agriculture and drought: context and challenges), *Innovations Agronomiques*, 2, 1–8, 2008, (in French). 5115
- 5 Kelly, P. M., Leuschner, H. H., Briffa, K. R., and Harris, I. C.: The climatic interpretation of pan-European signature years in oak ring-width series, *Holocene*, 12, 689–694, doi:10.1191/0959683602h1582rp, 2002. 5116
- Kovats, R., Valentini, R., Bouwer, L., Georgopoulou, E., Jacob, D., Martin, E., Rounsevell, M., and Soussana, J.-F.: Europe, in: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by: Barros, V., Field, C., Dokken, D., Mastrandrea, M., Mach, K., Bilir, T., Chatterjee, M., Ebi, K., Estrada, Y., Genova, R., Girma, B., Kissel, E., Levy, A., MacCracken, S., Mastrandrea, P., and White, L., Cambridge University Press, Cambridge, UK and New York, USA, 1267–1326, 2014. 5115
- 10 Labuhn, I., Daux, V., Pierre, M., Stievenard, M., Girardclos, O., Féron, A., Genty, D., Masson-Delmotte, V., and Mestre, O.: Tree age, site and climate controls on tree ring cellulose  $\delta^{18}O$ : A case study on oak trees from south-western France, *Dendrochronologia*, 32, 78–89, doi:10.1016/j.dendro.2013.11.001, 2014. 5116, 5117, 5119, 5120, 5121, 5129
- Leavitt, S. W.: Tree-ring C-H-O isotope variability and sampling, *Sci. Total Environ.*, 408, 5244–5253, doi:10.1016/j.scitotenv.2010.07.057, 2010. 5117
- 20 Leavitt, S. W. and Danzer, S. R.: Method for batch processing small wood samples to holocellulose for stable-carbon isotope analysis, *Anal. Chem.*, 65, 87–89, doi:10.1021/ac00049a017, 1993. 5120
- Leavitt, S. W., Treydte, K., and Yu, L.: Environment in time and space: opportunities from tree-ring isotope networks, in: *Isoscapes*, edited by: West, J. B., Bowen, G. J., Dawson, T. E., and Tu, K. P., Springer, Dordrecht, 113–135, doi:10.1007/978-90-481-3354-3, 2010. 5116
- 25 Levraut, F., Brisson, N., Pieri, P., and Bosc, A.: Climate change in the South-West zone: the main agricultural and forest impacts, in: *Climate Change, Agriculture and Forests in France: Simulations of the Impacts on the Mail Species, The Green Book of the CLIMATOR Project (2007-2010)*, edited by: Brisson, N. and Levraut, F., ADEME, Angers, 287–296, 2010. 5115
- 30 Lévy, G., Becker, M., and Duhamel, D.: A comparison of the ecology of pedunculate and sessile oaks: Radial growth in the centre and northwest of France, *Forest Ecol. Manag.*, 55, 51–63, doi:10.1016/0378-1127(92)90091-M, 1992. 5120

## French summer droughts since 1326 AD

I. Labuhn et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



- Li, J., Gou, X., Cook, E. R., and Chen, F.: Tree-ring based drought reconstruction for the central Tien Shan area in northwest China, *Geophys. Res. Lett.*, 33, 1–5, doi:10.1029/2006GL025803, 2006. 5115
- 5 Linares, J. C., Taïqui, L., Sangüesa-Barreda, G., Seco, J. I., and Camarero, J. J.: Age-related drought sensitivity of Atlas cedar (*Cedrus atlantica*) in the Moroccan Middle Atlas forests, *Dendrochronologia*, 31, 88–96, doi:10.1016/j.dendro.2012.08.003, 2012. 5115, 5128
- Loader, N., Santillo, P., Woodman-Ralph, J., Rolfe, J., Hall, M., Gagen, M., Robertson, I., Wilson, R., Froyd, C., and McCarroll, D.: Multiple stable isotopes from oak trees in southwestern Scotland and the potential for stable isotope dendroclimatology in maritime climatic regions, *Chem. Geol.*, 252, 62–71, doi:10.1016/j.chemgeo.2008.01.006, 2008. 5116, 5126
- 10 Masson-Delmotte, V., Raffalli-Delerce, G., Danis, P. A., Yiou, P., Stievenard, M., Guibal, F., Mestre, O., Bernard, V., Goosse, H., Hoffmann, G., and Jouzel, J.: Changes in European precipitation seasonality and in drought frequencies revealed by a four-century-long tree-ring isotopic record from Brittany, western France, *Clim. Dynam.*, 24, 57–69, doi:10.1007/s00382-004-0458-1, 2005. 5116, 5128
- 15 McKee, T. B., Doesken, N. J., and Kleist, J.: The relationship of drought frequency and duration to time scales, in: *Proceedings of the 8th Conference on Applied Climatology*. 17–22 January 1993, Anaheim, California, American Meteorological Society, Boston, MA, 179–184, 1993. 5118
- 20 Mérian, P., Bontemps, J.-D., Bergès, L., and Lebourgeois, F.: Spatial variation and temporal instability in climate-growth relationships of sessile oak (*Quercus petraea* [Matt.] Liebl.) under temperate conditions, *Plant Ecol.*, 212, 1855–1871, doi:10.1007/s11258-011-9959-2, 2011. 5128
- Nabuurs, G.-J., Lindner, M., Verkerk, P. J., Gunia, K., Deda, P., Michalak, R., and Grassi, G.: First signs of carbon sink saturation in European forest biomass, *Nature Climate Change*, 3, 792–796, doi:10.1038/nclimate1853, 2013. 5115
- 25 Naulier, M., Savard, M. M., Bégin, C., Gennaretti, F., Arseneault, D., Marion, J., Nicault, A., and Bégin, Y.: A millennial summer temperature reconstruction for northeastern Canada using oxygen isotopes in subfossil trees, *Clim. Past Discuss.*, 11, 521–553, doi:10.5194/cpd-11-521-2015, 2015. 5127
- 30 OBrien, L. V., Berry, H. L., Coleman, C., and Hanigan, I. C.: Drought as a mental health exposure, *Environ. Res.*, 131, 181–187, doi:10.1016/j.envres.2014.03.014, 2014. 5115

