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Maximum growing season temperature in Western Europe: multi proxy reconstructions in Fontainebleau from 1596 to 2000

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Abstract

In this study, we have combined a Burgundy grape harvest date record with new δ^{18}O measurements conducted on timbers and living trees cellulose from Fontainebleau castle and forest. Our reconstruction is expected to provide a reference series for the variability of growing season temperature (from April to September) in Western Europe from 1596 to 2000. We have estimated an uncertainty of 0.55°C on individual growing season maximum temperature reconstructions. We are able to assess this uncertainty, which is not the case for many documentary sources (diaries etc.), and even not the case for early instrumental temperature data.

We compare our data with a number of independent temperature estimates for Europe and the Northern Hemisphere. The comparison between our reconstruction and Manley mean growing season temperature data provides an independent control of the quality of CET data. We show that our reconstruction preserves more variance back in time, because it was not distorted/averaged by statistical/homogenisation methods.

Further works will be conducted to compare the δ^{18}O data from wood cellulose provided by transects of different tree species in Europe obtained within the EC ISONET project and the French ANR Program ESCARSEL, to analyse the spatial and temporal coherency between δ^{18}O records. The decadal variability will be also compared with other precipitation δ^{18}O records such as those obtained from benthic ostracods from deep peri-Alpine lakes or simulated by regional atmospheric models equipped with the modelling of water stable isotopes.

1 Introduction

For the last millennium, the magnitude of temperature variability remains uncertain (IPCC, 2007). Multi-proxy reconstructions show a large dispersion in the estimated decadal and centennial temperature range. Recent studies have highlighted the intrinsic limitations of dendrochronological records on multi-decadal time scales, due to the requirement to correct for age effects on tree growth (Esper et al., 2002). The segment length of individual tree records is an upper limit to the longest periodicities potentially recorded in such records (Briffa, 2000). Classically, reconstructions are discussed for high and low frequencies, below or above 40 or 80 years. Methods have been developed to combine low and high frequency records at hemispheric (Moberg et al., 2005) or regional scale (Guiot et al., 1983). However, it remains essential to understand how the initial proxy records capture temperature variability at various time scales.

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., 1998; 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 are not represented in these quantitative reconstructions of recent temperature variations, such as temperate climate areas of France.

The exact dating of each tree-ring provides a perfect annual resolution and continuous records can be obtained over hundred years. Trees are widespread, and have been used as building material for centuries. Therefore, living trees and timbers offer many sampling opportunities. Although tree-ring densities and/or widths have been successfully used to reconstruct summer temperatures in high latitudes or altitudes where temperature is a limiting factor controlling tree growth (Briffa et al., 2001; Guiot et al., 2005), they do not provide reliable reconstructions of temperature in temperate areas, where tree growth reacts to a variety of environmental factors. It was however shown that *Quercus* sp. ring width may be partly controlled by drought (Briffa, 2000). The oxygen and carbon 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 analyses of cellulose stable isotopic rates make possible paleoclimatic reconstructions with annual resolution in temperate region without major tree age effects (Raffalli-Delerce et al., 2003; McCarroll and Loader, 2004). δ^{13}C of tree ring cellulose is a proxy for temperature, relative humidity and more generally water stress (Wilson et al., 1977; Freyer, 1979; Leavitt et al., 1982; Stuiver et al., 1984; Lipp et al., 1991; Dupouey et al., 1993; Saurer et al., 1995; Robertson et al., 1997a, 1997b; Hemming et al., 1998; Barbour et al., 2001; McCarroll et al., 2001). δ^{18}O of tree ring cellulose was used successfully for reconstructing the oxygen isotopic composition of the precipitation of the growing season and climate parameters (such as surface air temperature, relative humidity, water stress...) of past centuries (e.g. among the most recent: Anderson et al., 2002; Robertson et al., 2001; Saurer et al., 2002; Raffali-Delerce et al., 2003; Danis et al., 2006).

The harvest dates of "Pinot Noir" grapes in Burgundy (eastern France, ~250 km south east of Fontainebleau) were also shown to be a proxy for the mean atmospheric temperature of April to September (Chuine et al., 2004) and have inter-annual variations strongly related to Fontainebleau maximum temperature from April to September (Etien et al., 2007[1]). To our knowledge, Burgundy is the longest grape harvest dates series available in France (ininterrupted series from 1370 to 2003; Chuine et al., 2004).

A multi-proxy calibration of growing season (April to September) maximum temperature has been obtained in Fontainebleau region (northern France) (Etien et al., 2007[1]). Homogenised instrumental records of maximum monthly temperature are available in Northern France for the past century, as well as documentary records of grape harvest dates and proxy records of seasonal climate obtained by the analysis of latewood tree-ring cellulose isotopic composition (δ^{18}O and δ^{13}C) from 15 living trees (*Quercus r.*) sampled in the Fontainebleau forest. Multiple linear regression statistical analyses

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[1] Etien, N., Daux, V., Guillemin, M. T., Masson-Delmotte, V., Stievenard, M., Breda, N., Boettger, T., Haupt, M., Mestre, O., 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), Clim. Change, in review, 2007.

have been used to assess the response function of documentary and tree-ring isotopic records to growing season maximum temperature. We have demonstrated that a significant proportion of climatic variability (R^2=0.66) can be reconstructed using a linear regression model of grape harvest dates, cellulose δ^{13}C and δ^{18}O (Etien et al., 2007[1]). It shows the potential of multiple proxy reconstructions to assess the past fluctuations of growing season maximum temperature prior to the instrumental period. Here, this calibration will be applied to the reconstruction of April to September maximum temperature in Fontainebleau area using a series of carbon and oxygen isotopic compositions of historical building timbers sampled in the Fontainebleau castle and Burgundy grape harvest dates from 1596 to 1899. Based on available meteorological data, interannual variations in Fontainebleau growing season temperature should be representative of a larger area from south-western France to North of Germany (Etien et al., 2007[1]).

