

Summer maximum temperature in northern France over the past century: instrumental data versus multiple proxies (tree-ring isotopes, grape harvest dates and forest fires)

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Abstract Changes in maximum spring and summer temperature are expected to have impacts on plant phenology and the occurrence of forest fires. Homogenised instrumental records of maximum spring and summer temperature are available in northern France for the past century, as well as documentary records of grape harvest dates and forest fire frequencies. Here we provide a new proxy of seasonal climate obtained by the analysis of latewood tree ring cellulose isotopic composition ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$ and δD), from 15 living oak trees (*Quercus petraea*) sampled in the Fontainebleau forest, near Paris. For the past 30 years, we have conducted a study on the inter-tree (for oxygen isotopes) and inter-station (for oxygen and hydrogen)

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isotopic variability. Multiple linear regression statistical analyses are used to assess the response function of documentary and tree-ring isotopic records to a variety of climatic and hydrological parameters. This calibration study highlights the correlation between latewood tree-ring $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, grape harvest dates and numbers of forest fire starts with maximum growing season (April to September) temperature, showing the potential of multiple proxy reconstructions to assess the past fluctuations of this parameter prior to the instrumental period.

1 Introduction

In order to extend the regional characteristics of climate change beyond the approximately 100 years of instrumental records, it is necessary to recover quantitative climate reconstructions using proxy records. In France, homogenised monthly temperature records have been compiled by Météo-France (Causinus and Mestre 2004). The annual mean temperature increase in France over the twentieth century is $\sim 0.9^\circ\text{C}$, slightly higher than the global 0.74°C increase (IPCC 2007). Recent extreme events such as the remarkable summer 2003 heat wave affecting western Europe (Granier et al. 2007) have been suggested to be precursor events for future climate change impacts (Beniston and David 2004; Pal et al. 2004; Schär et al. 2004; Seneviratne et al. 2006; Meehl and Tebaldi 2004).

Paleoclimatic data allow twentieth and early twenty-first century climate changes to be placed in the broader context of natural climate variability. Several attempts have been made to quantify European temperature changes during the past centuries (Overpeck et al. 1997; Jones et al. 1998; Mann et al. 1999; Crowley 2000; Briffa 2000; Briffa et al. 2001; Esper et al. 2002; Luterbacher et al. 2004; Guiot et al. 2005; Moberg et al. 2005). These European-scale reconstructions are mainly based on ancient instrumental records, high latitude or altitude tree-ring growth indices and, sometimes, historical records. Complex statistical methods are used to calibrate and integrate the available records. However, many regions, such as temperate climate areas of France, are not represented in these quantitative reconstructions of recent temperature variations. In these temperate areas, only documentary information on grape harvest dates have been used to show the exceptional character of summer 2003 temperatures in the context of the past centuries (Chuine et al. 2004; Menzel 2005).

Tree rings are invaluable proxies: exact dating of each ring provides a perfect annual resolution and continuous records can be obtained over hundreds years. Trees are widespread, and have been used as building material for centuries. Therefore, living trees, historical beams and fossil trunks well preserved in sediments, water or ice offer many sampling opportunities. Tree-ring densities and/or widths have been successfully used to reconstruct summer temperature in high latitudes or altitudes where summer temperature is a limiting factor controlling tree growth, using statistical approaches to account for tree aging (Briffa et al. 2001; Guiot et al. 1983). In temperate areas, tree growth is influenced by a variety of environmental factors, which prevents tree growth parameters from being used to quantify temperature changes.

The oxygen, carbon and hydrogen isotopic ratios in tree cellulose are sensitive bio-indicators, and offer the possibility to study integrated information on the

variability of the climate and water cycle even in temperate areas where classical dendroclimatology does not apply (McCarroll and Loader 2004). Recently, it was shown that the effects of tree age on the cellulose oxygen isotopic composition on *Quercus* sp. are not significant (Raffalli-Delerce et al. 2004; Masson-Delmotte et al. 2005), suggesting that isotopic dendroclimatology may avoid tree age biases.

The carbon isotopic composition of the atmosphere is ca. -8‰ (VPDB). The composition of tree leaves and woods varies between -20‰ and -30‰ , that is plant tissue is depleted in ^{13}C compared to atmospheric CO_2 . The isotopic discrimination at the leaf level is controlled by the tree physiology and by the environment (e.g. relative humidity, soil moisture, temperature, solar radiation and nutrient availability) as described by Farquhar et al. (1989):

$$\Delta^{13}\text{C}(\text{‰}) = a + (b - a)p_i/p_a, \quad (1)$$

where $\Delta^{13}\text{C}$ is the carbon discrimination, a is the fractionation due to the diffusion through stomata (4.4‰), b is the fractionation caused by carboxylation (27‰), p_i is the intercellular CO_2 partial pressure and p_a is the atmospheric CO_2 partial pressure. Further isotopic fractionations occur when leaf sugars are used to build tree components as cellulose or lignin, which entails additional isotopic changes (Switsur and Waterhouse 1998; Jaggi et al. 2002). As a result, climatic and soil water balance influences on plant–air exchanges induce local dependencies of the $\delta^{13}\text{C}$ of tree ring cellulose on temperature, relative humidity and water stress in general (Wilson and Grinsted 1977; Freyer 1979; Leavitt and Long 1982; Stuiver et al. 1984; Lipp et al. 1991; Dupouey et al. 1993; Saurer et al. 1995; Robertson et al. 1997a, b; Hemming et al. 1998; Barbour et al. 2001; McCarroll and Pawellek 2001).

The oxygen isotopic composition of precipitation is primarily driven by temperature at mid and high latitudes (Dansgaard 1964; Rozanski et al. 1993; Kohn and Welker 2005). Evaporative isotopic fractionation may occur within the soil. Most vegetation uses soil water *sensu stricto* and therefore can take up evaporatively enriched water (Dawson 1993; Dawson and Pate 1996). However, tree roots can reach depths significantly below the soil zone, where waters are generally well mixed (Darling 2004). The oxygen isotopic ratios of the xylem water are assumed to be the same as those of the extracted water (Wershaw et al. 1966; Bariac et al. 1990). Many isotopic fractionations occur between water and wood components. The critical fractionation process occurs in leaves where transpiration results in evaporative enrichment of leaf water. This enrichment depends mainly on the difference between the isotopic compositions of the source water and of the ambient vapour, and on the ratio of vapour pressures inside and outside of the leaf. The enrichment of the cellulose synthesized in photosynthetic tissues is approximately 27‰ (DeNiro and Epstein 1981; Sternberg et al. 1986; Barbour et al. 2000; Roden et al. 2000). During the synthesis of cellulose from sucrose, about 40% of the oxygen atoms are exchanged with those of xylem water (Sternberg et al. 1986). Therefore the oxygen isotopic signature of the tree ring cellulose is intermediate between the evaporative and the source water signal but does not seem to be biased during transport through the plant (Gessler et al. 2007). The processes involved in its acquisition are not fully quantified (Barbour et al. 2004). Nevertheless, the $\delta^{18}\text{O}$ of tree ring cellulose was used successfully for reconstructing the oxygen isotopic composition of the precipitation of the growing season and the climate parameters

(atmospheric temperature, relative humidity, etc.) of past centuries (e.g. among the most recent: Anderson et al. 2002; Robertson et al. 2001; Saurer et al. 2002; Raffalli-Delerce et al. 2004; Masson-Delmotte et al. 2005; Danis et al. 2006; Treydte et al. 2006).

The deuterium composition of tree ring cellulose is also related to environmental parameters but results from several fractionation processes. As for $\delta^{18}\text{O}$, the precipitation δD composition is influenced by temperature variations (Dansgaard 1964). The root water uptake transfers the soil moisture signal to the plant without fractionation (Bariac et al. 1990; Williams et al. 2005). Isotopic enrichment is due to leaf transpiration (Wershaw et al. 1966; Roden et al. 2000); this deuterium enrichment is influenced by changes in relative humidity (Craig and Gordon 1965). During photosynthesis, the isotopic composition of xylem and leaf water is transferred to the synthesised organic matter. These processes are similar to those involved in determining the oxygen isotope composition of organic matter. Two specific processes differ: enzymes have kinetic D isotope effects, which discriminate against D in particular C–H groups of metabolites (Augusti et al. 2006); during cellulose synthesis, other enzymes act as catalysts for the exchange of ~40% of hydrogen atoms between xylem water and sugars (Yakir and DeNiro 1990; Terwilliger and DeNiro 1995; Roden et al. 2000; Waterhouse et al. 2002). The tree effects linked with leaf enrichment, Péclet effect (Barbour et al. 2004), and xylem exchanges appear to be quantitatively comparable for oxygen and deuterium (Roden et al. 2000). These theoretical considerations suggest that the environmental factors governing tree ring cellulose deuterium composition should be similar to those controlling its oxygen composition, with a key role for precipitation isotopic composition and relative humidity during the growth season.

This study aims at comparing homogenised instrumental data and multiple proxy records obtained either from documentary sources (regional grape harvest dates from two areas; number of fire starts in Fontainebleau forest) and from multiple parameters measured on tree rings (growth index, latewood carbon, hydrogen and oxygen stable isotopic ratios). The various records are presented in Section 2 (Material and methods). Section 3 (Results) presents the variability of our new measurements of oxygen and deuterium cellulose isotopic composition and of Fontainebleau meteorological parameters. Our analysis then focuses on the imprint of climate change on some aspects of plant phenology (through grape harvest dates), risks (number of fire starts in forest), tree growth and isotopic composition (calibration study). The reliability of homogenised temperature reconstructions is discussed in terms of growing season maximum temperature. This approach is described in Section 4 (Discussion). Finally, in the conclusions and perspectives, we show that our analysis builds a multiple proxy method that will be used for quantifying past temperature change using longer proxy records.

2 Material and methods

The investigation region is situated near Fontainebleau, northern France (2.67° E, 48.38° N), between the Gatinais and Briard plateau and the Brière plain. The Fontainebleau forest covers a 280 km² area, and culminates at 144 m above sea level. Stampian limestones form the substrates. Oak roots develop in a loamy soil.

Fontainebleau has a typical temperate oceanic climate with regular year-round distribution of precipitation (between 50 and 70 mm/month). The yearly amplitude of monthly maximum temperature is 20°C.

This region was selected for its proximity to Paris, the availability of forest trees and timber wood from ancient buildings for isotopic analyses, the availability of documentary information and homogenised meteorological records. We first discuss the meteorological data, the hydrological forest modelling that is used to quantify hydrological parameters, and the historical records. Then, we describe the sampling, dating and analysis of tree-ring latewood cellulose stable isotopic ratios, including a specific sampling to quantify the inter-tree dispersion.

2.1 Meteorological data, hydrological modelling and historical records

Monthly temperature (since 1879) and precipitation (since 1883) data measured at various places around Fontainebleau have been homogenized to constitute reference meteorological series by Météo-France (Moisselin et al. 2002; Caussinus and Mestre 2004) (Fig. 1). The homogenization of old data (prior to 1950) consists of estimating systematic bias for each past period and correcting the data from these biases. This principle is robust but outliers can remain in corrected time series.

The systematic biases may result from different types of perturbations:

- Bad quality meteorological data due to the instruments. These can be easily identified as soon as the systematic error is larger than 4°C for temperatures. Below 2°C, the quality control cannot detect systematic biases.
- Repeated ruptures due for instance to changes in the location of the meteorological instruments in the full dataset. In this case, the reconstruction is less precise because there is no solid reference series.
- Missing data (typically in the first half of the century, between World War 1 and 2). In this case, the homogenisation method may provide poor results.