## French summer droughts since 1326 AD

I. Labuhn et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Paerl, H. W., Hall, N. S., and Calandrino, E. S.: Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change, *Sci. Total Environ.*, 409, 1739–1745, doi:10.1016/j.scitotenv.2011.02.001, 2011. 5115
- Palmer, W. C.: Meteorological Drought, US Weather Bureau, Washington, D.C., 1965. 5118
- 5 Ponton, S., Dupouey, J., Bréda, N., Feuillat, F., Bodénès, C., and Dreyer, E.: Carbon isotope discrimination and wood anatomy variations in mixed stands of *Quercus robur* and *Quercus petraea*, *Plant Cell Environ.*, 24, 861–868, doi:10.1046/j.0016-8025.2001.00733.x, 2001. 5120
- Quesada, B., Vautard, R., Yiou, P., Hirschi, M., and Seneviratne, S. I.: Asymmetric European summer heat predictability from wet and dry southern winters and springs, *Nature Climate Change*, 2, 736–741, doi:10.1038/nclimate1536, 2012. 5115
- 10 R Development Core Team: R: A Language and Environment for Statistical Computing, available at: <http://www.r-project.org>, last access: 16 March 2015. 5122
- Raffalli-Delcerce, G., Masson-Delmotte, V., Dupouey, J. L., Stievenard, M., Bréda, N., Moiselein, J. M., and Munksgaard, B.: Reconstruction of summer droughts using tree-ring cellulose isotopes: a calibration study with living oaks from Brittany (western France), *Tellus B*, 56, 160–174, doi:10.1111/j.1600-0889.2004.00086.x, 2004. 5116
- 15 Reynolds-Henne, C. E., Siegwolf, R. T. W., Treydte, K. S., Esper, J., Henne, S., and Saurer, M.: Temporal stability of climate-isotope relationships in tree rings of oak and pine (Ticino, Switzerland), *Global Biogeochem. Cy.*, 21, 1–12, doi:10.1029/2007GB002945, 2007. 5126, 5128
- 20 Rozas, V. and Olano, J. M.: Environmental heterogeneity and neighbourhood interference modulate the individual response of *Juniperus thurifera* tree-ring growth to climate, *Dendrochronologia*, 31, 105–113, doi:10.1016/j.dendro.2012.09.001, 2013. 5128
- 25 Saurer, M., Cherubini, P., Reynolds-Henne, C. E., Treydte, K. S., Anderson, W. T., and Siegwolf, R. T. W.: An investigation of the common signal in tree ring stable isotope chronologies at temperate sites, *J. Geophys. Res.*, 113, G04035, doi:10.1029/2008JG000689, 2008. 5116, 5126
- Schleser, G. G. H., Helle, G., Lucke, A., Vos, H., and Lücke, A.: Isotope signals as climate proxies: the role of transfer functions in the study of terrestrial archives, *Quaternary Sci. Rev.*, 18, 927–943, 1999. 5128
- 30 Schoch, W., Heller, I., Schweingruber, F., and Kienast, F.: Wood anatomy of Central European Species, available at: [www.woodanatomy.ch](http://www.woodanatomy.ch) (last access: 11 March 2014), 2004. 5120