The power spectrum of the multiple Fontainebleau tree-ring records will be linked with the power spectrum of the Burgundy historical grape harvest record and the temperature reconstruction derived from the linear regression model described in Etien et al. (2007)[1]. The originality of this analysis is the use of raw tree ring isotopic data, without any standardisation: we take advantage of the annual resolution of the records and assume limited age effects.

Our multi-proxy reconstruction is finally compared to the different temperature reconstructions available for Europe and Northern Hemisphere for the period 1600 to 1900. Therefore, reconstructions of past temperature at Fontainebleau will help understanding climatic variations on a much broader scale and to fill a geographical gap in European climate reconstructions (Luterbacher et al., 2004; Guiot et al., 2005).

2 Material and method

2.1 Sampling site

In this section, we focus on the region near Fontainebleau, northern France (Fig. 1). 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.

Fontainebleau is located in northern France (2.67° E, 48.38° N) between the Gatinais and Briard plateau and the Brière plain (Fig. 1). 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. At present day, the Fontainebleau forest covers a 280 km^2 area and culminates at 144 m above sea level. Stampian limestones form the substrates and oak roots develop in a loamy soil. For this study, the building wood is assumed to originate from forests of the neighbourhood. Fieldwork was achieved with the support of Office National des Forêts and the Conservation du Musée-Château de Fontainebleau. In Fontainebleau forest, 15 trees were sampled in year 2000 (3 cores at 120° per tree at DBH) and cover the time period from 1829 to 2000. For older periods, we have sampled timbers from historical buildings in Fontainebleau's castle: 5 timbers from "salle des Bals" (ballroom) and "Clocher" (steeple) (spanning the time period from 1596 to 1743). 9 timbers from "Théâtre" (theatre) (dated from 1748 to 1850) and 4 timbers from "Petites Ecuries" (little stables) (dated from 1596 to 1750). We sampled cores with diameters ranging from 5 to 8 mm. Meteorological data are available from the nearest weather station (La Faisanderie, located about 2 km to the east of Fontainebleau town where beam were sampled in the castle).

2.2 Fontainebleau Forest and Castle history

In order to expand the isotopic records obtained from living trees, we have made the hypothesis that the *Quercus* sp. timber wood of historical buildings from the Château de Fontainebleau (Fontainebleau Castle) was provided by trees felled down in the surrounding Fontainebleau forest.

The first historical descriptions of a castle in Fontainebleau are found in documentary sources from the 12th century. Without a precise knowledge of date of foundation works, it is known that there was already a fortified castle. The only remain from this initial building is the keep of the Oval yard, where many French kings lived: Philippe-Auguste (1165–1223), saint-Louis (1214–1270) and Philippe Le Bel (1268–1314). In 1259, the castle was transformed into a convent-hospital, entrusted to the Order of the Holy Trinity.

Much later, during the Renaissance, the castle experienced spectacular transformations. François (I) (1494–1547), King of France, launched in 1528 the reconstruction and the renovation of the castle. Preserving the Middle Age keep, he ordered the construction of groups of buildings on the Oval yard: Porte Dorée ("Golden Gate"), Salle de Bal ("ballroom") and Saint-Saturnin chapel; groups of buildings forming the present-day White Horse yard, on a land bought from the Order of the Holy Trinity; and the gallery called "François Ier" that linked the two sets of buildings. At his death, his son Henry the 2nd (1519–1559) and Catherine de Médicis (1519–1589) expanded this work and added new buildings in the Fountain Yard. At the beginning of the 18th century, a major fire devastated many buildings of the Fontainebleau Castle (V. Droguet, personal communication).

Our timber wood sampling was focused on the frame of four sites: ballroom (Salle de Bal), steeple (Clocher), little stables (Petites Ecuries) and theatre (Théâtre). Dendrochronological results reveal three main sets of ages. The first set of data corresponds to beams from the Salle de Bal (1596–1743), Clocher (1598–1698) and Petites Ecuries (1596–1750). The construction of the ballroom, located on the first floor of the south wing of the Oval yard, started in 1528 under the reign of François (I) and ended in 1550 under Henry (II). The construction of the steeple, above the Trinity Chapel, was also ordered by Henry (II) and was finished in 1550. The historical construction dates do not systematically coincide with the dating of our beam samples (1596–1743). The steeple was devastated by the 18th century fire and its frame had to be completely rebuilt. However, the ballroom was not struck by this fire and no reconstruction is documented in the castle annals. Finally, historical sources confirm the building of the little stables in the course of the 18th century (V. Droguet, personal communication).

Therefore, trees felled down in the 18th century provided this first set of timbers for the reconstruction of three different buildings. This hypothesis is also consistent with documentary sources describing the use of the Fontainebleau woodland (National Forest Office documents).

Due to its climatic and geological context, this woodland was dominated by *Quercus* sp., with a spontaneous growth and representing always at least 60% of the trees. In 1848, the forest management was transferred to the national level, after three earlier series of reformations (in 1664, 1717 and 1754). In 1664, the forest description was alarming. Half of its area was cleared of trees and only 13% of its surface had mature plantations. This resulted from common practice pasture (more than 12000 cattle and 6000 pigs), from game damage and from numerous forest fires. The exceptional 1709 winter frost further killed many trees. It must be noted that, since 1566, the woodland had been declared as a royal domain and could not be exploited. The few mature plantations belonged to the King of France who could use them at his convenience.

The 9 timbers sampled in the Petites Ecuries, Salle de Bal and Clocher span a time period from 1596 to 1750 and all the corresponding trees had at least 40 years in 1664, therefore corresponding to the few mature plantations of that time.