Relative humidity data (since 1950) were provided by Météo-France. Daily meteorological data (temperature, precipitation, global radiation, wind speed, vapour pressure deficit) and daily maximum leaf area index have been recorded at “La Faisanderie” weather station, 5 km north of Fontainebleau (48°4' N, -2°7' W) since 1971. These daily data were used to run the lumped water balance model described in Granier et al. (1999). The outputs are the main terms of the hydrological cycle in the forest stands: soil water deficit (SWD), Potential Evapotranspiration (PE), Actual Evapotranspiration (AE).

The harvest dates of “Pinot Noir” grapes in Burgundy (eastern France, ~250 km south east of Fontainebleau) were shown to be a proxy for the mean atmospheric temperature from April to September (Chuine et al. 2004) and are available from the fourteenth century to 2003. This series was constructed from an ensemble of harvest dates recorded in the “Hospices Civils de Beaune” (Beaune city localisation in Fig. 2a) and other registers. For periods where several documentary sources are available, the Burgundy grape harvest date (GHD_B) is obtained by averaging the various local dates. Here we use this Burgundy record together with another record of grape harvest dates from Argenteuil (GHD_A) (~80 km north west of Fontainebleau; unknown grape variety; Legrand 1978), covering the time period from 1900 to 1976. All grape harvest dates are expressed as the number of days

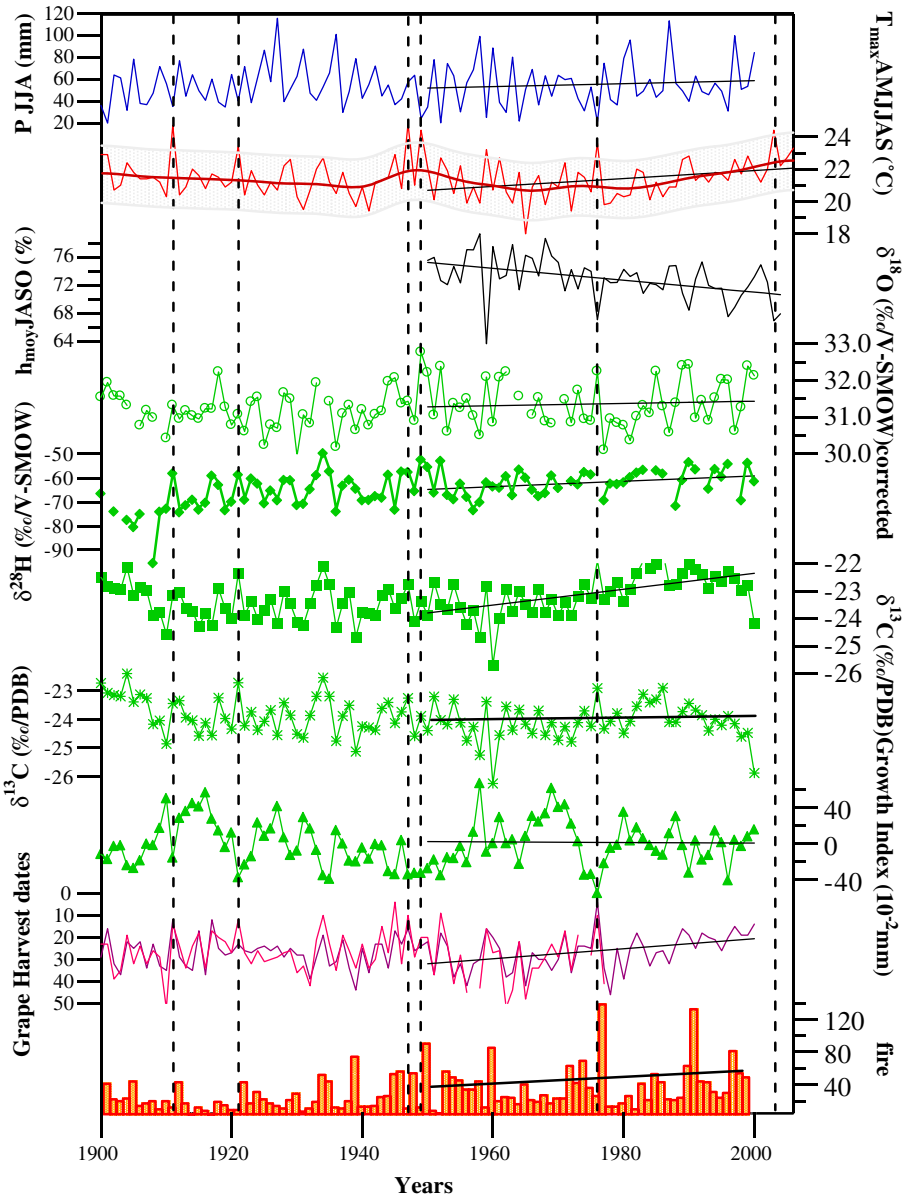


Fig. 1 From *top to bottom*, time series of meteorological parameters: June to August precipitation (P_{JJA} , in millimeters); April to September maximum temperature (T_{max} AMJJAS, in degree Celsius); July to October average relative humidity (h_{moy} JASO, in percent). Tree ring parameters: isotopic records measured on latewood cellulose ($\delta^{18}O$, δ^2H and $\delta^{13}C$ in per mill); growth index (10^{-2} mm). Historical environmental records: grape harvest dates from Argenteuil (north of Paris) and Burgundy (east of France) (expressed in deviations of days from August 31st); forest guard record of number of fire starts. The *dashed lines* correspond to the five warmest years (from April to August) of the century

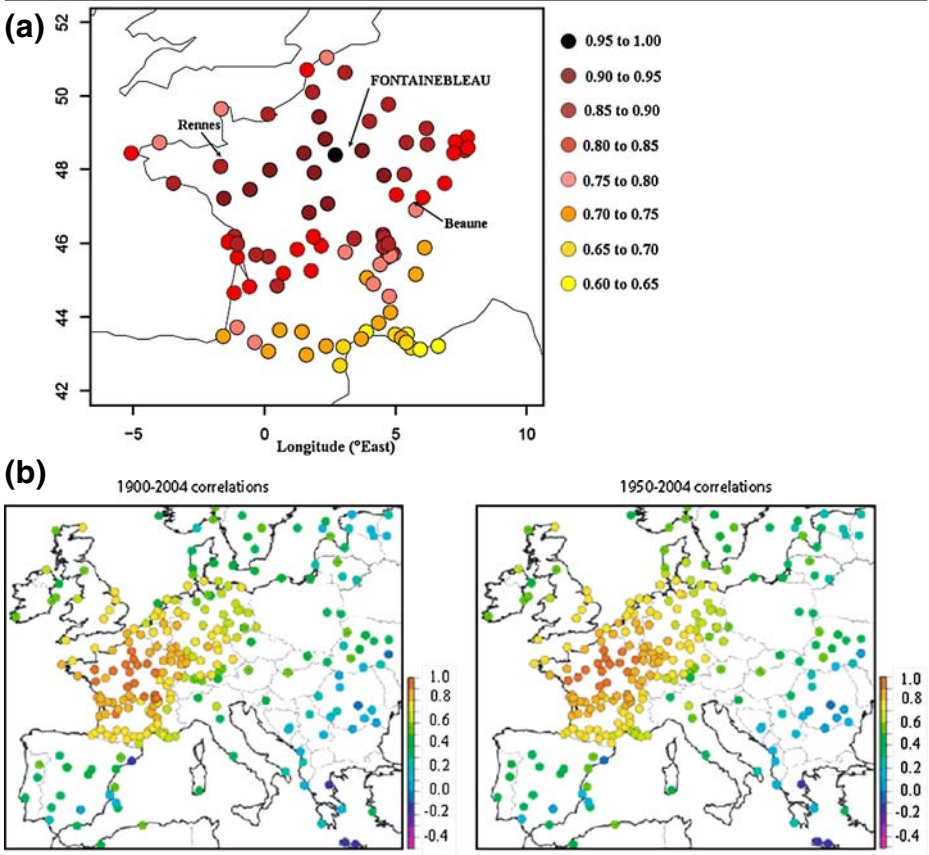


Fig. 2 **a** Map of France showing the location of the sampling sites of Fontainebleau and Rennes, and the R correlation values between a set of French sites and Fontainebleau for the maximal growing season temperature (T_{max} AMJJAS) from 1900 to 2000. Homogenised data are provided by Météo-France. **b** Map of Europe showing R correlation values between a French data set of Météo-France and an ECA data set for the other European country and Fontainebleau for the maximal growing season temperature of Fontainebleau (T_{max} AMJJAS) from 1900 to 2000

after August 31st (Fig. 1). Grape harvest dates were shown to depend strongly on March–April to August–September maximum temperature (Chuine et al. 2004). The hotter the spring and summer are, the earlier the grape harvest. Nevertheless they are not phenological but historical data, and variation through time can occur due to anthropic, non climatic, effects (e.g. change of grape harvest dates for politico-economical reasons; Daux et al. 2007).

Another documentary source of Fontainebleau forest sensitivity to climate change and human pressure can be found in the chronicles of the forest guards. From 1900 to 1998, a record of the monthly number of fire starts has been systematically archived (Fig. 1). Here we use this record in terms of total number of fire starts per summer (hereafter called “forest fires”) in Section 4.

2.2 Tree-ring data

Thirty living sessile oaks (*Quercus petraea*) were sampled on two forest stations (15 trees per station) at Fontainebleau in year 2000. The largest distance between individual trees is less than 500 m. Three cores were taken from each oak, at 120° from one another on the circumference at 1.3 m above ground level. The sampling strategy was determined with the assistance of the “Office National des Forêts” (National Forest Agency).

The ring widths were measured under a binocular microscope. The tree-rings of the living oaks were cross-dated for late-wood using a master series of ring width. This series rests on more than 400 oaks from the Fontainebleau forest analysed by the phytoecology team of the National Institute of Agronomical Research (INRA, Nancy, France). On average, these dominant trees are 100 to 120 years old. It is well known that late-wood ring widths cannot be used directly as climatic proxies due to a strong juvenile effect. This study aims at exploring the climate potential of the raw dendro-isotopic data, with the minimum statistical treatments. Here, we have used the following procedure to obtain average growth indices for the 15 trees sampled for isotopic analyses:

- For each tree, second order polynomial regressions were calculated, in order to correct only the juvenile effect (polynomial fits of larger order would have secondary impacts after the juvenile period);
- Individual growth records were corrected from these polynomial fits; we are aware that growth index can also be constructed by dividing the raw data by the polynomial fits. As the two approaches give exactly the same results in terms of correlations with climatic parameters (see Section 4), we just use the deviation from the polynomial fits.
- The average of the de-trended records provides our growth index time series (hereafter GI).

The GI variation through time is represented in Fig. 1 and its links with climatic parameters and other proxy records are discussed in Section 3.

Fontainebleau oak tree rings have a growth pattern typical of temperate area oaks, with wood being produced from early spring to late summer and a clear visible distinction between early wood (spring) and late wood (summer). Early wood is synthesized from carbohydrates stored from previous years (Barbaroux and Bréda 2002). As a result, significant differences between the isotopic composition of the early and late wood can exist (Lipp et al. 1991; Livingston and Spittlehouse 1996; Switsur et al. 1996). In order to maximise the signature of environmental parameters of the growing season, we have systematically separated the latewood from the early wood in each ring and used only latewood for isotopic ratio measurements. Hereafter, all the reported isotopic data refer only to late wood cellulose isotopic composition.