## French summer droughts since 1326 AD

I. Labuhn et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Schulze, E. D., Mooney, H. A., Sala, O. E., Jobbagy, E., Buchmann, N., Bauer, G., Canadell, J., Jackson, R. B., Loreti, J., Oesterheld, M., and Ehleringer, J. R.: Rooting depth, water availability, and vegetation cover along an aridity gradient in Patagonia, *Oecologia*, 108, 503–511, doi:10.1007/BF00333727, 1996. 5129
- 5 Schweingruber, F. H.: *Tree Rings: Basics and Applications of Dendrochronology*, Kluwer, Dordrecht, 1988. 5123
- Seneviratne, S., Nicholls, N., Easterling, D., Goodess, C., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., and Zhang, X.: Changes in climate extremes and their impacts on the natural physical environment, in: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC), edited by: Field, C., Barros, V., Stocker, T., Qin, D., Dokken, D., Ebi, K., Mastrandrea, M., Mach, K., Plattner, G.-K., Allen, S., Tignor, M., and Midgley, P., Cambridge University Press, Cambridge, UK and New York, USA, 109–230, 2012. 5115
- 10 Shi, C. M., Masson-Delmotte, V., Risi, C., Eglin, T., Stievenard, M., Pierre, M., Wang, X. C., Gao, J., Breon, F. M., Zhang, Q. B., and Daux, V.: Sampling strategy and climatic implications of tree-ring stable isotopes on the southeast Tibetan Plateau, *Earth Planet. Sc. Lett.*, 301, 307–316, doi:10.1016/j.epsl.2010.11.014, 2011. 5117
- Sousa, P. M., Trigo, R. M., Aizpurua, P., Nieto, R., Gimeno, L., and Garcia-Herrera, R.: Trends and extremes of drought indices throughout the 20th century in the Mediterranean, *Nat. Hazards Earth Syst. Sci.*, 11, 33–51, doi:10.5194/nhess-11-33-2011, 2011. 5115
- 20 Stahle, D. W., Fye, F. K., Cook, E. R., and Griffin, R. D.: Tree-ring reconstructed megadroughts over North America since AD 1300, *Climatic Change*, 83, 133–149, doi:10.1007/s10584-006-9171-x, 2007. 5115
- 25 Sternberg, L. d. S. L. O.: Oxygen stable isotope ratios of tree-ring cellulose: the next phase of understanding, *New Phytol.*, 181, 553–562, doi:10.1111/j.1469-8137.2008.02661.x, 2009. 5116, 5126
- Szczepanek, M., Pazdur, A., Pawelczyk, S., Böttger, T., Haupt, M., Halas, S., Bednarz, Z., Krapiec, M., and Szychowska-Krapiec, E.: Hydrogen, carbon and oxygen isotopes in pine and oak tree rings from Southern Poland as climatic indicators in years 1900–2003, *Geochronometria*, 25, 67–76, 2006. 5126
- 30 Treydte, K., Frank, D., Esper, J., Andreu, L., Bednarz, Z., Berninger, F., Boettger, T., D'Alessandro, C. M., Etien, N., Filot, M., Grabner, M., Guillemin, M. T., Gutierrez, E.,

## French summer droughts since 1326 AD

I. Labuhn et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Haupt, M., Helle, G., Hiltavuori, E., Jungner, H., Kalela-Brundin, M., Krapiec, M., Leuenberger, M., Loader, N. J., Masson-Delmotte, V., Pazdur, A., Pawelczyk, S., Pierre, M., Planells, O., Pukiene, R., Reynolds-Henne, C. E., Rinne, K. T., Saracino, A., Saurer, M., Sonninen, E., Stievenard, M., Switsur, V. R., Szczepanek, M., Szychowska-Krapiec, E., Todaro, L., Waterhouse, J. S., Weigl, M., and Schleser, G. H.: Signal strength and climate calibration of a European tree-ring isotope network, *Geophys. Res. Lett.*, 34, L24302, doi:10.1029/2007GL031106, 2007. 5126

van der Schrier, G., Briffa, K. R., Jones, P. D., and Osborne, T. J.: Summer moisture variability across Europe, *J. Climate*, 19, 2818–2834, doi:10.1175/JCLI3734.1, 2006. 5118

Vicente-Serrano, S. M., Beguería, S., López-Moreno, J. I., Angulo, M., and El Kenawy, A.: A new global 0.5 degree gridded dataset (1901–2006) of a multiscalar drought index: comparison with current drought index datasets based on the Palmer Drought Severity Index, *J. Hydrometeorol.*, 11, 1033–1043, doi:10.1175/2010JHM1224.1, 2010. 5118

Vicente-Serrano, S. M., Lopez-Moreno, J.-I., Beguería, S., Lorenzo-Lacruz, J., Sanchez-Lorenzo, A., García-Ruiz, J. M., Azorin-Molina, C., Morán-Tejeda, E., Revuelto, J., Trigo, R., Coelho, F., and Espejo, F.: Evidence of increasing drought severity caused by temperature rise in southern Europe, *Environ. Res. Lett.*, 9, 044001, doi:10.1088/1748-9326/9/4/044001, 2014. 5115

Vidal, J.-P., Martin, E., Franchistéguy, L., Habets, F., Soubeyroux, J.-M., Blanchard, M., and Baillon, M.: Multilevel and multiscale drought reanalysis over France with the Safran-Isba-Modcou hydrometeorological suite, *Hydrol. Earth Syst. Sci.*, 14, 459–478, doi:10.5194/hess-14-459-2010, 2010. 5115, 5118