The second series of timber wood samples corresponds to timbers cored in the roof of the Théâtre (1748–1850). After the plundering of the French Revolution, mainly affecting furniture and decoration, the 19th century was a period of limited reconstructions. However, Napoleon (III) ordered the construction of a theatre in buildings from the north wing of the main yard dating from the 1770s. The frame of that building was completely renovated during the construction of this theatre (V. Droguet, personal communication) and documentary sources are fully consistent with the dendrochronological data. These samples therefore correspond to trees cut in the 1850s. It must be noted that, from 1716 to 1853, the Fontainebleau forest was the object of an uninterrupted and intense artificial repopulation operation. Due to the difficulty to succeed in creating deciduous repopulations, there was a transient introduction of *Pinus* sp. trees, only conserved as a definitive species in poor soils. The period covered by the samples taken from the Théâtre beams (1748 to 1850) correspond to the years when the forest management was strongly controlled and oriented towards the repopulation of deciduous plantations (Guignan, 2004). We managed to core at least four beams in order to get more than four samples per year. This requirement could not be satisfied over the periods 1596 to 1610 and 1733 to 1759.

The last set of tree samples is provided by direct sampling of living Fontainebleau forest *Quercus* r. (1829 to 2000) (Etien et al., 2007[1]); these trees have grown in a managed forest.

2.3 Sample preparation

Each ring of our samples has first to be dated. The basic principle of cross dating depends on special growth conditions of pointer years, which, according to their intensity or duration, produce extreme thin or large rings (Fritts, 1976; Schweingruber, 1985; Schweingruber et al., 1990). In temperate climates, trees make a new ring every year whose width varies with multiple factors amongst which climate predominates, and where thinning and biotic attack may have important consequences as well. By measuring and analyzing growth rings of tens of trees, a reference year-by-year growth index can be established for each species and region. The sampling of woods of different ages enables the correlation between each growth sequence and the construction of a continuous chronology.

Living oak tree rings were cross-dated by the Phytoecology team of INRA Nancy and late and total wood with the help of a master series constructed with more than 400 oaks from Fontainebleau Forest (Etien et al., 2007[1]). On average, these dominant trees are 150 years old (data set from 1829 to 2000). Dating of beam wood samples of the "Château de Fontainebleau" was done in collaboration with dendrochronology laboratories from the University of Rennes (V. Bernard) and Besançon (S. Durost).

All the samples were compared with each other. When an undated sample or site sequence is compared against a dated sequence, known as a reference chronology, an indication of the cross-matching quality must be determined. We use one of the cross-correlation algorithms most commonly used and published, derived from Baillie and Pilcher's CROS programme, based on the Student's t-test (Baillie and Pilcher, 1973). From statistical theory, t-values over 3.5 should be considered as significant, although in reality dendrochronologists prefer to see t-value ranges of 5, 6, and higher, and for these to be well replicated from different, independent chronologies with local and regional chronologies well represented. Examples of spurious t-values in excess of 7 have been noted, so it is essential that cross-matching with reference chronologies be well replicated, and that this is confirmed with visual matches between the two graphs.

It is general practice to cross-match samples from within the same phase to each other first, combining them into a site master, before comparing with the reference chronologies. This presents the advantage of averaging out the 'noise' of individual trees and is much more likely to obtain higher t-values and stronger visual matches. In Fontainebleau, tree-ring cross-matching reveal two sets of ages. The first set corresponds to the timbers coming from the Salle de Bal (1596–1743), Clocher (1598–1698) and Petites Ecuries (1596–1750). The second one corresponds to the beams sampled in the frame-roof of the Théâtre (1748–1850).

In reality, the probability of a particular date being valid is itself a statistical measure depending on the t-values. Consideration must also be given to the length of the sequence being dated as well as those of the reference chronologies. A sample with 30 or 40 years growth is likely to match with high t-values at varying positions, whereas a sample with 100 consecutive rings is much more likely to match significantly at only one unique position. Samples with ring counts as low as 50 may occasionally be dated, but only if the matches are very strong, clear and well replicated, with no other significant matching positions. Here, it is essential for intra-site matching when dealing with such short sequences. Consideration should also be given to evaluating the reference chronology against which the samples have been matched: those with well-replicated components which are geographically near to the sampling site are given more weight than an individual site or sample from the opposite end of the country. In spite of the problems of heterogeneity between the old stand of the 16th century with slow radial increments and the young of the 18th century with fast radial increments, the cross-matching of the local tree-ring chronology with that built by J. Pilcher from very ancient living oaks (>400 years) validate the dating (Bernard, 1998; Pilcher, 1987; http://www.ncdc.noaa.gov/paleo/ftp-treering.html) (Table 1). The visual agreement between ring-width curves from Fontainebleau and regional chronologies is backed up by t-values above 7 (Table 1).

Due to strong age effects, it is well known that ring widths cannot be used directly as climatic proxies. Here, we have used the following procedure to obtain average growth indices for the 15 trees and the 18 beams sampled:

- For each tree and beam, second order polynomial regressions were calculated;
- Individual growth records were corrected from these polynomial fits;
- The average of the detrended records provides our growth index time series (hereafter called GI).

The ring widths and GI variation through time is represented in Fig. 2a. The growth index varies between −112.9 and +151.1, with, by construction, a mean value of 0. The mean GI is calculated as the average of all the individual sample GI. This average GI is affected by the introduction of different samples. As a result, this average GI cannot be as pertinent as signals obtained from RCS methods (Guiot et al., 2005) for climate reconstructions. Even after correction for growth heterogeneities and detrending, GI shows no clear relationships with temperature (Etien et al., 2007[1]).

2.4 Isotopic analyses

Each ring was cut with a scalpel under a binocular magnifier to separate late wood from early wood. Early wood is elaborated 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 maximize the signature of environmental parameters of the growing season, we have systematically separated the latewood from the earlywood in each ring and used only latewood for isotopic ratio measurements. Tree-rings formed in the same calendar year were pooled together. 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 α-cellulose extracted from wood according to the SOXHLET method elaborated by Green (1963) and modified by Leavitt and Danzer (1993). 50% of sample mass is lost at the end of the treatment. In the case of the narrowest rings, the remaining mass of individual ring may be as small as 2 mg.