The annual rings of the cores were sectioned with a scalpel under a binocular microscope. Tree-rings formed in the same calendar year were pooled together: 15 trees over the period 1900–2000, and 15 trees specifically for inter-site and inter-tree variability studies conducted only for several years (see Section 3.1). Samples were

then milled with a 0.08 mm sieve in order to homogenise the material. Because wood is composed of various metabolites that undergo different isotopic fractionations (Benner et al. 1987), isotopic analyses were performed on cellulose extracted from wood according to the SOXHLET method elaborated by Green (1963) and modified by Leavitt and Danzer (1993). 0.09–0.15 mg of the resultant cellulose samples are loaded in tin-foil cups for carbon isotope ratios analysis, and 0.2–0.3 mg in silver-foil cups for oxygen isotopic analysis.

The oxygen and carbon isotopic composition are determined with a Carbo Erba® elemental analyser coupled to a Finnigan MAT252 mass spectrometer (at LSCE, Gif/Yvette, France) according to the procedure described in Raffalli-Delerce et al. (2004). The calibration with respect to the international VSMOW (for oxygen) and VPDB (for carbon) standards is performed with the cellulose standard Whatmann® CC31 (one CC31 is run for two samples). One to two replicates of each sample is measured. The standard deviation for repeated analysis of the CC31 cellulose is $\pm 0.25\%$ for $\delta^{18}\text{O}$ and $\pm 0.1\%$ for $\delta^{13}\text{C}$. Unfortunately, there was not enough material to conduct all isotopic analyses including replicates, resulting in six missing years for oxygen (Fig. 1). The raw late wood cellulose $\delta^{18}\text{O}$ data are directly used for comparison with environmental parameters (no statistical detrending). By contrast, tree ring $\delta^{13}\text{C}$ data should, in principle, be corrected for the progressive 1‰ decrease of atmospheric $\text{CO}_2\delta^{13}\text{C}$ observed from 1951 to 1996, which parallels the increase in atmospheric CO_2 concentration and results from fossil fuel burning, deforestation and expansion of agriculture (Mook et al. 1983; Friedli et al. 1986; Francey et al. 1995). Several $\text{CO}_2\delta^{13}\text{C}$ records based on direct measurements (e.g. Keeling et al. 1995), and from firn and ice bubble air from Antarctica (Francey et al. 1999) are available. We take into account latitudinal and seasonal fluctuations of $\text{CO}_2\delta^{13}\text{C}$ to obtain a correction suitable for Northern Hemisphere mid-latitude growing season (Masson-Delmotte et al. 2005, M. Leuenberger calibration data, ISONET program). Hereafter, we use two carbon isotope time series: direct latewood measurements ($\delta^{13}\text{C}$) and the corrected record $\delta^{13}\text{C}_{\text{cor}}$, which refers to the $\delta^{13}\text{C}$ values corrected from $\text{CO}_2\delta^{13}\text{C}$ recent trend.

The determination of non-exchangeable δD values in cellulose are based on nitration of wood cellulose (Alexander and Mitchell 1949), followed by online combustion and IRMS measurements of cellulose nitrate samples (Knöller et al. 2007). The calibration with respect to the IAEA-VSMOW standard is performed with the two long-term validated versus IAEA-VSMOW and IAEA-SLAP wood cellulose nitrate standards. The standard deviation in replicated measurements is lower than 3‰. The lack of material resulted in nine missing years for deuterium (Fig. 1).

3 Results

This section is organised in three parts. First, we discuss an analysis of the inter-tree and inter-station variation of tree latewood oxygen isotopic composition and determine the appropriate sampling size. Second, we present an inter-station variability of the hydrogen isotopic composition of the cellulose. Finally, we detail the variability

and trends of climatic parameters showing large and persistent correlations with documentary and tree-ring data.

3.1 Inter-tree variability of the oxygen isotopic composition

During year 2002, a total of 1,056 measurements were conducted on groups of trees or cores (three, five, six, ten or 15 samples) in order to test the inter-tree variability of the isotopic signature. This preliminary study was conducted with an earlier experimental setup using more cellulose (0.50 mg per measurement). The amount of matter requested for each isotopic analysis was too large to allow individual tree ring analysis and required to combine at least three cores. The inter-tree variability of the carbon isotope signature of oak cellulose from Rennes area has been studied by Raffalli-Delercet et al. (2004). They have shown the dominant influence of tree versus year effect on carbon discrimination (see their Fig. 5). Due to lack of matter, we had to choose between the two isotopes (C or O) and we decided to put our efforts on the analysis of the inter-tree dispersion of the $\delta^{18}\text{O}$ only.

We have chosen specific years of the past 30 years for which high quality meteorological and hydrological data are available. The years 1973–1975, 1977–1983, 1985–1986, 1989–1991, 1993–2000 were devoted to the inter-stations comparison. Moreover, we tested if the inter-tree dispersion was constant or not for non consecutive years (in order to avoid back effects) with very different tree ring growths. For this purpose, we have selected 5 years: 1971 (large rings), 1976 and 1992 (very narrow rings), 1984 and 1987 (average ring widths). The comparison of the isotopic dispersion for these specific years was conducted in order to determine the appropriate sampling size (number of trees to be pooled).

3.1.1 Comparison of the two stations

The latewood oxygen isotopic composition of the cellulose of each group of 15 trees (one group per station) was measured over 23 years. A mean offset of 0.13‰ is observed between the two stations. In more than 87% of these years, the $\delta^{18}\text{O}$ inter-station difference is less than the analytical precision (0.25‰). This systematic difference is also small when compared to the inter-annual variability.

The maximum deviation is reached for the years 1980 (average rings), 1985 (narrow rings) and 1990 (very narrow rings) with differences of 0.28‰, 0.42‰ and 0.54‰. The meteorological conditions of these years, where the inter-station variability is largest, are analysed hereafter.

The year 1980 underwent persistent cold conditions from winter (an outstanding 50 cm snow cover in Fontainebleau forest during 1 month) to the end of July, with the fourth coldest average summer temperature and the weakest insolation recorded in Paris since 1933. An average August temperature was observed but associated with intense thunderstorms in the South of the Paris region.

January 1985 was marked by the coldest spell recorded in Paris since 1838. This cold episode induced large damages (including abnormally high human death rate) and affected vegetation. Subsequent cold frosts occurred during the following April in almost all of France. The crops, very affected by the cold wave of January, are put once again at hard test. Summer 1985 was cooler than average but October and September were unusually hot and dry.

The year 1990 was marked by many winter storms in the Paris area. Forests were severely damaged (many trees uprooted in Fontainebleau forest). February and March were warm and exceptional droughts occurred from May onwards. The summer of 1990 was very hot and persistent warmth was recorded until October (Séchet 2004). Meteorological chronicles do not report on conditions harmful to the vegetation during the other years considered in this test.

This preliminary inter-tree study suggests that inter-individual variability of the $\delta^{18}\text{O}$ signal in cellulose may increase to a significant degree (from ca. 0.1‰ up to 0.5‰) when the growing conditions are restrictive for tree growth (cold, storm or drought). Such a study should of course be expanded in a more systematic manner by comparing tree ring cellulose isotopic records from individual trees over a longer time period and using statistics to assess objectively the influence of extreme meteorological conditions on inter-tree variation.

3.1.2 Determination of the appropriate sampling size

As shown above, the variability between groups of 15 trees is small compared to the analytical uncertainty. In order to optimize the minimum number of trees to be pooled to obtain a reliable local isotopic signal, we have analysed $\delta^{18}\text{O}$ variability between smallest groups of trees. Because we needed a minimum of 0.4–0.5 mg of cellulose (at the time of the inter-tree study, in 2002), individual tree analyses were not possible. We have compared the isotopic signature of three groups of three trees for year 1987, and three groups of five trees for 1971, 1976, 1984 and 1992. For years 1971, 1984, 1987 (average to large rings) the inter-group standard deviation is systematically lower than the analytical precision (0.15‰; Table 1). For years 1976 and 1992 (narrow rings), the inter-group standard deviation is as high as 0.5‰ and 0.75‰ Table 1.

During years 1971, 1984 and 1987 (low inter-group isotopic dispersion), the vegetation was weakly constrained by climatic conditions: in 1971, the winter was mild, spring and summer rainy with a sunny and dry end of the growth season; the year 1984 was marked by a cold spell at the beginning of June, followed by warm and wet summer; 1987 underwent a very cold winter which extended until May but the summer was generally wet and warm during August and September (Séchet 2004).

In contrast, years 1976 and 1992 (high inter-group isotopic dispersion) were harmful to the vegetation: 1976 was characterised by a record spring drought over the past century in northern France, followed by a spring heat wave (May) and a persistent summer drought affecting north western France; 1992 started like 1976

Table 1 $\delta^{18}\text{O}$ measured in different groups of trees, mean values of $\delta^{18}\text{O}$ and standard deviation between the groups for the years 1971, 1984, 1987, 1976 and 1992

	Number of trees	Group 1	Group 2	Group 3	Mean value of $\delta^{18}\text{O}$	Standard deviation
1971	5	31.07	31.05	31.21	31.11	0.09
1984	5	31.13	30.79	30.86	30.93	0.18
1987	3	30.52	30.50	30.83	30.61	0.18
Mean						0.15
1976	5	31.71	32.37	31.40	31.83	0.50
1992	5	29.98	31.48	30.73	30.73	0.75

with a strong winter and spring drought, followed by intense thunderstorms and record rainfall amounts and floods (Séchet 2004).

Therefore, we conclude that samples of three pooled trees are appropriate to reconstruct the local oxygen isotopic composition of the oak cellulose for average years without significant biases compared to larger groups. However, our analysis shows that the inter-trees variability can be at least twice as high during years harmful to the vegetation. In the studied set of years, extreme $\delta^{18}\text{O}$ years represent 15% of the whole set. As a result, the inter-annual variability of the isotopic signature of cellulose must be considered with caution because of individual effects, still visible on a group of 15 trees.

Further studies of the robustness of the relationships between late wood cellulose $\delta^{18}\text{O}$ and climate could include frequency analyses. A larger inter-tree dispersion of $\delta^{18}\text{O}$ during weak growth years would be expected to distort the climate– $\delta^{18}\text{O}$ relationships at high frequencies. However, preliminary spectral analyses conducted by Etien et al. (2008) suggest that cellulose $\delta^{18}\text{O}$ capture correctly the inter-annual variance.

Finally, several factors can distort the reliability of cellulose $\delta^{18}\text{O}$ as a climate proxy: the representativity of the number of trees, but also the eco-physiological reaction of the trees, which is not controlled by a single environmental parameter. For these reasons, we have developed a multi-proxy method in order to minimize the uncertainties linked with each proxy.

3.2 Inter-station variability of the hydrogen isotopic composition

Deuterium measurements were conducted on pooled samples from each station over the past 30 years. The inter-annual variations of isotopic ratios of non-exchangeable hydrogen in cellulose are correlated between the two stations ($R = 0.50$). A systematic offset of 12.8‰ is observed between the two stations (not shown). In addition, the inter-annual standard deviation is twice as large for one station (8.1‰) compared to the other (4.8‰) over the same period. Knöller et al. (2007) observed a difference up to 47.3‰ between replicates of a standard. They attribute this large variation to evaporative effects during the analysis procedure. Similarly, Leavitt (2008) reports 40‰ tree to tree difference. Evaporative effects during D/H measurement as well as large inter-tree variability may explain the large inter-station variability both in terms of mean level and in terms of inter-annual dispersion observed in Fontainebleau samples. The difficulty in using such a proxy precludes further interpretations.