Vidal, J.-P., Martin, E., Kitova, N., Najac, J., and Soubeyroux, J.-M.: Evolution of spatio-temporal drought characteristics: validation, projections and effect of adaptation scenarios, *Hydrol. Earth Syst. Sci.*, 16, 2935–2955, doi:10.5194/hess-16-2935-2012, 2012. 5115

Voelker, S. L.: Age-dependent changes in environmental influences on tree growth and their implications for forest responses to climate change, in: *Size- and Age-Related Changes in Tree Structure and Function*, edited by: Meinzer, F. C., Lachenbruch, B., and Dawson, T. E., Springer, Dordrecht, 455–479, 2011. 5128

Wigley, T. M. L., Briffa, K. R., and Jones, P. D.: On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology, *J. Appl. Meteorol.*, 23, 201–213, doi:10.1175/1520-0450(1984)023<0201:OTAVOC>2.0.CO;2, 1984. 5123





## French summer droughts since 1326 AD

I. Labuhn et al.

**Table 2.** Pearson correlation coefficients ( $r$ ) between  $\delta^{18}\text{O}_c$  and monthly meteorological variables, as well as their summer (JJA) and growing season (AMJJAS) averages. Correlations in italics/bold are significant at the 0.01/0.001 level. See text for data sources.

Month	Precipitation		Average temperature		Maximum temperature		SPEI	
	FON $\delta^{18}\text{O}$	ANG $\delta^{18}\text{O}$						
Jan	-0.19	-0.09	-0.04	0.12	-0.03	0.15		
Feb	-0.18	-0.11	0.03	0.15	0.06	0.17		
Mar	-0.13	<i>-0.24</i>	0.05	<i>0.23</i>	0.08	<i>0.27</i>		
Apr	0.03	0.06	0.17	0.15	0.15	0.17		
May	-0.25	-0.25	<i>0.26</i>	<b>0.32</b>	<i>0.28</i>	<b>0.34</b>		
Jun	<b>-0.48</b>	<b>-0.47</b>	0.18	<b>0.41</b>	<i>0.25</i>	<b>0.48</b>		
Jul	<b>-0.39</b>	<b>-0.40</b>	<b>0.53</b>	<b>0.55</b>	<b>0.57</b>	<b>0.60</b>		
Aug	<i>-0.30</i>	-0.14	<b>0.34</b>	<b>0.45</b>	<b>0.36</b>	<b>0.48</b>		
Sep	0.15	0.12	0.19	0.17	0.20	0.19		
Oct	-0.08	0.09	0.19	0.25	0.20	0.22		
JJA	<b>-0.60</b>	<b>-0.53</b>	<b>0.49</b>	<b>0.62</b>	<b>0.54</b>	<b>0.70</b>	<b>-0.69</b>	<b>-0.68</b>
AMJJAS	<b>-0.49</b>	<b>-0.40</b>	<b>0.48</b>	<b>0.57</b>	<b>0.51</b>	<b>0.65</b>	<b>-0.62</b>	<b>-0.57</b>

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)

[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)