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$^{\circledR}$ elemental analyser coupled to a Finnigan MAT252 mass spectrometer (at LSCE, Gif/Yvette, Fr) according to the procedure described in Raffalli-Delerce et al. (2003). We use an internal laboratory reference (Whatmann$^{\circledR}$ CC31) of cellulose which has been intercompared for δ^{13}C and δ^{18}O between the European laboratories involved in the ISONET European project (Boettger et al., 2007). CC31 is analysed, once for 3 samples along the sequences of analyses. The measured sample values are corrected from the accepted values of the reference (–25.54‰ for δ^{13}C and +31.85 ‰ for δ^{18}O). The calibration of the mass spectrometer coupled to the elemental analyser is conducted with the laboratory standards (CC31). We obtain a standard deviation of ±0.25‰ for δ^{18}O and ±0.10‰ for δ^{13}C on the measurement of the isotopic composition of 10 consecutive CC31 standards (0 to 2 values being rejected). When this repeatability condition is established, the samples are analysed. The analysis of carbon and oxygen isotopes of each sample is repeated at least once and up to four times. Repeated measurements are conducted so that outlier measurements are rejected and standard deviations of final isotopic measurements of ±0.25‰ for δ^{18}O and ±0.10‰ for δ^{13}C measurements of each sample are obtained. Altogether, with replication, more than 3000 measurements were conducted on individual tree or beam cores.

Where the records of the different sites overlap and enough matter is available, their respective tree-rings were not pooled in order to test the signal coherency (Fig. 2b). There is an overlap of 24 years between the δ^{13}C data obtained for the combined set Clocher and Salle de Bal with the site Petites Ecuries (from 1698 to 1721) and an overlap of 22 years between the site Théâtre and the period covered by living trees data (1828 to 1849). The mean value of δ^{13}C for the 24 years overlap is −24.35‰ for samples from Salle des Bals and Clocher site and −23.70‰ for samples from Petites Ecuries site. For the 22 years of overlap, the mean value of δ^{13}C is −23.85‰ for beams of Théâtre site and −23.55‰ for living trees. The observed shifts (0.65‰ and 0.3‰) between the different parts of the record are more than twice the value of analytical precision and are considered as significant.

δ^{13}C variability between individuals growing under similar conditions seems to be characteristic of C3 plant in general and the variability of the results is not improved by any treatment (using wholewood, holocellulose or α-cellulose) (Van de Water et al., 2002). Several studies that have used individual trees, as opposed to pooled samples, report age related trends in carbon isotopic ratios (e.g. McCarroll and Pawelleck, 2001; Raffalli-Delerce et al., 2003; Masson-Delmotte et al., 2005). Tree-age effect appears as a rise in δ^{13}C followed by a decline and has been attributed to different factors such as changes in access to light, CO_2 isotopic composition gradients, or changes in tree hydraulic conductivity along its growth (see for instance Schleser and Jayasekera, 1985;

Cernusak et al., 2001; McDowell et al., 2002; Schäfer et al., 2000; Monserud and Marshall, 2001). From the estimates of beam ages, it is expected that the trends observed from sets "Clocher and Salle de Bal" and "Théâtre" should be affected by age effects (Fig. 2b), but this age effect cannot account for the observed δ^{13}C trend measured on the set from "Petites Ecurie" (Fig. 2b). When coring beams, it is possible that the core is too short and does not span the first rings of the tree, inducing wrong estimated of tree age. Moreover, our analytical procedure requires enough matter to conduct replicate cellulose δ^{13}C and δ^{18}O analysis, and we therefore cannot work on individual beam samples. As we do not have enough beam matter to produce individual records, we cannot assess the precise source for ^{13}C trends (inter-beam variability for instance) or perform a rigorous correction for juvenile effects. Over the instrumental period, standardisation methods have been previously applied for tree-ring δ^{13}C records, in order to analyse the climate signal preserved in tree-ring δ^{13}C (see McCarroll and Loader, 2004, for a review). Such standardisation methods remain however questionable when analysing climate changes reflected in low-frequency variations in the absolute isotopic ratios in trees. We therefore remain cautious about the decadal or longer fluctuations of our stacked δ^{13}C record, due to significant shifts between individual trees, small sets of trees, and possible age effects.

Due to the lack of material, it was not possible to produce similar inter-site comparisons for δ^{18}O data. A very short comparison is restricted to a 7 years overlap (1844–1850) corresponding to the Théâtre site and living trees. The mean value of δ^{18}O signal for this overlap period is 31.26‰ for beams of Théâtre site and 30.80‰ for living trees. However, our δ^{18}O measurement methodology provides us an uncertainty of ±0.25‰ (Etien et al., 2007[1]). At most, the sum of the uncertainties between the two signals (beams and living trees) reaches ±0.5‰. The difference between δ^{18}O signals of this overlap is 0.46‰. The difference between fossil oaks and living trees signals is not significant if we consider the maximal uncertainties on measurements. Overlap periods are highlighted in Fig. 2b. Etien et al. (2007)[1] have shown that for the living Fontainebleau oaks, samples of three pooled trees are appropriate to reconstruct the local oxygen isotopic composition. As already mentioned, in this study, the number of different trees (or beams) pooled to make a sample is superior to 3 except between 1596 to 1610 and 1733 to 1759.

The four hundred years long signal (as shown in Fig. 3a) is produced by averaging the yearly values of carbon and oxygen of the different sites when measured separately.