3.3 Variability and trends in climate and environmental records

Using the R software (<http://www.r-project.org/>), we have systematically tested the correlations between inter-annual fluctuations of Fontainebleau growth index (GI), the isotopic composition of the cellulose ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$, $\delta^{13}\text{C}_{\text{cor}}$, δD), documentary records (Argenteuil and Burgundy grape harvest dates, Fontainebleau forest fires) and monthly temperatures (minimum and maximum), precipitation, relative humidity and water balance parameters (SWD, Global Radiation, PE, AE). Note that these correlations have been analysed on different time periods due to the length of the various records (Section 2). From systematic analyses conducted with all the

individual months and combinations of months, Table 2 displays only the subsets of climatic and hydrological parameters showing at least one significant correlation with our environmental archives. Here we restrict the description of variability and trends of climatic parameters showing large and persistent correlations with documentary and tree ring data (Table 2). Figure 1 displays these key data sets.

The first key meteorological parameter is the growing season average of monthly maximum temperature (hereafter T_{\max} AMJJAS, with AMJJAS standing for April–May–June–July–August–September). This parameter is persistently correlated with annual mean temperature (Table 2, $R = 0.8$, $p < 2 \times 10^{-16}$). Homogenised T_{\max} AMJJAS data back to 1900 show a mean value of 21.4°C together with large inter-annual variations ranging from 18.0°C to 24.8°C. A linear increase is observed between 1960 and 2006, corresponding to +1.9°C over 46 years. In Fontainebleau, as well as in Europe, summer 2003 appears as an extreme in growing season maximum temperature (record heat wave) (Fig. 1). We consider an extreme warm growing season as a year with T_{\max} AMJJAS standing 1.5 standard deviation above the 30-year running mean. With this criterion, we observe only one extreme warm growing season from 1950 to 2000 (in 1976). Before 1950, such record warmth is encountered 4 times with peak summer temperature above 23.1°C in 1911, 1921, 1947 and 1949. However, these older values must be scrutinized due to changing meteorological observation procedures and homogenisation limitations.

The spatial representativity of our study area can be assessed by analysing the spatial correlations between Fontainebleau T_{\max} AMJJAS and other similar records. Other French T_{\max} AMJJAS records are strongly correlated with Fontainebleau data at the inter-annual scale over the past centuries (Fig. 2a). Within France, inter-annual correlation coefficients of local T_{\max} AMJJAS with Fontainebleau T_{\max} AMJJAS vary between 0.6 near the Mediterranean Sea, 0.80 at similar latitudes in western or eastern France and up to 0.9 for the neighbouring areas (such as Paris). Albeit focused on one specific area where environmental records are available, our analysis is relevant for the large areas affected synchronously by inter-annual changes in maximum growing season temperature, from south-western France to North of Germany ($R > 0.80$) (Fig. 2b).

The second key meteorological parameter is the late summer mean relative humidity (hereafter h_{moy} JASO). In Fontainebleau, h_{moy} JASO varies between 68% and 79% over the period 1951–2004. The linear trend observed over the period 1950–2000 results in a 4% decrease over this 50 year interval. Warm summers are systematically drier over the past 50 years as recorded in the anti-correlation between T_{\max} AMJJAS and h_{moy} JASO ($R = -0.64$, $p = 3.65 \times 10^{-7}$). Due to the short relative humidity record (only back to 1950), it is not possible to assess the persistency of this relationship.

The third key meteorological parameter is the summer precipitation amount (hereafter P_{JJA}). Generally, the correlations between precipitation and tree-ring or documentary records are less significant than the correlations obtained with temperature. When comparing summer (JJA) or annual precipitation amounts and T_{\max} AMJJAS, it appears that these variables are significantly anti-correlated from 1900 to 1950 (Table 3, $R = -0.50$ and $p = 0.0002$ for P_{JJA} , $R = -0.59$ and $p = 9 \times 10^{-6}$ for P_{ann}) but the anti-correlation is weaker since 1950 (Table 3, $R = -0.38$ and $p = 0.006$ for P_{JJA} , $R = -0.32$ and $p = 0.02$ for P_{ann}). This change of correlation between meteorological parameters is important because moisture availability

Table 2 Correlation coefficients and *p*-values of the regressions between meteorological and hydrological parameters

		$\delta^{18}\text{O}$	δD	$\delta^{13}\text{C}$	$\delta^{13}\text{C}_{\text{Cor}}$	GI	GHD _A	GHD _B	Fire
T_{max} An	<i>R</i>	0.43	0.19	0.26	0.32	-0.19	-0.58	-0.58	0.47
	<i>p</i>	1×10^{-6}	0.06	0.004	0.0004	0.03	3×10^{-10}	6×10^{-12}	5×10^{-8}
T_{max} AMJJAS	<i>R</i>	0.58	0.26	0.38	0.34	-0.29	-0.73	-0.68	0.47
	<i>p</i>	6×10^{-12}	0.01	2×10^{-5}	0.0002	0.001	2×10^{-16}	2×10^{-16}	6×10^{-8}
P_{ann}	<i>R</i>	-0.31	-0.06	-0.52	0.34	0.27	0.38	0.10	-0.40
	<i>p</i>	0.001	0.55	3×10^{-9}	0.002	0.003	0.0001	0.29	1×10^{-5}
P_{JJA}	<i>R</i>	-0.52	-0.28	-0.47	-0.38	0.33	0.39	0.23	-0.32
	<i>p</i>	6×10^{-9}	0.008	9×10^{-8}	3×10^{-5}	0.0003	0.0001	0.01	0.0004
h_{moy} An	<i>R</i>	-0.40	-0.37	-0.44	-0.52	0.49	0.42	0.38	-0.67
	<i>p</i>	0.004	0.01	0.001	9×10^{-5}	0.0003	0.03	0.007	1×10^{-7}
h_{moy} JASO	<i>R</i>	-0.44	-0.45	-0.48	-0.61	0.43	0.58	0.59	-0.69
	<i>p</i>	0.002	0.002	0.0004	3×10^{-6}	0.001	0.002	8×10^{-6}	6×10^{-8}
SWD An	<i>R</i>	0.61	0.34	0.29	0.22	-0.23	-0.63	-0.38	0.50
	<i>p</i>	0.0003	0.09	0.1	0.2	0.19	0.07	0.03	0.004
SWD JJA	<i>R</i>	0.65	0.39	0.40	0.38	-0.54	-0.67	-0.51	0.54
	<i>p</i>	9×10^{-5}	0.05	0.02	0.03	0.002	0.05	0.003	0.002
R_g An	<i>R</i>	0.70	0.51	0.44	0.54	-0.20	-0.89	-0.56	0.65
	<i>p</i>	1×10^{-5}	0.008	0.01	0.002	0.28	0.001	0.001	7×10^{-5}
PE	<i>R</i>	-0.59	-0.35	-0.30	-0.24	0.29	0.56	0.33	-0.39
	<i>p</i>	0.0005	0.08	0.09	0.18	0.1	0.12	0.07	0.03

AE	R	-0.60	-0.38	-0.37	-0.31	0.45	0.70	0.44	-0.65
	P	0.0003	0.06	0.04	0.09	0.01	0.03	0.01	8×10^{-5}
$\delta^{18}\text{O}$	R	0.47	0.47	0.17	0.32	-0.14	-0.26	-0.15	0.40
δD	R	0.47	0.47	0.10	0.36	-0.27	-0.25	-0.18	0.41
	P	4×10^{-6}							
$\delta^{13}\text{C}$	R	0.17	0.10		0.80	-0.14	-0.05	0.03	0.15
	P	0.0006	0.33						
$\delta^{13}\text{C}_{\text{cor}}$	R	0.32	0.36	0.80		-0.13	-0.08	-0.003	0.44
	P	2×10^{-10}	0.0004	2×10^{-16}					
GI	R	-0.14	-0.27	-0.14	-0.13		0.27	0.26	-0.32
	P	0.004	0.008	0.004	0.009				
GHD _A	R	-0.26	-0.25	-0.05	-0.08	0.27		0.77	-0.43
	P	3×10^{-6}	0.03	0.35	0.17	1×10^{-6}			
GHD _B	R	-0.15	-0.18	0.03	-0.003	0.26	0.77		-0.36
	P	0.004	0.09	0.49	0.9	7×10^{-8}	2×10^{-16}		
Fire	R	0.40	0.41	0.15	0.44	-0.32	-0.43	-0.36	
	P	2×10^{-6}	6×10^{-5}	0.09	1×10^{-7}	0.0002	2×10^{-6}	2×10^{-5}	

R correlation coefficients and p-values are calculated for the availability time period of climatic parameters

and temperature fluctuations can have compensating effects on plant growth and stomatal conductance. In order to assess the impact of such changes, we systematically performed correlation analyses for the first and second halves of our records (see Table 3).

Inter-annual changes in tree ring parameters are also displayed on Fig. 1. In Fontainebleau, latewood $\delta^{18}\text{O}$ ranges from 30.0‰ to 32.8‰ with an average 20th level at 31.3‰. A linear increase of 0.15‰ is observed over the past 50 years and of 0.89‰ over the past 20 years (almost 2 standard deviations above the twentieth century level). The mean Fontainebleau deuterium value is -65.0‰ , with amplitude of 45.8‰ for inter-annual variations. The linear trend of deuterium over the past 50 years (5.7‰) represents only 1/10 of the inter-annual variability. The mean Fontainebleau $\delta^{13}\text{C}$ is -24.1‰ and varies from -26.4‰ to -22.4‰ , with a linear decrease of 0.7‰ over the past 50 years. The carbon isotopic data are displayed on Fig. 1 after correction for atmospheric $\text{CO}_2\delta^{13}\text{C}$ changes (see Section 2). The mean Fontainebleau $\delta^{13}\text{C}_{\text{cor}}$ is -23.4‰ and varies from -25.7‰ to -22.1‰ , with a linear increase of 0.7‰ over the past 50 years (mainly due to a step increase in the late

Table 3 Correlation coefficients of the regressions between proxies ($\delta^{18}\text{O}$, δD , $\delta^{13}\text{C}$, GHD_A , GHD_B and forest fires) and climatic parameters (temperature and precipitation)

	$T_{\text{max}}\text{AMJJAS}$	$\delta^{18}\text{O}$	δD	$\delta^{13}\text{C}$	GHD_A	GHD_B	Forest fires
<i>T_{max} ann</i>							
1900–1950	0.77	0.40	0.35	0.49	-0.46	-0.46	0.55
1951–2000	0.84	0.46	0.21	0.11	-0.75	-0.73	0.55
<i>T_{max} AMJJAS</i>							
1900–1950	1.00	0.57	0.40	0.55	-0.68	-0.60	0.62
1951–2000	1.00	0.62	0.37	0.20	-0.81	-0.82	0.65
<i>P_{ann}</i>							
1900–1950	-0.60	-0.50	-0.28	-0.54	0.53	0.25	-0.53
1951–2000	-0.32	-0.34	-0.03	-0.39	0.36	0.03	-0.56
<i>P_{JJA}</i>							
1900–1950	-0.52	-0.59	-0.26	-0.47	0.37	0.25	-0.35
1951–2000	-0.38	-0.60	-0.47	-0.45	0.45	0.25	-0.42
$\delta^{18}\text{O}$							
1900–1950	0.57	1.00	0.49	0.43	-0.47	-0.19	0.55
1951–2000	0.62	1.00	0.45	0.22	-0.32	-0.42	0.59
δD							
1900–1950	0.40	0.49	1.00	0.25	-0.32	-0.23	0.45
1951–2000	0.37	0.45	1.00	0.33	-0.46	-0.39	0.35
GHD_A							
1900–1950	-0.68	-0.47	-0.32	-0.39	1.00	0.69	-0.48
1951–2000	-0.81	-0.32	-0.46	-0.17	1.00	0.88	-0.66
GHD_B							
1900–1950	-0.60	-0.19	-0.23	-0.28	0.69	1.00	-0.22
1951–2000	-0.82	-0.42	-0.39	-0.03	0.88	1.00	-0.58
Forest fires							
1900–1950	0.62	0.55	0.45	0.47	-0.48	-0.22	1.00
1951–2000	0.65	0.59	0.35	0.34	-0.66	-0.58	1.00

Meteorological parameters are restricted to those available over the whole past century and correlation coefficients are obtained for the time intervals 1900–1950 and 1951–2000. The figures in italics are statistically significant (0.95% confidence level using Student's test).