**French summer droughts since 1326 AD**

I. Labuhn et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



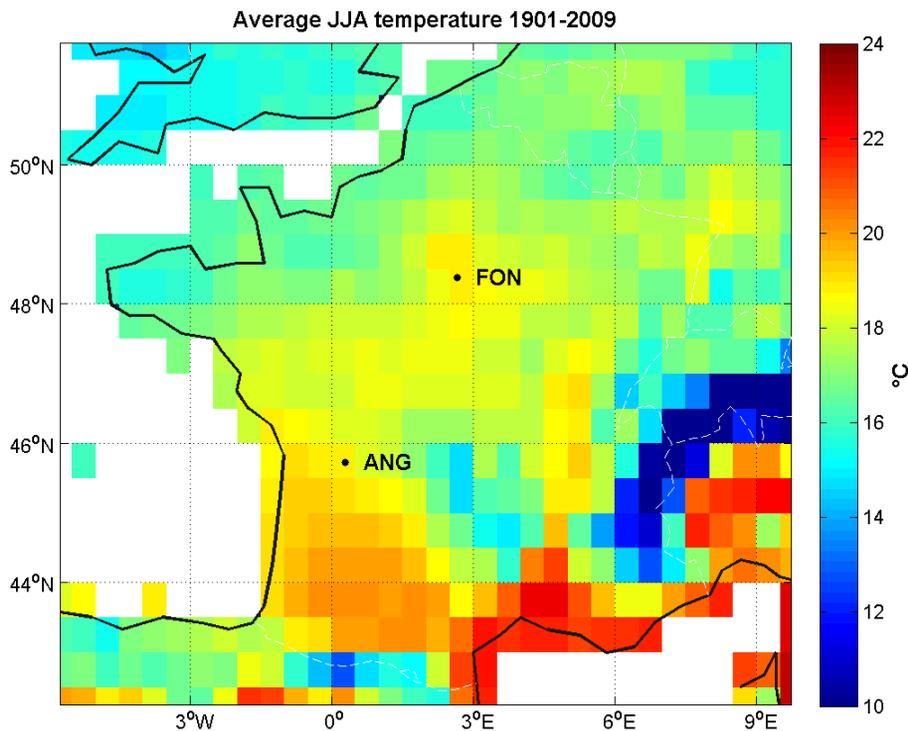
Back

Close

Full Screen / Esc

Printer-friendly Version

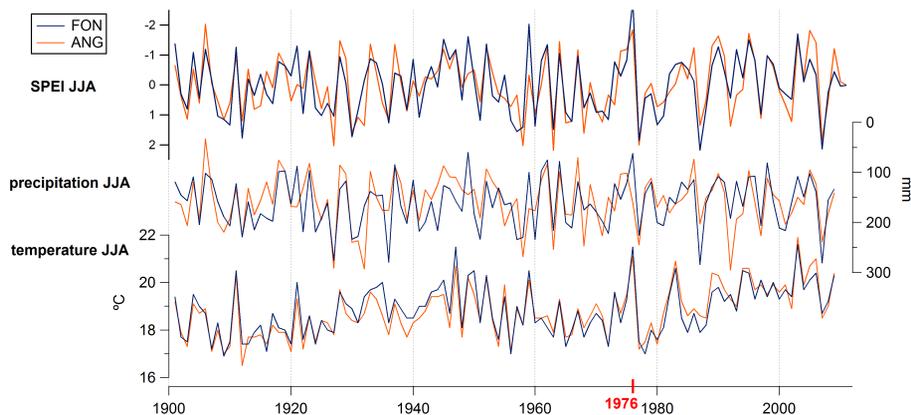
Interactive Discussion



**Figure 1.** Map of France showing the locations of the tree ring chronologies from Fontainebleau (FON) and Angoulême (ANG). The color scale indicates the average summer (June–August) temperature 1901–2009.

## French summer droughts since 1326 AD

I. Labuhn et al.

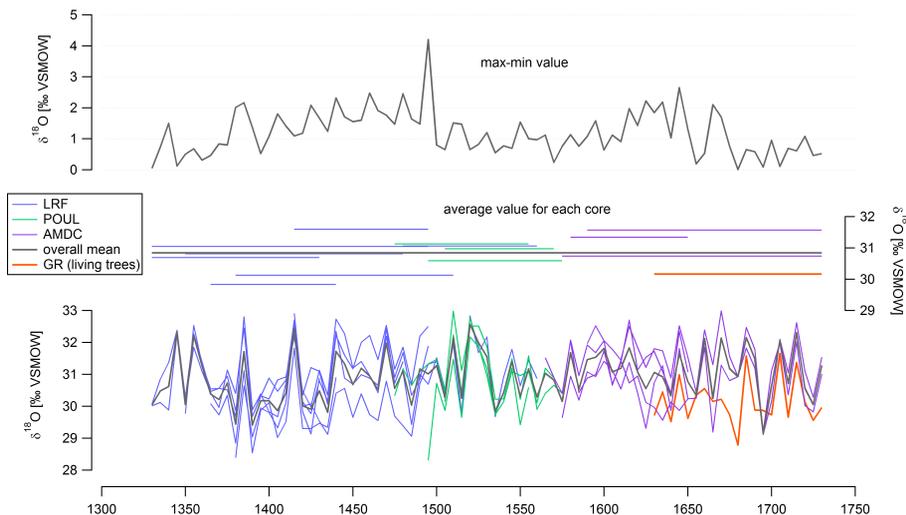


**Figure 2.** Time series of the drought index SPEI (negative values indicate dry conditions), precipitation and temperature, June–August (JJA) averages for Fontainebleau (FON) and Angoulême (ANG). Note that the axes for SPEI and precipitation are reversed, so that upward values reflect warm and dry years. The year of the exceptional drought 1976 is marked in red. See text for data sources.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

## French summer droughts since 1326 AD

I. Labuhn et al.



**Figure 3.** Inter-tree comparison. Bottom:  $\delta^{18}\text{O}_c$  measured every 5th year for individual timber cores from different buildings in Angoulême (LRF, POUL, and AMDC). The orange line shows the  $\delta^{18}\text{O}$  of living trees (GR). Middle: time spans and average  $\delta^{18}\text{O}$  values for the respective cores. The thick gray line is the mean  $\delta^{18}\text{O}$  of all timber cores over the whole period. Top: range of measured values for each year (maximum minus minimum value).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