2.5 Grape harvest data

In France, harvest dates (minimum authorized harvest date) have been ordained by regional authorities at least since the early 13th century in Burgundy (Beaune municipal archives), and have been carefully registered in parochial archives and later in municipal archives. Vine harvest date records are handwritten, have absolute chronologies and are homogeneous in time (Chuine et al., 2004). Vine development annual cycle strongly depends on climate conditions. Grape harvest dates are influenced by the temperature from March/April to August/September, earlier harvest dates occurring during warm spring and summer years (Le Roy Ladurie et al., 2006). 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 maximum atmospheric temperature from April to September ($R=-0.71$) (Etien et al., 2007[1]). The main series was constructed from an ensemble of incomplete harvest dates series published in registers of 16 cities or villages in Burgundy (Fig. 2c). For periods where several documentary sources are available, the Burgundy grape harvest date is obtained by using the median of the local dates. Dates are expressed as a delay with regard to 31 August (Le Roy Ladurie et al., 2006). This Burgundy series is available from the 14th century to 2003 (Chuine et al., 2004). The error, shown in Fig. 2c, is calculated using the maximum standard deviation between local series overlapping (at most 3 days). This maximum deviation, unchanging from 1354 to 2006, is applied to the whole series. Although the grape harvest date record has exhibited a good potential to quantify past temperature changes, such historical data can be biased by anthropogenic, non climatic, effects (Daux et al., 2007). Historians have for instance shown that Burgundy wine producers may have systematically delayed their harvests in order to obtain good quality wines, with high alcohol content, as expected by Burgundy wine consumers (Le Roy Ladurie et al., 2006).

3 Results

3.1 Proxy records

Here, we restrict the description of variability and trends to proxy records measured from 1596 to 2000 (δ^{18}O, Burgundy grape harvest dates, and δ^{13}C). Figure 3a displays these key data sets.

In Fontainebleau, latewood δ^{18}O ranges from 29.1‰ to 33.2‰ with an average level at 31‰±0.7‰. The low frequency component of δ^{18}O has been calculated using a Singular Spectrum Analysis performed using the Spectra software (Ghil, 1997b). This analysis highlights a step increase between a first plateau from 1596 to 1743 with an average δ^{18}O of ~30.8‰ and a second plateau from 1812 to 2000 with an average δ^{18}O reaching 31.3‰. δ^{18}O values are not auto correlated with previous year values. An important result is that our data show without ambiguity a 0.5‰ δ^{18}O increase in the end of the 18th century. One could argue that this isotopic change could be caused by different origins of the timber wood samples. Indeed, isotopic analyses conducted on individual tree samples from living trees in Fontainebleau Forest have shown that inter-tree differences of δ^{18}O can reach 0.54‰ (Etien et al., 2007[1]). Here we can rule out a "tree effect" because the δ^{18}O data exhibit similar mean isotopic levels in the beginning of the 18th century (Theater samples) than over the previous centuries (Salle de Bal, Clocher and Petites Ecuries samples). Because the period of strong δ^{18}O increase corresponds to a common timber wood origin with 9 beams (Theater samples), the signal is not likely to be due to sampling effects but to real climate effects. Finally, the δ^{18}O record shows a linear increase of 0.15‰ over the past 50 years and of 0.89‰ over the past 20 years (almost 2 standard deviations above the 20th century level)

(Etien et al., 2007[1]). The 15 years running mean curve has reached an unprecedented level (>31.5‰) in 1992 (Fig. 3a).

Figure 3a displays interannual fluctuations of Burgundy grape harvest dates. These dates occur in average 27 days after 31 August and display a significant range of interannual fluctuations (up to 57 days). Grape harvests were shifted towards earlier dates by 11 days over the past 50 years (the extreme warm year 2003 is not included in Fig. 3a for grape harvest dates). Similarly to δ^{18}O, grape harvest dates show no auto correlation. The 15 years running mean curve shows that the wine grapes have been harvested as early as they are presently only once during the last 400 years (around 1685). Let us note that δ^{18}O and grape harvest exhibit different features: the level of the δ^{18}O has been particularly high over the last 15 years and its increase rate over the last 50 years has been moderate; the value of the grape harvest date has been high over the last fifteen years, but not unprecedented, but its increase rate has been the highest of the last 400 years.

The mean Fontainebleau δ^{13}C is −23.7±0.6‰ and varies from −26.3 to −22‰. The signal shows no trend over the past 50 years. Tree-ring δ^{13}C data should, in principle, be corrected for the progressive 1‰ decrease of atmospheric $CO_2\delta^{13}C$ 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). We take into account latitudinal and seasonal fluctuations of $CO_2\delta^{13}C$ to obtain a correction suitable for Northern Hemisphere mid-latitude growing season (M. Leuenberger calibration data, ISONET program) following Masson-Delmotte et al. (2005). Hereafter, we use the corrected record of the isotopic composition of cellulose ($\delta^{13}C_{corr}$) which refers to the δ^{13}C values corrected from $CO_2\delta^{13}C$ recent trend. The mean Fontainebleau $\delta^{13}C_{corr}$ is −23.5±0.7‰ and ranges from −25.8 to −21.6‰, with a linear increase of 1.43‰ over the past 50 years (mainly due to a step increase in the late 1970s). By contrast with grape harvest dates and cellulose δ^{18}O, δ^{13}C shows a significant auto correlation (n=1997, R^2=0.22 with one year lag and 0.20 with two year lag). Figure 3a shows clearly the strong influence of wood sample number and origin on δ^{13}C records (as mentioned above in Sect. 2.4).

Figure 3b presents Grape harvest dates, δ^{18}O, Fontainebleau reconstructed T_{max} AMJJAS and Central England T_{mean} AMJJAS records for the period from 1600 to 1800. The comparison between the variability of each parameter will be discussed in Sect. 3.3.

3.2 Calibration

Multiple linear regression were performed in the calibration study (Etien et al., 2007[1]) to assess the response of environmental records (δ^{13}C, δ^{18}O, δ^{2}H, Burgundy and Argenteuil grape harvest dates, tree-ring growth indices of Fontainebleau forest oaks and number of fire starts in the Fontainebleau forest) to climatic fluctuations of the past century. Correlations between environmental parameters and proxy records were systematically tested by using the R software (http://www.r-project.org/). This statistical analysis highlighted one climate variable, the maximum growing season temperature (from April to September, hereafter called T_{max} AMJJAS) which exhibits the most robust correlation with tree ring isotopic data and documentary records. A methodology combining available proxy records to estimate past variations of T_{max} AMJJAS was also proposed (Etien et al., 2007[1]).