1970s). The growth index varies between -55 and $+66$, with, by construction, a mean value of 0. No growth index trend is detected over the past 50 years.

Finally, Fig. 1 displays inter-annual fluctuations of documentary data. Burgundy and Argenteuil grape harvest dates occur in average 25 and 27 days after August 31st respectively, and display a significant range of inter-annual fluctuations (by 34 and 48 days respectively). At both places, grape harvests dates have linearly shifted towards earlier dates by 10 days over the past 50 years. On average, 32 forest fire starts are recorded during summer months; this number of events fluctuates between five and 139 events. Long term trends may combine forest risks due to both local human pressure (forest as recreational area) (Polton 1995) and climatic conditions; an increasing number of fire starts ($+20$ events per summer) is detected over the past 50 years. Spring–summer extreme warmth can generate high number of forest fire starts, early grape harvest, high $\delta^{18}\text{O}$, δD and $\delta^{13}\text{C}$. In the individual records different years appear as extreme years. Figure 1 highlights the five warmest years ($T_{\text{max}} \text{AMJJAS} > 30$ years running mean $T_{\text{max}} \text{AMJJAS} + 1.5\sigma$): 1911, 1921, 1947, 1949 and 1976. All the proxies have extreme values in 1976 (note that there is no δD for this year). All the proxies but $\delta^{18}\text{O}$ have extreme values in 1911 and 1921. 1949 and 1947 show extreme values for three of the records ($\delta^{18}\text{O}$, δD and forest fire starts for 1949; $\delta^{13}\text{C}$, GHD_A and GHD_B for 1947).

4 Discussion of the potential for temperature multi-proxy reconstruction

In this section, we assess the potential of the tree ring and documentary data presented in Section 3 for climate reconstructions. We have 6 different indicators of Fontainebleau tree growth and isotopic behaviour: growth index, cellulose $\delta^{18}\text{O}$, δD and $\delta^{13}\text{C}$, and forest fire starts, and two grape harvest date records (GHD_A and GHD_B). Each of this proxy record is associated with its own uncertainties (accuracy of the measurements or historical sources, number of samples, robustness of the links with climate and environmental changes, anthropogenic effects...).

We therefore explore first the links between each of the proxy records, climatic and environmental data, and second, the added value of the best possible linear combination of these proxies in order to build a reliable past temperature reconstruction method. Finally, we take advantage of this multi-proxy dataset to discuss the quality of the homogenised temperature data.

4.1 Linear relationships between tree ring records and climate fluctuations

Amongst the various dendroclimatic parameters, stronger relationships with environmental parameters are obtained for grape harvest dates (GHD_A and GHD_B), $\delta^{18}\text{O}$, number of fire starts, $\delta^{13}\text{C}$, $\delta^{13}\text{C}_{\text{cor}}$, growth index and last by the δD . The graphical representation of the inter-annual variability of these parameters and climate and hydrological variables (not shown here) clearly points to linear relationships (Etien 2008) and we therefore apply linear analyses methods.

Latewood cellulose δD shows significant but weak correlations ($|R| < 0.40$) with $T_{\text{max}} \text{AMJJAS}$ ($p = 0.01$), summer precipitation (June–July–August) ($p = 0.008$), SWD ($p = 0.05$) and actual and potential evapotranspiration ($p \sim 0.10$). A stronger correlation is observed with summer relative humidity (July–August–September–

October, hereafter JASO) ($R = -0.45$, $p = 0.002$) and total radiation ($R = 0.51$, $p = 0.008$).

The growth index only displays a significant linear correlation with water stress indicators ($|R| \sim 0.5$ for JASO relative humidity ($p = 0.001$), summer soil water deficit ($p = 0.002$) and actual evapotranspiration ($p = 0.01$)), supporting the view that oak growth is mainly controlled by moisture availability in temperate areas (Kelly et al. 2002).

The raw $\delta^{13}\text{C}$ inter-annual variations are correlated with T_{max} AMJJAS, precipitation, SWD, actual evapotranspiration and global radiation. Although a large number of significant correlations are observed between $\delta^{13}\text{C}$ and meteorological and hydrological parameters, these correlations remain weak (almost 60% of the results have correlation coefficients $|R| < 0.4$). As expected from the control of soil water availability on stomatal conductance (McCarroll and Loader 2004), the best correlations are obtained for global radiation ($R = 0.44$, $p = 0.01$ for $\delta^{13}\text{C}$ and $R = 0.54$, $p = 0.002$ for $\delta^{13}\text{C}_{\text{cor}}$) and annual and summer relative humidity ($R = -0.48$, $p = 0.0004$ for $\delta^{13}\text{C}$ and $R = -0.61$, $p = 2 \times 10^{-6}$ for $\delta^{13}\text{C}_{\text{cor}}$).

The highest correlation coefficients (R) of cellulose stable isotopes are obtained between cellulose $\delta^{18}\text{O}$ and late summer environmental parameters: June–October mean relative humidity ($R = -0.44$, $p = 0.002$), June–August precipitation ($R = -0.52$, $p = 5 \times 10^{-9}$), April–September maximum temperature ($R = 0.58$, $p = 6 \times 10^{-12}$). Cellulose $\delta^{18}\text{O}$ also exhibits strong correlations ($|R| \geq 0.6$) for total radiation ($p = 1 \times 10^{-5}$), evapotranspiration ($p = 3 \times 10^{-4}$) and SWD ($p = 9 \times 10^{-5}$).

The dependence of $\delta^{18}\text{O}$ and δD on temperature and relative humidity is in agreement with previous results (Burk and Stuiver 1981; Edwards et al. 1985; Buhay and Edwards 1995; Feng and Epstein 1996; Baillie et al. 2000; Raffalli-Delercé et al. 2004; Szczepanek et al. 2006). Local temperature has an indirect influence on cellulose $\delta^{18}\text{O}$ and δD , via the precipitation $\delta^{18}\text{O}$ or δD relationship with temperature, but modulated through the evaporation of leaf water. Moisture availability influences leaf enrichment and therefore cellulose $\delta^{18}\text{O}$ or δD by regulation of stomatal conductance, directly (via relative humidity effects) or indirectly (via soil moisture deficit effects). It is more surprising to observe a strong linear relationship between cellulose δD and $\delta^{18}\text{O}$ and total radiation. We suggest that this correlation arises from two combined effects: (1) the close link between net radiation and photosynthesis; and (1) the correlations between the various meteorological parameters ($R = 0.73$, $p = 2 \times 10^{-6}$ between T_{max} AMJJAS and total radiation).

These statistical analyses highlight a strong tree ring isotope correlation with the temperature from April to September and relative humidity averaged from July to October. The growing season of oak begins by the end of April; the late wood formation starts by the end of June and finishes some time in October (Nicault et al. 2001). The “growing season” imprint of meteorological parameters is therefore coherent with the oak latewood growing season.

4.2 Linear relationships between documentary data, tree ring and climate variables

Historical records exhibit correlation coefficients comparable to those obtained for cellulose $\delta^{18}\text{O}$ and climatic parameters. Grape harvest dates and forest fires are

strongly related ($|R| \geq 0.5$) to annual and AMJJAS maximum temperature ($p = 2 \times 10^{-16}$ and $p = 6 \times 10^{-8}$ for GHD and forest fires respectively), total radiation ($p = 0.001$ and $p = 7 \times 10^{-5}$ respectively), JASO relative humidity ($p = 6 \times 10^{-6}$ and $p = 6 \times 10^{-8}$ respectively), actual evapotranspiration ($p = 0.03$ and $p = 8 \times 10^{-5}$ respectively) and summer SWD ($p \sim 0.01$ for both). They show no significant correlation with the $\delta^{13}\text{C}$. Correlations above 0.4 are obtained between forest fires and $\delta^{18}\text{O}$ ($R = 0.40$, $p = 2 \times 10^{-6}$), forest fires and δD ($R = 0.41$, $p = 6 \times 10^{-5}$), forest fires and $\delta^{13}\text{C}_{\text{cor}}$ ($R = 0.44$, $p = 2 \times 10^{-7}$), forest fires and growth index ($R = -0.32$, $p = 2 \times 10^{-3}$) and forest fires and grape harvest dates ($R \sim -0.40$, $p \sim 1 \times 10^{-5}$ for GHD_A and GHD_B).

This correlation analysis shows the imprint of AMJJAS maximum temperature, JASO relative humidity and total radiation on tree ring isotopic composition and historical records. However, this analysis is limited by the length of the records (only 50 years for relative humidity and 30 years for total radiation). In order to test the persistence of the correlations, we restrict the analysis to the meteorological parameters available over the whole past century and compare the correlation coefficients obtained for the time intervals 1900–1950 and 1951–2000 (Table 3). Most parameters show quite significant differences between these two periods. We restrict this discussion to the relationships which appear to be robust with time. Cellulose $\delta^{18}\text{O}$ shows a persistent correlation with T_{max} AMJJAS, as well as forest fires. Although grape harvest dates show higher correlation coefficients with summer temperature than $\delta^{18}\text{O}$, on average, these coefficients appear to be more variable through time.

For the variables responding most strongly to T_{max} AMJJAS, we have obtained the following inter-annual regression slopes: -5.9 ± 0.63 days/ $^{\circ}\text{C}$ for GHD_A and -4.3 ± 0.46 days/ $^{\circ}\text{C}$ for GHD_B ; 11.3 ± 1.8 forest fires per degree Celsius; $0.30 \pm 0.05\%$ / $^{\circ}\text{C}$ for $\delta^{18}\text{O}$; $0.20 \pm 0.06\%$ / $^{\circ}\text{C}$ for $\delta^{13}\text{C}$; $0.21 \pm 0.05\%$ / $^{\circ}\text{C}$ for $\delta^{13}\text{C}_{\text{cor}}$; $2.0 \pm 0.64\%$ / $^{\circ}\text{C}$ for δD and $-7.2 \pm 2 \times 10^{-2}$ mm/ $^{\circ}\text{C}$ for the growth index. These results arise from inter-annual fluctuations; different calibrations are obtained when considering the linear trends over the past 50 years.