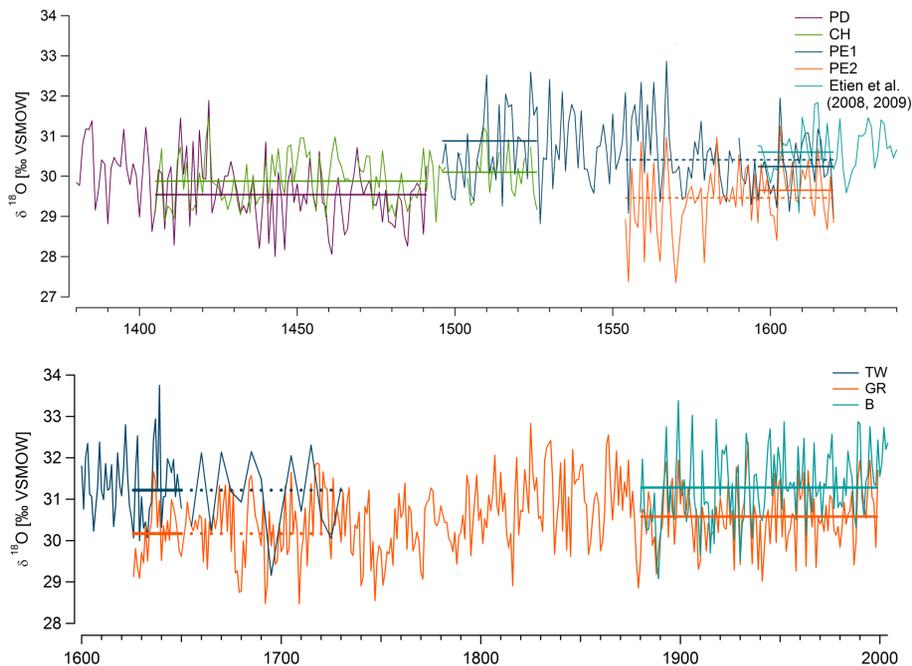
Printer-friendly Version

Interactive Discussion



## French summer droughts since 1326 AD

I. Labuhn et al.



**Figure 4.** Cohort offsets. Top: the  $\delta^{18}\text{O}_c$  series for different tree cohorts from Fontainebleau. Bottom: the  $\delta^{18}\text{O}_c$  series for living tree cohorts (B and GR), and timber wood (TW) from Angoulême. Horizontal lines indicate the mean of each series for the period of overlap. TW samples have been measured every 5th year only in the period covered by the dotted line.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

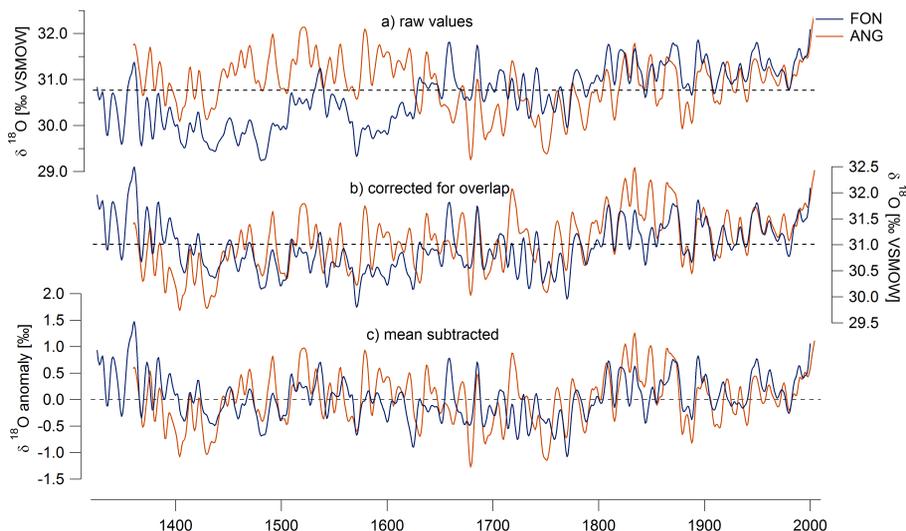
Printer-friendly Version

Interactive Discussion



## French summer droughts since 1326 AD

I. Labuhn et al.



**Figure 5.** Cohort offset correction for cellulose  $\delta^{18}\text{O}$  chronologies from Fontainebleau (FON) and Angoulême (ANG) (low-pass filtered data). Different methods were used in order to combine overlapping tree cohorts to a site chronology: **(a)** raw values; **(b)** correction for the offset between cohorts (see Fig. 4), by adjusting the mean of the older cohorts to the mean of the respective younger cohorts; **(c)** all cohorts were normalized by subtracting the mean of each cohort from the respective  $\delta^{18}\text{O}$  values before combining them. In each case, an average weighted by the number of trees was calculated for overlap periods between cohorts.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