For the Fontainebleau site, only four of these parameters mentioned above are available until 1596: δ^{18}O, δ^{13}C, growth indices and Burgundy grape harvest dates (GHD). Following Etien et al.'s approach, we use an Akaïke test to construct the most efficient set of proxy records. The lowest Akaïke Information Criterion (best combination of proxies, (Akaïke, 1973) is obtained while combining Burgundy grape harvest dates, δ^{18}O and $\delta^{13}C_{\text{corr}}$ of oak cellulose. The relationship between T_{max} AMJJAS and these parameters is:

$$T_{\text{max}}\ \text{AMJJAS} = 4.16 + 0.12 \times \delta^{13}C_{\text{corr}} + 0.70 \times \delta^{18}O - 0.08 \times \text{GHD} \quad (1)$$

The multiple determination coefficient (R^2) is equal to 0.590, the adjusted R-squared is equal to 0.576 and the R correlation between reconstructed and instrumental $T_{\max}$ AMJJAS data of calibration period is 0.768. The probability of a type I risk is 0.298, $3.6.10^{-6}$ and $1.28.10^{-10}$ for $\delta^{13}C_{corr}$, $\delta^{18}O$ and GHD respectively. As $\delta^{13}C$ corresponds to the highest risk and is a parameter potentially affected by disruption factors (CO_2 effect, age effect, wood origin, see Sects. 2.4 and 3.1) we tested the relevance of removing it from the multiple parameters regression. Equation (1) transforms to:

$$T_{\max}\ \mathrm{AMJJAS} = -0.013 + 0.75 \times \delta^{18}O - 0.08 \times \mathrm{GHD} \qquad (2)$$

The multiple determination coefficient (R^2) is equal to 0.585, the adjusted R-squared is equal to 0.576 and the R correlation between reconstructed and instrumental $T_{\max}$ AMJJAS data is 0.765. The probability of a type I risk is $2.6.10^{-7}$ and $5.7.10^{-11}$ for $\delta^{18}O$ and GHD, respectively.

The strength of the relationship is nearly the same with or without the $\delta^{13}C_{corr}$ proxy. Therefore, we decided to build reconstructions based on $\delta^{18}O$ and GHD only, in order to avoid the problems caused by age-related trends of $\delta^{13}C$. We have tested that there is no significant differences on the reconstructed temperatures when using the high frequency component of corrected $\delta^{13}C$. Moreover, the lowest Akaïke Information Criterion is not obtained while combining Burgundy grape harvest dates, $\delta^{18}O$ and detrended $\delta^{13}C_{corr}$ of oak cellulose.

The confidence interval (mean difference between homogenised and reconstructed $T_{\max}$ AMJJAS) was obtained using a bootstrap methodology with 1000 experiments and is estimated to be ±0.55°C. This "linear model" uncertainty has to be compared to the analytical $\delta^{18}O$ measurements uncertainty (±0.25‰) (Etien et al., 2007[1]), inducing reconstruction error of up to ±0.19°C. Uncertainties may also arise from the variability of $\delta^{18}O$ between different trees. However, it was shown that a mean offset of 0.13‰ is observed between two groups of 15 trees growing in similar environmental conditions and that in more than 87% of the case, the $\delta^{18}O$ inter-parcel difference is less than the analytical precision (Etien et al., 2007[1]). Unfortunately, this variability can increase to a significant degree (from ca. 0.1‰ up to 0.5‰) when the growing conditions are restrictive (Etien et al., 2007[1]). In this case, the error introduced on the reconstructed temperature can reach ±0.38°C (including both analytical precision and dispersion between neighbouring trees). Grape harvest dates are expressed as a delay with regard to 31 August (Le Roy Ladurie et al., 2006), with an error of three days (see Sect. 2.5), which can induce a reconstruction error of up to ±0.24°C. At most, the sum of these uncertainties reaches ±0.62°C, a magnitude comparable to the "linear model" bootstrap uncertainty.

The minimum uncertainty of 0.55°C, calculated with the bootstrap method, is an uncertainty in the linear reconstruction model fitting and does not include all the measurements errors as variability between various samples for extreme years and instrumental biases of ancient thermometers and measurements conditions.

For the instrumental period only, Fig. 4 shows the R^2 coefficients of the correlations between δ^{18}O, grape harvest dates, reconstructed T_{max} AMJJAS and homogenised instrumental T_{max} AMJJAS. On average, from 1880 to 2000, R^2 coefficients are, respectively, of 0.37 for δ^{18}O, 0.52 for grape harvest dates and 0.62 for reconstructed T_{max} AMJJAS with respect to instrumental T_{max} AMJJAS. We have analysed the stability of these correlations over sub-intervals of 30 years. The time period from 1910 to 1940 appears as remarkable due to minimal correlation coefficients, the lowest (δ^{18}O versus measured T_{max} AMJJAS) reaching R^2=0.21 (R^2 is significant above 0.21, n=30, p=0.01 according to a Student test). The poor correlation of the records could be linked to the historical context of this 30 years time period spanning World I and II. It cannot be excluded that missing data alter the quality of instrumental record homogenisation during this time period and therefore that the lower correlation may result from homogenised data.

3.3 Reconstruction and comparison with other reconstruction

Figure 5a displays Fontainebleau T_{max} AMJJAS reconstruction described in Eq. (2). Reconstructed maximum growing season temperature range from 18.3°C to 24.6°C with an average level at 21.1±0.55°C. The 15 years running mean curve shows that the reconstructed temperature has reached since 1994 a mean level of 22°C, a value never observed before. An important result is that our data show without ambiguity a 0.8°C increase for the time period from 1975 to 2000. This recent trend is common to the 2 proxies used in the reconstruction: the δ^{18}O record shows a linear increase of 0.89‰ over the past 20 years, and grape harvests were shifted towards earlier dates by 13 days since 1963. Extreme years have been detected using each proxy, assuming that an extreme year is defined as deviation above or below the average parameter by more than 1.5 standard deviation. These extreme years are reported on Fig. 3a. The years recognised as extreme are not the same in δ^{18}O and grape harvest dates records (only 1686 and 1893 are shared). For the instrumental period, the agreement between δ^{18}O and measured $T_{\max}$ AMJJAS is only 22%, and 75% between GHD and measured $T_{\max}$ AMJJAS. Obviously, the δ^{18}O proxy is not highly capable in extreme values reconstruction. This is in agreement with Etien et al. (2007)[1] who concluded that the inter-tree isotopic variability increased during extreme years leading to a deteriorated accuracy of the δ^{18}O values. Nevertheless, for instrumental period, all the extreme warm values in the δ^{18}O record correspond to hot (above 1 standard deviation in the measured $T_{\max}$ AMJJAS series) or dry years (as 1918 or 1989).