When considering the ratio of proxy versus temperature long term trends, these alternative calibrations are systematically lower than inter-annual regression slopes for historical records (for instance, 2 days/ $^{\circ}\text{C}$ for forest fires), but higher for isotopic data (for instance, 1.1%/ $^{\circ}\text{C}$ for $\delta^{18}\text{O}$). This change in slopes from inter-annual to multi-decadal scales may arise from different interplays of the various meteorological parameters affecting our proxy records or from different response functions for extreme years and for long term trends.

This statistical linear analysis enables us to focus on one climate variable (T_{max} AMJJAS) which exhibits the strongest (correlation coefficients) and most robust (smallest p -values, stability of the relationships along the first and second halves of the twentieth century) correlation with tree ring isotopic data and documentary records. In the next section, we reverse the analysis and focus on a methodology combining available proxy records to estimate past variations of T_{max} AMJJAS.

While this result is obtained from linear statistic analyses, there are strong physical and physiological processes linking the growing season temperature and our proxy records. The metabolic processes involved in photosynthesis, respiration, cellulose

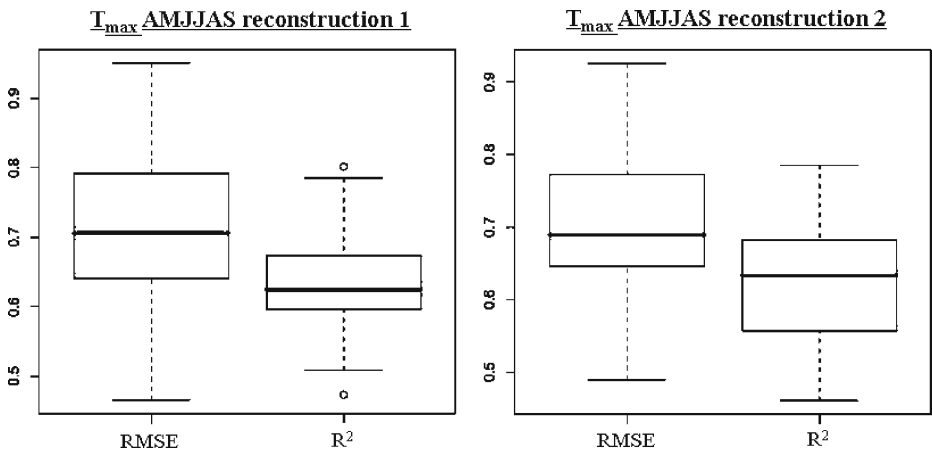


Fig. 3 Boxplots of the RMSE and R^2 distributions obtained by the cross-validation method (100 iterations). Each box is bounded on the *right* and *left* by the first ($x_{0.25}$) and third ($x_{0.75}$) quartiles. The medians lie inside the boxes (*thick line*). The ‘whiskers’ connect the smallest and largest values that are not outliers (<1.5 times the inter-quartile range) to the boxes. Outliers are indicated by *dots*

synthesis or grape maturation are linked with plant phenology and therefore depend on temperature (e.g. Chuine et al. 2004). Hydrological processes do also influence tree isotopic behaviour, either through the impact of water stress on stomatal conductance or through the links between precipitation isotopic composition and temperature, and vine growth. The combination of independent proxies such as those discussed here can help to improve the detection of temperature variations and get rid of hydrological biases.

4.3 Multi-proxies calibration

We have performed multiple linear regression analyses in order to reconstruct Fontainebleau T_{\max} AMJJAS using the isotopic composition ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$) of the cellulose of Fontainebleau oaks, the forest fire starts at Fontainebleau, and regional grape harvest dates. First, we have checked the co-linearity of the various predictors by means of a Variance Inflation Factor (VIF) criterion. We have shown that $\delta^{13}\text{C}$ and $\delta^{13}\text{C}_{\text{cor}}$ are highly co-linear, as expected. We have chosen to exclude $\delta^{13}\text{C}_{\text{cor}}$, which is less strongly correlated to T_{\max} AMJJAS than $\delta^{13}\text{C}$ ($R = 0.38$ for $\delta^{13}\text{C}$ and $R = 0.34$ for $\delta^{13}\text{C}_{\text{cor}}$ respectively). The VIF values of the remaining predictors are inferior to 3, which is far below the pathological value of 10 (Azais and Bardet 2005). Though they do not exhibit VIF values above 10 and are highly correlated to instrumental T_{\max} AMJJAS, we have excluded the Argenteuil GHD from the calibration since the series has many missing values and no record after 1977. To construct the most efficient set of proxy records, we used the backward selection of predictors combined with the Akaike Information Criterion (AIC). This criterion permits model selection and avoids overfitting (Akaike 1973). In this approach, the model which minimizes AIC is considered to be the most appropriate model.

Table 4 Values of root mean square error (RMSE) and correlation coefficient (R) calculated with a cross-validation method on reconstruction 1 (with $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, GHD_B and fire) and reconstruction 2 (with $\delta^{18}\text{O}$, $\delta^{13}\text{C}$ and GHD_B)

	Reconstruction 1		Reconstruction 2	
	RMSE	R^2	RMSE	R^2
Median	0.71	0.63	0.70	0.63
Mean	0.71	0.63	0.70	0.64
1st quartile	0.64	0.58	0.63	0.58
3rd quartile	0.77	0.68	0.77	0.69

With our data set, the lowest AIC value is obtained while combining $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ of oak cellulose, Burgundy grape harvest dates and the number of forest fire starts in Fontainebleau (growth indices and δD are not selected by the AIC test). As follows:

$$\begin{aligned} \Delta T_{\max} \text{ AMJJAS} = & (0.34 \pm 0.13) \times \Delta\delta^{13}\text{C} + (0.53 \pm 0.16) \times \Delta\delta^{18}\text{O} \\ & - (0.08 \pm 0.01) \times \Delta\text{GHD}_B + (0.006 \pm 0.003) \\ & \times \Delta\text{fire} \quad (R = 0.81, p\text{-value} < 2.10^{-16}). \end{aligned} \tag{2}$$

We confirmed our calibration by a cross-validation scheme. Two thirds of the data (calibration samples) were randomly sampled without replacement; a multiple linear regression was calculated on these data and the quality of the reconstruction was assessed on the last third of the data (verification samples). The determination coefficient and the difference between instrumental and predicted T_{\max} AMJJAS were calculated. After 100 iterations of this method, we determined a mean $r^2 = 0.63$ and a root mean square error of the linear model $\text{RMSE} = 0.70^\circ\text{C}$ (Fig. 3). The reconstructed T_{\max} AMJJAS displays a maximum amplitude of 5°C (against 6.8°C in the homogenised data) and a standard deviation from the mean of 0.9°C (1.15°C for the homogenised data). In perspective of climate reconstruction, we also propose a multiple linear regression equation without the forest fire predictor which is seldom available:

$$\begin{aligned} \Delta T_{\max} \text{ AMJJAS} = & (0.37 \pm 0.12) \times \Delta\delta^{13}\text{C} + (0.64 \pm 0.13) \times \Delta\delta^{18}\text{O} - (0.09 \pm 0.01) \\ & \times \Delta\text{GHD}_B \quad (R = 0.81, p\text{-value} < 2.10^{-16}). \end{aligned} \tag{3}$$

The same cross-validation method has been applied to this new set of predictors. Results are similar to those obtained above (see Table 4).

Interestingly, reconstructed T_{\max} AMJJAS (according to Eqs. 2 or 3) are systematically lower than homogenised T_{\max} AMJJAS for the extreme warm years of 1911, 1921, 1947 and 1949, while our reconstruction supports the higher temperature shown in homogenised data in 1976 (see Fig. 4). This discrepancy questions the reliability of the proxies (see Section 3.1) but also of ancient instrumental record (already mentioned in Section 2.1). An over-estimation of early instrumental maximum summer temperature has important consequences for the detection and attribution of climate change. Until now, detection studies conducted on French homogenised temperature data showed significant changes for minimum summer temperatures but failed for maximum summer temperatures (Planton and Terray 2007; Della-Marta et al. 2007). We suggest here that homogenisation methods may fail to

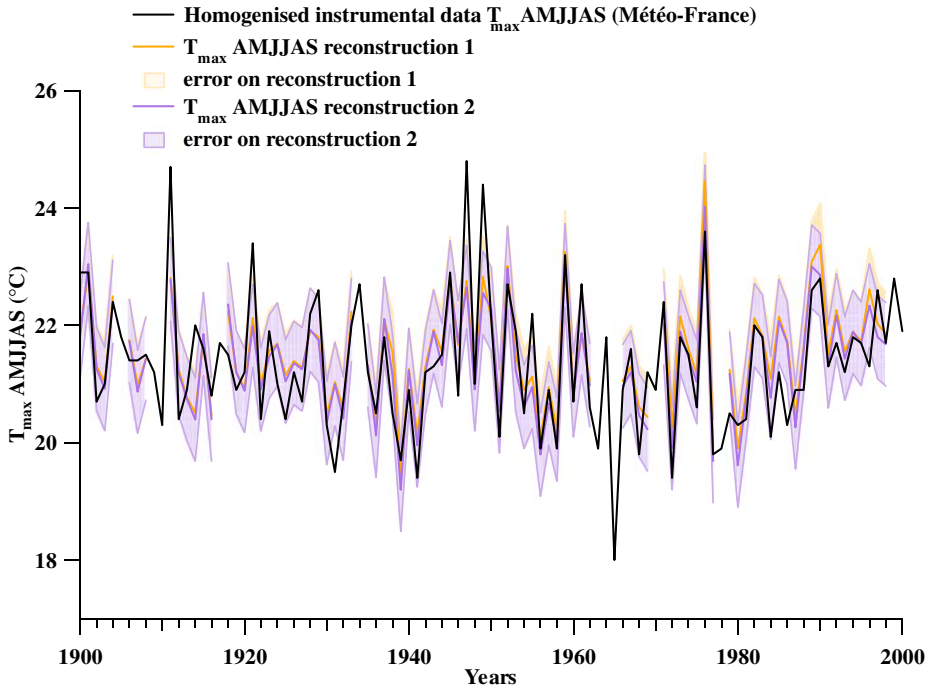


Fig. 4 Comparison of the reconstructed data (*orange line* and associated reconstruction statistical uncertainty for reconstruction 1; *purple line* and associated reconstruction statistical uncertainty for reconstruction 2) versus homogenised instrumental data of maximum growing season (T_{\max} AMJJAS) temperature (in degree Celsius) at Fontainebleau (France)

correct the lack of shading inducing a specific overestimation of maximum summer temperatures for instruments deployed prior to ~ 1950 in France as also suggested for the Alpine region (Frank et al. 2007). Multi-proxy reconstructions offer the possibility to question the reliability of long term meteorological records and could provide more homogeneous sources of information for detection and attribution over the twentieth century.

If our proxy records can be faithfully combined to reconstruct past temperature, then it is suggested that prior to 1950, instrumental records may systematically overestimate late summer maximum temperature extremes. Our analysis points out that growing season maximum temperature and summer precipitation amount have varying relationships between the first and second part of the twentieth century (Table 3). Since both water stress and summer temperature have an influence on plant phenology and forest fires, then different combinations of temperature and moisture signals may affect the proxy records. It is possible that our reconstruction performs best for warm, dry and sunny summers than just for warm summers, due to cumulative effects of temperature and precipitation on proxy records. Moreover, the inter-tree variability of the $\delta^{18}\text{O}$ increases drastically when the climatic conditions during the growing season are restrictive (coldness, storm, drought; Section 3.1.), which can deteriorate the reliability of the reconstruction for these years.