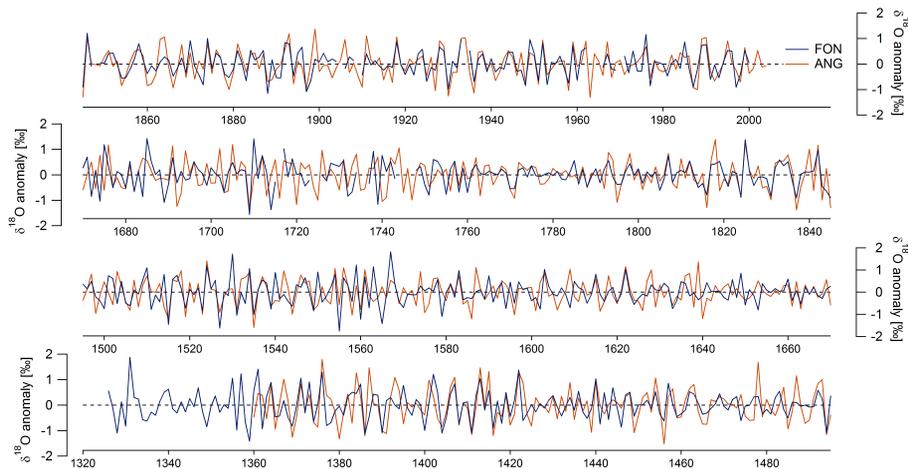
Printer-friendly Version

Interactive Discussion



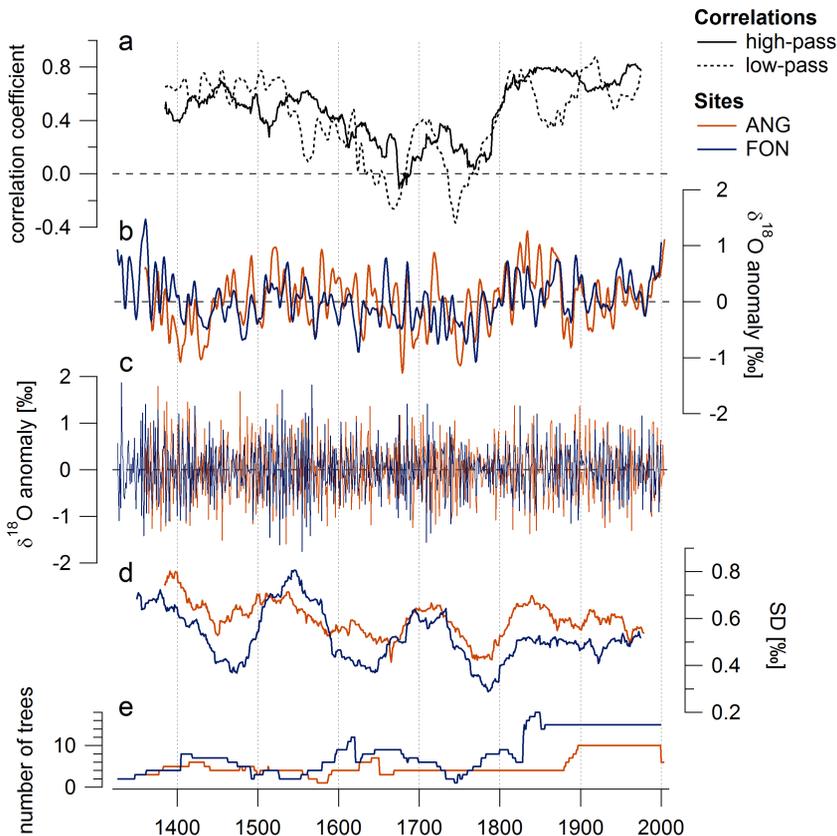
**French summer droughts since 1326 AD**

I. Labuhn et al.



**Figure 6.** Inter-annual variability in cellulose  $\delta^{18}\text{O}$  chronologies from Fontainebleau (FON) and Angoulême (ANG), high-pass filtered data.

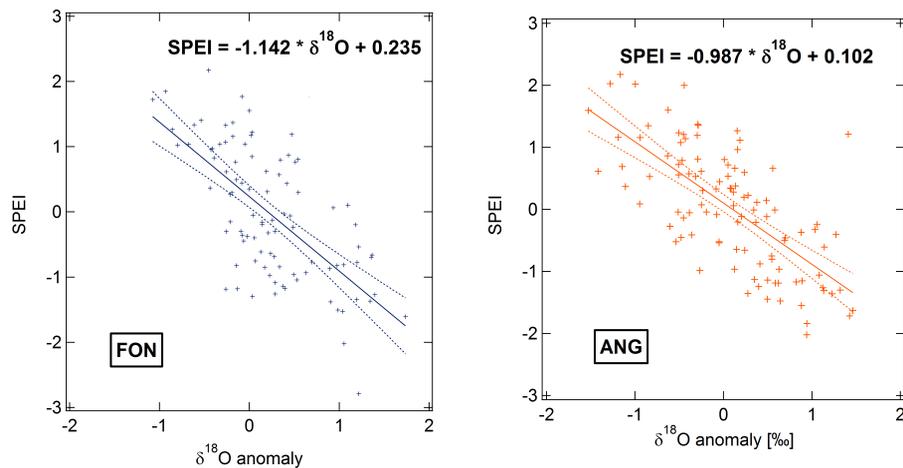
[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)



**Figure 7.** Comparison of cellulose  $\delta^{18}\text{O}$  chronologies from Fontainebleau (FON) and Angoulême (ANG). **(a)** 51 year running correlations between FON and ANG; **(b)** low-pass filtered data; **(c)** high-pass filtered data; **(d)** standard deviation (SD) of the high-pass filtered data calculated for 51 year running windows; **(e)** number of trees.