We compare the decadal-scale fluctuations which are common to both proxy records and therefore appear clearly in the reconstruction. This is the case for warm episodes of the 1610s, 1640s, 1660s, 1900s, 1950s. Such periods have been described by Le Roy Ladurie et al. (2006) and compared with Alpine glacier retreats observed in the 1640s, 1860s. Our growing season maximum temperature reconstruction for Fontainebleau therefore captures some warm summers that may be linked to phases of Alpine glacier retreat in the middle 17th century and with the end of the Little Ice Age.

The decadal coherency between δ^{18}O and grape harvest dates disappears during the interval from 1770 to 1870. This mismatch partly arises from different centennial trends described in Sect. 3.1. Indeed, δ^{18}O data clearly show an increasing (warming) trend, while harvests occur later ("cooling trend"). Extrem warm years may be associated with specific timing of heat waves, which can affect differently cellulose δ^{18}O and grape harvest dates if they occur at the flowering season or the time of maximum photosynthesis. Specific hydrological effects are also expected to have different imprints on proxy records. We have shown that our δ^{18}O trend is not affected by tree sampling. By contrast, historical studies (Le Roy Ladurie et al., 2006) suggest that grape harvest dates were likely influenced by anthropogenic effects. Wine producers, in particular those managing the best Burgundy vineyards, indeed tended to modify their practices to adjust their quality to the consumer demand. Grape harvest dates were artificially delayed to obtain higher sugar contents and therefore wines with higher alcohol proof.

Figure 3b highlights the variability of Central England T_{mean} AMJJAS, Fontainebleau reconstructed T_{max} AMJJAS, δ^{18}O and grape harvest dates records from 1660 to 1800. Periods of early harvesting mentioned by Le Roy Ladurie (2006) are also indicated by vertical grey bars. These group of years do not systematically coincide with extreme warm temperatures (as it had been previously defined); however, they coincide with warm years in terms of grape harvest dates, δ^{18}O, Fontainebleau reconstructed T_{max} AMJAS and Central England T mean in most cases (7 years out of 8, with the exception of 1662–1671). The vertical blue bar displays the cold period of 1687 to 1700 and highlights cold trends in each parameter. Two other cold episodes can be observed in the intervals: 1671–1676 and ~1770. Vertical red lines are displayed for specific warm events such as the beginning of the Grindelwald glacier retreat, starting in 1640 (Zumbühl, 1980) or the growing seasons of 1788 et 1794 documented as very dry and hot with an exceptionnal intra-annual meteorological variability. Figure 3b shows that such intra-annual variability results in a lack of coherency between grape harvest dates and δ^{18}O. Finally, vertical dashed bars are used to show the time period where changes in agricultural practices are documented and are expected to affect strongly grape harvest dates.

Using proxies with different centennial trends for the reconstruction leads to smooth the variability. As a result, our multi-proxy reconstruction only captures a weak centennial trend over the late 18th–19th centuries. At this stage, we have just used the inter-annual calibration. It could be possible to refine the methodology by keeping low frequency component of grape harvest dates, following the approach of Moberg et al. (2005) and Guiot et al. (1983).

In the beginning of this section, we have discussed the relevance of our record in terms of past changes in temperature, addressing changes in mean state and inter-annual variability. In principle, it would be of major interest to compare this reconstruction with direct instrumental measurements. However, no homogenised temperature record is available for central or western France prior to 1873 (Paris Montsouris), and no temperature record is available prior to 1659 (CET Manley, 1974). Having shown that Fontainebleau growing season temperature (T_{max} AMJJAS) is well correlated (R^2>0.80) with 20th century temperature from South-Western France to Northern Germany (Etien et al., 2007[1]), we have searched long homogenised temperature data in North-Western Europe. We have therefore used two datasets of ancient instrumental meteorological observations from other regions: Central England temperature record from Manley (1974), from 1659 to 1973, updated by Parker et al. (2005), and De Bilt data from the Netherlands, updated with the EC EMULATE project (http://www.cru.uea.ac.uk/projects/emulate/) from 1706 to 2006. Ancient instrumental mean growing season temperature series of Central England (T_{mean} AMJJAS) range from 10.9 to 14.9°C with an average level at 13.6±0.7°C (T_{max} AMJJAS ranges from 14.9 to 19.7°C with a mean value of 17.4±0.9°C). The T_{mean} AMJJAS of De Bilt series is 13.9±0.7 and varies from 11.7 to 16.2°C (T_{max} AMJJAS ranges from 16.9 to 21.9°C with an average level at 19±0.9°C). Our calibration is designed to reconstruct maximum temperatures. The oldest homogenised Central England and De Bilt temperature series are only available for T_{mean} AMJJAS. For the periods when both T_{mean} and T_{max} are available, they show a good correlation (R^2=0.80 and 0.94, respectively, for De Bilt and Central England) (Fig. 5a). Being aware of this, we compare our reconstruction with early instrumental T_{mean} data.

In order to assess the reliability of our proxy record, we have compared some of the results with available past temperature reconstructions. Among the various efforts to quantify past temperature changes, two types of datasets are available: first, reconstructions of the average Northern Hemisphere temperature (Jones et al., 1998; Mann et al., 1999; Moberg et al., 2005; Rutherford et al., 2005; Smith et al., 2006); second, gridded reconstructions for Europe, making possible to extract temperature estimates for large areas (Briffa et al., 1988; Guiot et al., 2005; Luterbacher et al., 2004). These reconstructions are generally based on long instrumental records (Manley, 1974), tree-ring width or density records, and/or historical information. Only few reconstructions take into account other proxy records (Luterbacher et al., 2004; Smith et al., 2006). None of these reconstructions include temperature records from central or western France.