5 Conclusions and perspectives

In this study, we have first determined the inter-tree variability of the isotopic signal. This aspect is important to assess the climate effect versus the individual effects on our records. Second, we have used multiple linear regression analyses to assess the response of our environmental records to climatic fluctuations of the past century; this study includes indirectly a quantification of the impacts of twentieth century climate change on local phenology (grape harvest dates, tree growth) and on the frequency of forest fires. Finally, we propose a multi-proxy method to reconstruct past growing season (from April to September) temperature and discuss the robustness of the reconstructed versus homogenized data.

Carbon and oxygen isotopic composition of oaks grown in the Fontainebleau (France) temperate area are related to climatic (temperature, precipitation, relative humidity, radiation) and hydrologic parameters (soil water deficit, potential and actual evapotranspiration). By contrast, our calibration study shows that the late-wood ring width and δD are related in a complex and weak way to the meteorological conditions. The inter-tree variability of the oxygen isotopic composition is quite low compared to the analytical precision. Our analysis shows that a sample of three pooled trees yields an isotopic signal representative of the stand.

This multi-proxy study is very promising and suggests that a significant proportion of the climatic variability can be reconstructed using a combination of grape harvest dates, cellulose $\delta^{13}C$ and $\delta^{18}O$ and number of forest fire starts. However, this last parameter is seldom available from documentary sources. Grape harvest dates of Argenteuil and Burgundy have inter-annual variations strongly related to Fontainebleau maximum temperature from April to September. They also are very good markers of water stress (relative humidity and soil water deficit). Many grape harvest dates series are published; to our knowledge, Burgundy is the longest record in France (uninterrupted series from 1370 to 2003; Chuine et al. 2004). The multi-proxy calibration restricted to $\delta^{18}O$, $\delta^{13}C$, and Burgundy grape harvest dates enable the capture of 65% of T_{max} AMJJAS. This offers the potential for quantifying fluctuations in growing season maximum temperature over the past centuries. It will be applied to the reconstruction of T_{max} AMJJAS in Fontainebleau area using a series of carbon and oxygen isotopic compositions of historical building beams sampled in the Fontainebleau castle and Burgundy grape harvest dates. Based on available meteorological data, inter-annual variations in Fontainebleau growing season temperature should be representative of a large area in Western Europe. Therefore, reconstructions of past temperature at Fontainebleau will help in understanding climatic variations on a much broader scale and will fill a geographical gap in European climate reconstructions (Luterbacher et al. 2004; Guiot et al. 2005). Finally, our comparison between homogenised data and proxy records questions the reliability of maximum temperature measurements prior to 1950, which has consequences in terms of detection of anthropogenic effects.

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References

- Akaike H (1973) Information theory and extension of the likelihood ratio principle. In: Pietrov BN, Csaki F (eds) Proceedings of the second international symposium of information theory. Akademiai Kiado, Budapest, pp 257–281
- Alexander WJ, Mitchell RI (1949) Rapid measurement of cellulose viscosity by the nitration method. *Anal Chem* 21:1497–1500
- Anderson WT, Bernasconi SM, McKenzie JA, Saurer M, Schweingruber F (2002) Model evaluation for reconstructing the oxygen isotopic composition in precipitation from tree ring cellulose over the last century. *Chem Geol* 182:121–137
- Augusti A, Betson TR, Schleucher J (2006) Hydrogen exchange during cellulose synthesis distinguishes climatic and biochemical isotopes fractionations in tree rings. *New Phytol* 172(2):490–499
- Azais JM, Bardet JM (2005) Le modèle linéaire par l'exemple: regression, analyse de la variance et plans d'expériences illustrés avec R, SAS et Splus. Dunod, Paris, p 326
- Baillie MGL, Pilcher JR, Pollard AM, Ramesh R (2000) Climatic significance of D/H and C-13/C-12 ratios in Irish oak cellulose. *Indian Academy of Science—Earth and Planetary Sciences* 109(1):117–127, March
- Barbaroux C, Bréda N (2002) Contrasting seasonal dynamics and distribution of carbohydrate reserves in the stem wood of adult ring porous (sessile oak) and diffuse porous tree (common beech). *Tree Physiol* 22:1201–1210
- Barbour MM, Schurr U, Henry BK et al (2000) Variation in the oxygen isotope ratio of phloem sap sucrose from castor bean. Evidence in support of the Pecllet effect. *Plant Physiol* 123(1):671–679
- Barbour MM, Andrews TJ, Farquhar GD (2001) Correlations between oxygen isotope ratios of wood constituents of *Quercus* and *Pinus* samples from around the world. *Aust J Plant Physiol* 28: 335–348
- Barbour MM, Roden JS, Farquhar GD, Ehleringer JB (2004) Expressing leaf water and cellulose oxygen isotope ratios as enrichment above source water reveals evidence of a Pecllet effect. *Oecologia* 138(2):426–435
- Bariac T, Jusserand C, Mariotti A (1990) Evolution spatiotemporelle de la composition isotopique dans le continuum sol-plante-atmosphère. *Geochim Cosmochim Acta* 54:413–424
- Beniston M, David B (2004) Extreme climatic events and their evolution under changing climatic conditions. *Glob Planet Change* 44(1):4–9
- Benner R, Fogel ML, Sprague EK, Hodson RE (1987) Depletion of $\delta^{13}\text{C}$ in lignin and its implications for stable isotope studies. *Nature* 329:708–710
- Briffa KR (2000) Annual climate variability in the Holocene: interpreting the message of ancient trees. *Quat Sci Rev* 19:87
- Briffa KR, Osborn TJ, Schweingruber FH et al (2001) Low-frequency temperature variations from a northern tree ring density network. *J Geophys Res* 106:2929–2941
- Buhay WM, Edwards TWD (1995) Climate in south-western Ontario, Canada, between AD 1610 and 1885 inferred from oxygen and hydrogen isotopic measurements of wood cellulose from trees in different hydrologic settings. *Quat Res* 44(2):438–446
- Burk R, Stuiver M (1981) Oxygen isotope ratios in trees reflect mean annual temperature and humidity. *Science* 211:1417–1419
- Caussinus H, Mestre O (2004) Detection and correction of artificial shifts in climate series. *Appl Stat* 53(2):405–425
- Chuine I, Yiou P, Viovy N et al (2004) Historical phenology: grape ripening as a climate indicator. *Nature* 432:289–290
- Craig H, Gordon LI (1965) Deuterium and oxygen-18 variations in the ocean and marine atmospheres. In: Tongiorni E (ed) Proceedings of a conference on stable isotopes in oceanographic studies and palaeotemperatures. Lischi and Figli, Pisa, Italy, pp 9–130
- Crowley TJ (2000) Causes of climate change over the past 1000 years. *Science* 289:270–277
- Danis PA, Masson-Delmotte V, Stievenard M et al (2006) Reconstruction of past precipitation delta O-18 using tree-ring cellulose delta O-18 and delta C-13: a calibration study near Lac d'Annecy, France. *Earth Planet Sci Lett* 243 (3–4):439–448

- Dansgaard W (1964) Stable isotopes in precipitation. *Tellus* 16:436–468
- Darling WG (2004) Hydrological factors in the interpretation of stable isotopic proxy data present and past: a European perspective. *Quat Sci Rev* 23(7–8):743–770
- Daux V, Yiou P, Le Roy Ladurie E, Mestre O, Seguin B, Chuine I, Garnier E, Viovy N (2007) Temperature and grape harvest dates in France, international colloquium “global warming, which impacts on the vineyards”, 28–30 March. Perard and Fontaine (eds) Dijon, France, p 9
- Dawson TE (1993) Water sources of plants as determined from xylem–water isotopic composition, distribution and water relations. In: Ehleringer JR, Happ AE, Farquhar GD (eds) *Stable isotopes and plant carbon–water relations*. Academic, New York, pp 465–496
- Dawson TE, Pate JS (1996) Seasonal water uptake and movement in root systems of Australian phraeatophytic plants of dimorphic root morphology: a stable isotope investigation. *Oecologia* 107:13–20
- Della-Marta PM, Haylock MR, Luterbacher J, Wanner H (2007) Doubled length of western European summer heat waves since 1880. *J Geophys Res* 112:D15103. doi:10.1029/2007JD008510
- DeNiuro MJ, Epstein S (1981) Isotopic Composition of cellulose from aquatic organisms. *Geochim Cosmochim Acta* 45(10):1885–1894
- Dupouey JL, Leavitt S, Choiselet E, Jourdain S (1993) Modelling carbon isotope fractionation in tree rings based on effective evapotranspiration and soil water status. *Plant Cell Environ* 16:939–947
- Edwards TWD, Aravena R, Fritz P, Morgan AV (1985) Interpreting paleoclimate from ^{18}O and ^2H in plant cellulose comparison with evidence from fossil insects and relict permafrost in south-western Ontario. *Can J Earth Sci* 22:1720–1726
- Esper J, Cook ER, Schweingruber FH (2002) Low-frequency signals in long tree ring chronologies for reconstructing past temperature variability. *Science* 295:2250–2253
- Etien N (2008) Variabilité climatique récente en France: l’apport des isotopes de la cellulose du bois final des chênes de Fontainebleau. Thèse soutenue à l’Université Paris 6.
- Etien N, Daux V, Masson-Delmotte V, Stievenard M, Bernard V, Durost S, Guillemain M-Th, Mestre O, Pierre M (2008) A bi-proxy reconstruction of Fontainebleau (France) growing season temperature from A.D. 1596 to 2000. *Climate of the Past* 4:91–106
- Farquhar GD, Ehleringer JR, Hubick KT (1989) Carbon isotope discrimination and photosynthesis. *Annu Rev Plant Physiol Plant Mol Biol* 40:503–537
- Feng XH, Epstein S (1996) Climatic trends from isotopic records of tree rings: the past 100–200 years. *Clim Change* 33(4):551–562
- Francey RJ, Tans PP, Allison CE, Enting IG, White JWC, Troler M (1995) Changes in oceanic and terrestrial carbon uptake since 1982. *Nature* 373:326–330
- Francey RJ, Allison CE, Etheridge DM, Trudinger CM, Enting IG, Leuenberger M, Langensfeld RL, Michel E, Steele LP (1999) A 1000 year high precision record of $\delta^{13}\text{C}$ in atmospheric CO_2 . *Tellus* 51B:170–193
- Frank D, Büntgen U, Böhm R, Maugeri M, Esper J (2007) Warmer early instrumental measurements versus colder reconstructed temperatures: shooting at a moving target. *Quat Sci Rev* 26:3298–3310
- Freyer HD (1979) On the ^{13}C record in tree rings. Part 1. ^{13}C variations in northern hemispheric trees during the last 150 years. *Tellus* 31:124–137
- Friedli H, Löhcher H, Oeschger H, Siegenthaler U, Stauffer B (1986) Ice core record of the $^{13}\text{C}/^{12}\text{C}$ ratio of atmospheric CO_2 in the past two centuries. *Nature* 324:237–238
- Gessler A, Peuke AD, Keitel C, Farquhar GD (2007) Oxygen isotope enrichments of organic matter in *Ricinus communis* during the dial course and as affected by assimilate transport. *New Phytol* 174:600–613
- Granier A, Bréda N, Biron P, Vilette S (1999) Lumped water balance model to evaluate duration and intensity of drought constraints in forest stands. *Ecol Model* 116:269–283
- Granier A, Reichstein M, Bréda N et al (2007) Evidence for soil water control on carbon and water dynamics in European forests during the extremely dry year: 2003. *Agric For Meteorol* 143(1–2):123–145
- Green JW (1963) Wood cellulose. In: Whistler RL, Green JW (eds) *Methods in carbohydrate chemistry*. Academic, New York, pp 9–21
- Guiot J, Berger AL, Munaut AV, Till C (1983) Some new mathematical procedures in dendroclimatology with examples for Switzerland and Morocco. *Tree-Ring Bull* 42:33–48
- Guiot J, Nicault A, Rathgeber C, Edouard JL, Guibal F, Pichard G, Till C (2005) Last-Millennium summer-temperature variations in western Europe based on proxy data. *Holocene* 15(4): 489–500