**French summer droughts since 1326 AD**

I. Labuhn et al.

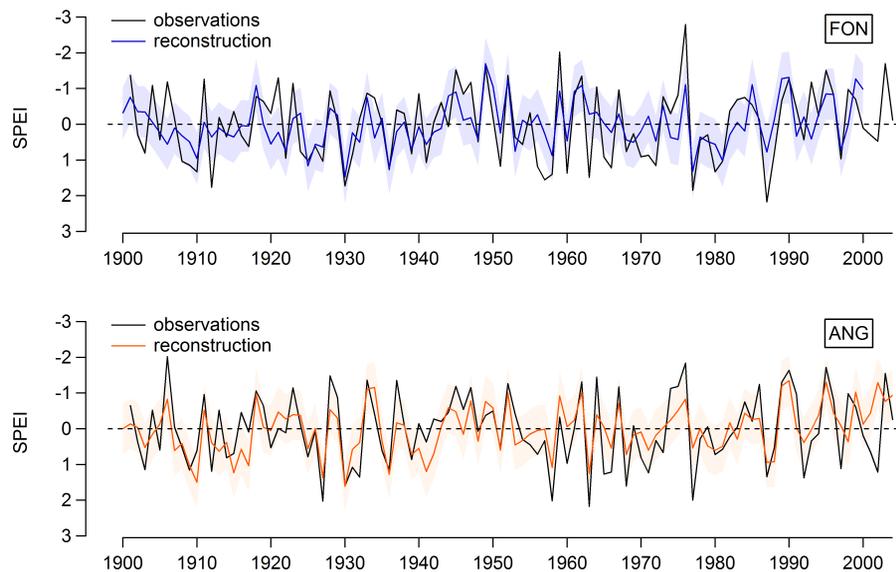


**Figure 8.** Linear regression between the drought index SPEI (June–August) and cellulose  $\delta^{18}\text{O}$  for FON (left) and ANG (right). The equations describing the regression line provide the models for drought reconstruction.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

## French summer droughts since 1326 AD

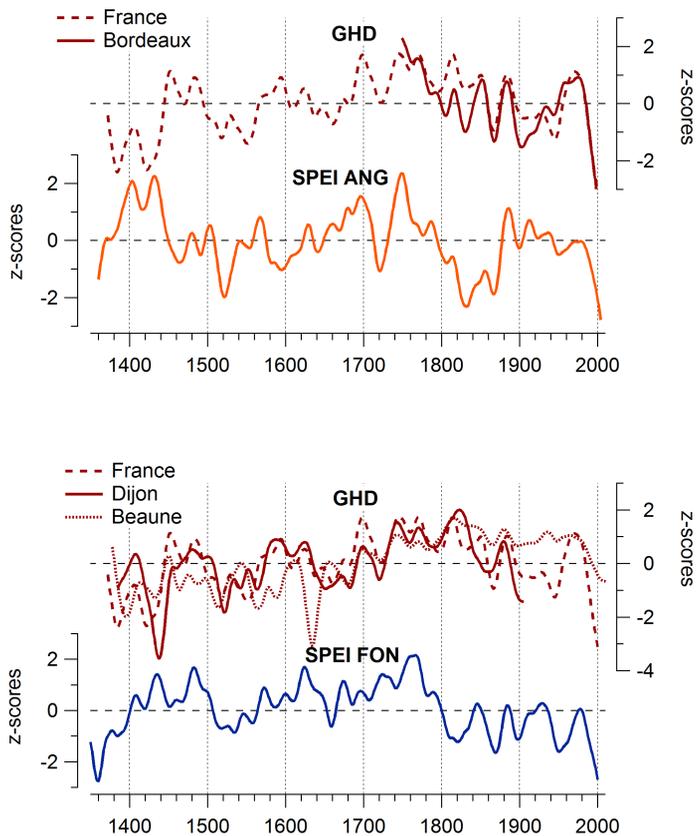
I. Labuhn et al.



**Figure 9.** Observed and reconstructed drought indices SPEI (June–August). Negative values indicate dry conditions. The shaded areas mark the confidence intervals of the reconstructions.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)





**Figure 11.** Comparison between grape harvest dates (GHD; from Daux et al., 2012) and the tree-ring reconstructed drought index SPEI. Top: Angoulême (ANG) drought reconstruction vs. GHD from Bordeaux. Bottom: Fontainebleau (FON) drought vs. GHD from Dijon and Beaune in Burgundy. The dashed line is a composite GHD record for France.

**French summer droughts since 1326 AD**

I. Labuhn et al.

[Title Page](#)

[Abstract](#) | [Introduction](#)

[Conclusions](#) | [References](#)

[Tables](#) | [Figures](#)

[◀](#) | [▶](#)

[◀](#) | [▶](#)

[Back](#) | [Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