- Hemming DL, Switsur VR, Waterhouse JS, Heaton THE, Carter AHC (1998) Climate and the stable carbon isotope composition of tree ring cellulose: an intercomparison of three tree species. *Tellus* 50B:25–32
- IPCC Climate Change (2007) The physical science basis. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK, 996 pp
- Jaggi M, Saurer M, Fuhrer J, Siegwolf R (2002) The relationship between the stable carbon isotope composition of needle bulk material, starch, and tree rings in *Picea abies*. *Oecologia* 131:325–332
- Jones PD, Briffa KR, Barnett TP, Tett SFB (1998) High resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with General Circulation Model control-run temperatures. *Holocene* 8:455–471
- Keeling CD, Whorf TP, Wahlen M, Plicht JV (1995) Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980. *Nature* 375:666–670
- Kelly PM, Leuschner HH, Briffa KR, Harris IC (2002) The climatic interpretation of pan-European signature years in oak ring-width series. *Holocene* 12(6):689–694
- Knöller K, Boettger T, Haupt M, Weise SM (2007) Routine hydrogen isotope measurements of cellulose nitrate by high temperature pyrolysis—reference materials and precision. *Rapid Commun Mass Spectrom* 21:3085–3092
- Kohn MJ, Welker JM (2005) On the temperature correlation of $\delta^{18}\text{O}$ in modern precipitation. *Earth Planet Sci Lett* 231(1–2):87–96
- Leavitt SW (2008) Current advances in tree-ring isotope dendrochronology and reconstruction of climatic conditions in recent centuries. In: Geol. Assoc. Canada annual meeting, 26–28 May 2008. SY4: recent advances in isotopic reconstruction of climatic changes over the last centuries - temperature and precipitation series. Quebec City, 26 May 2008
- Leavitt SW, Danzer SR (1993) Method for batch processing small wood samples to holocellulose for stable-carbon isotope analysis. *Anal Chem* 65:87–89
- Leavitt SW, Long A (1982) Evidence for $^{13}\text{C}/^{12}\text{C}$ fractionation between tree leaves and wood. *Nature* 298:742–744
- Legrand JP (1978) Fluctuations météorologiques, vendanges et activité solaire. *La Météorologie* VI(12):73–89
- Lipp J, Trimborn P, Fritz P, Moser H, Becker B, Frenzel B (1991) Stable isotopes in tree-ring cellulose and climatic change. *Tellus* 43B:322–330
- Livingston NJ, Spittlehouse DL (1996) Carbon isotope fractionation in tree ring early and late wood in relation to intra-growing season water balance. *Plant Cell Environ* 19(6):768–774
- Luterbacher J, Dietrich D, Xoplaki E, Grosjean M, Wanner H (2004) European seasonal and annual temperature variability, trends and extremes since 1500. *Science* 303:1499–1503
- McCarroll D, Loader NJ (2004) Stable isotopes in tree rings. *Quat Sci Rev* 23:771–801
- McCarroll D, Pawellek F (2001) Stable carbon isotope ratios of *Pinus sylvestris* from northern Finland and the potential for extracting a climate signal from long Fennoscandian chronologies. *Holocene* 11:517–526
- Mann ME, Bradley RS, Hughes MK (1999) Northern hemisphere temperatures during the past millennium: inferences, uncertainties and limitations. *Geophys Res Lett* 6(6):759–762
- Masson-Delmotte V, Raffalli-Delercé G, Danis PA, Yiou P, Stievenard M, Guibal F, Mestre O, Bernard V, Goosse H, Hoffmann G, Jouzel J (2005) Changes in European precipitation seasonality and in drought frequencies revealed by a four century long tree-ring isotopic record from Brittany, western France. *Clim Dyn* 24:57–69
- Meehl GA, Tebaldi C (2004) More intense, more frequent, and longer lasting heat waves in the 21st century. *Science* 305:994–997
- Menzel A (2005) A 500 year pheno-climatological view on the 2003 heatwave in Europe assessed by grape harvest dates. *Meteorol Z* 14(1):75–77
- Moberg A, Sonechkin DM, Holmgren K et al (2005) Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* 433:613–617
- Moisselin JM, Schneider M, Canellas C, Mestre O (2002) Les changements climatiques en France au XXe siècle: étude des longues séries homogénéisées de données de température et de précipitations. *La Météorologie* 38:45–56
- Mook WG, Koopmans AF, Carter AF, Keeling CD (1983) Seasonal, latitudinal, and secular variations in the abundance and isotopic ratios of atmospheric carbon dioxide 1: results from Land stations. *J Geophys Res* 88:10915–10933

- Nicault A, Rathgeber C, Tessier L et al (2001) Intra-annual variations of radial growth and ring structure. *Ann For Sci* 58(7):769–784
- Overpeck J, Hughen K, Hardy D et al (1997) Arctic environmental change of the last four centuries. *Science* 278:1251–1256
- Pal JS, Giorgi F, Bi XQ (2004) Consistency of recent European summer precipitation trends and extremes with future regional climate projections. *Geophys Res Lett* 31(13), Art. No. L13202
- Planton S, Terray L (2007) Détection et attribution à l'échelle régionale: le cas de la France. *La Météorologie* 58:25–29
- Polton JC (1995) Tourisme et nature au XIXe siècle. Guides et itinéraires de la forêt de Fontainebleau (vers 1820–1880). Edition du CTHS, Paris, p 295
- Raffalli-Delercq G, Masson-Delmotte V, Dupouey JL, Stievenard M, Breda N, Moisselin JM (2004) Reconstruction of summer droughts using tree-ring cellulose isotopes: a calibration study with living oaks from Brittany (western France). *Tellus* 56B:160–174
- Robertson I, Rolfe J, Switsur VR, Carter AHC, Hall MA, Barker AC, Waterhouse JS (1997a) Signal strength and climate relationships in the $^{13}\text{C}/^{12}\text{C}$ ratios of tree ring cellulose from oak in southwest Finland. *Geophys Res Lett* 24:1487–1490
- Robertson J, Waterhouse JS, Barker AC, Carter AHC, Switsur VR (1997b) Signal strength and climate relationships in $^{13}\text{C}/^{12}\text{C}$ of tree ring cellulose from oak in east England. *J Geophys Res* 102:19507–19516
- Robertson J, Waterhouse JS, Barker AC, Carter AHC, Switsur VR (2001) Oxygen isotope ratios of oak in east England: implications for reconstructing the isotopic composition of precipitation. *Earth Planet Sci Lett* 191:21–31
- Roden JS, Lin G, Ehleringer JR (2000) A mechanistic model for interpretation of hydrogen and oxygen isotope ratios in tree-ring cellulose. *Geochim Cosmochim Acta* 64:21–35
- Rozanski K, Araguas-Araguas L, Gonfiantini R (1993) Isotopic patterns in modern global precipitations. In: KLLPK Swart, McKenzie J, Savin S (eds) *Climate change in continental isotopic records*. AGU Geophysical Monograph, pp 1–37
- Saurer M, Siegenthaler U, Schweingruber F (1995) The Climate–Carbon isotope relationship in tree rings and the significance of site conditions. *Tellus* 47B:320–330
- Saurer M, Schweingruber F, Vaganov EA, Shiyatov SG, Siegwolf R (2002) Spatial and temporal oxygen isotope trends at the northern tree-line in Eurasia. *Geophys Res Lett* 29(10):1–4
- Schär C, Vidale PL, Lüthi D, Frei C, Häberli C, Liniger MA, Appenzeller C (2004) The role of increasing temperature variability in European summer heat waves. *Nature* 427:332–336
- Séchet G (2004) Quel temps! Chronique de la météo de 1900 à nos jours. Hermé, Paris, p 256
- Seneviratne SI, Lüthi D, Litschi M, Schär C (2006) Land-atmosphere coupling and climate change in Europe. *Nature* 443:205–209
- Sternberg L, De Niro M, Savidge R (1986) Oxygen isotope exchange between metabolites and water during biochemical reactions leading to cellulose synthesis. *Plant Physiol* 82:423–427
- Stuiver M, Burk RL, Quay PD (1984) $^{13}\text{C}/^{12}\text{C}$ ratios in tree-rings and the transfer of biospheric carbon to the atmosphere. *J Geophys Res* 89:11731–11748
- Switsur R, Waterhouse J (1998) Stable isotopes in tree ring cellulose. In: Griffiths EH (ed) *Stable isotopes*. BIOS Scientific, Oxford, pp 303–321
- Switsur R, Waterhouse JS, Field EM, Carter AHC (1996) Climatic signals from stable isotopes in oak trees from East Anglia, Great Britain. In: Dean JS, Meko DM, Swetnam TW (eds) *Tree rings, environment and humanity*. Radiocarbon. Department of Geosciences, University of Arizona, Tucson, pp 637–645
- Szczepanek M, Pazdur A, Pawelczyk S, Bottger T, Haupt M, Halas S, Bednarz Z, Krapiec M, Szychowska-Krapiec E (2006) 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
- Terwilliger VJ, DeNiro MJ (1995) Hydrogen isotope fractionation in wood-producing avocado seedlings: biological constraints to paleoclimatic interpretations of δD values in tree ring cellulose nitrate. *Geochim Cosmochim Acta* 59(24):5199–5207
- Treydte KS, Schleser GH, Helle G, Frank DC, Winiger M, Haug GH, Esper J (2006) The twentieth century was the wettest period in northern Pakistan over the past millennium. *Nature* 440:1179–1182
- Waterhouse JS, Switsur VR, Barker AC, Carter AHC, Robertson I (2002) Oxygen and hydrogen isotope ratios in tree rings: how well do models predict observed values? *Earth Planet Sci Lett* 201(1):421–430

- Wershaw RL, Friedman I, Heller SJ (1966) Hydrogen isotope fractionation in water passing through trees. In: Hobson F, Speers M (eds) *Advances in organic geochemistry*. Pergamon, New York, pp 55–67
- Williams DG, Coltrain JB, Lott M, English NB, Ehleringer JR (2005) Oxygen isotopes in cellulose identify source water for archaeological maize in the American Southwest. *J Archaeol Sci* 32(6):931–939
- Wilson AT, Grinsted MJ (1977) $^{12}\text{C}/^{13}\text{C}$ in cellulose and lignin as paleothermometers. *Nature* 265:133–135
- Yakir D, DeNiro MJ (1990) Oxygen and hydrogen isotope fractionation during cellulose metabolism in *Lemna gibba*. L. *Plant Physiol* 93:325–332