We have tested the linear correlation between our Fontainebleau T_{max} AMJJAS reconstruction and other temperature series displayed on Fig. 5a. Figure 5b displays the significant correlation coefficients (R^2) obtained with some of the series: instrumental T_{mean} AMJJAS and T_{max} AMJJAS from Central England and De Bilt, reconstructed T_{mean} AMJJAS of Western Europe (Guiot et al., 2005), reconstructed T_{mean} AMJJAS at 50° N, 0° W (Briffa et al., 1988), reconstructed European T_{mean} JJA (25 W–40 E; 35 N–70 N; multiproxy reconstruction, Luterbacher et al., 2004), and reconstructed T_{mean} JJA of the Northern Hemisphere (multi-proxy reconstruction, Jones et al., 1998). We have analysed the stability of the correlations over four century-long time periods: 1600 to 1700, 1700 to 1800, 1800 to 1900 and 1900 to 2000. The best correlation is obtained with Central England T_{max} AMJJAS (R^2=0.39 from 1878 to 2000) and Central England T_{mean} AMJJAS (R^2=0.27 from 1659 to 2000). A very good correlation is also obtained with De Bilt data (R^2=0.32 for T_{mean} AMJJAS from 1706 to 2000 and 0.27 for T_{max} AMJJAS from 1901 to 2000). For both sites, the best correlation with Fontainebleau appears over the 19th century. For this century, R^2 is between 0.4 and 0.5. It is surprising to obtain better correlations between Fontainebleau reconstructed T_{max} AMJJAS and the growing season temperatures in Central England and De Bilt over the

19th century than over the 20th. This result suggests that the high coherency between Northern France, Central England and the Netherlands temperatures observed from instrumental data (R^2 between 0.4 and 0.5) persist back over the 19th century and that the quality of Central England and De Bilt homogenised data is very good. The comparison of our reconstructed T_{max} AMJJAS and Central England and De Bilt data reveals a mismatch at the decadal scale in the early 20th century (~1920–1930). Our reconstruction shows a small maximum centred on 1925 which is not seen in the other records (Fig. 5a). This may explain the lower correlation obtained for the 20th century. Again, we highlight a problem occurring in the interval between World War I and II.

Prior to the 19th century, ancient instrumental records must be taken with caution. De Bilt data are independent of Central England temperature from 1740 onwards. Before 1740, Central England temperature data have been used for the homogenisation of T_{mean} at De Bilt. The sources used by Manley to produce the ancient Central England Temperature are not known (P. Jones, personal communication). It is expected that Central England temperature may be biased in summer (overestimation of warmth due to observation methods) prior to 1740 (P. Jones, personal communication). The good correlations between reconstructed T_{max} AMJJAS at Fontainebleau, and De Bilt and Central England T_{mean} AMJJAS over the 16th and 17th centuries support the quality of reconstructions and early instrumental records, despite these known biases.

We now compare our Fontainebleau record with multi-proxy European temperature reconstructions. Guiot et al. (2005) has used dendrochronological data, Greenland ice core δ^{18}O data, grape harvest date records and instrumental temperature data, with a focus on Southern Europe growing season temperature. The correlation observed over the 19th and 20th century is good (though less good than with Central England or the Netherlands) and reflects the coherency between North and South France temperature. Surprisingly, the correlation with this reconstruction increases from the present to the past. We suggest that this is an artefact of the data used for Guiot et al. (2005) reconstruction and an increasing weight of earlier Burgundy harvest dates (Le Roy Ladurie, 1990).

Briffa et al. (1988) has produced reconstruction of T_{mean} AMJJAS for Europe using latewood density series from coniferous trees. Despite the fact that his reconstruction is better for Northern Europe, we obtain a relatively high correlation over the 19th and 20th centuries with the grid point closest to Fontainebleau (50° N, 0° E). This correlation however collapses for the time period from 1750 to 1800, possibly because Briffa et al. (1988) reconstruction relies then mostly on Northern Europe tree-ring data.

Luterbacher et al. (2004) produced regional seasonal European temperature datasets using ancient instrumental data, documentary-based temperature indices and proxy records (Northern Eurasian tree rings, Greenland ice cores). For the 18th to 20th century, T_{mean} JJA does not show significant correlation with our reconstruction. An increased correlation is observed for the 16th century, potentially linked with some of the records used in his approach (e.g. Central England Temperature).

3.4 Spectral properties

Spectral analyses of Fontainebleau tree-ring records (δ^{13}C, δ^{18}O, growth indices), burgundy historical grape harvest records and the temperature reconstructions derived from the linear regression model described in Sect. 3.2 have been conducted with the Analyseries software (Paillard et al., 1996) using a Blackman-Tuckey method with Bartlett windows. The resolution has been adjusted to capture 50% of variance, with a bandwidth of 0.024 yr^{-1}. The results have been compared to calculations conducted with other methods (Maximum Entropy, Multi Taper Method, Singular Spectrum Analysis) and have been shown to be robust with respect to the spectral analysis methodology.

The power spectra are compared to the power spectrum of the homogenised temperature data for the period from AD 1879 to 2000. Then, the power spectra are compared over different time intervals of similar length (148 years): 1596 to 1743; 1748 to 1896; and 1853 to 2000. These intervals have been restricted to a length of 148 years because there are missing cellulose δ^{18}O from 1743 to 1748. Other missing data have been replaced by the average of the 2 previous and 2 following years.

3.4.1 Instrumental period

From 1879 to 2000, T_{max} AMJJAS (April-May-June-July-August-September) is the target variable for our multi-proxy reconstruction (Etien et al., 2007[1]). The instrumental signal of T_{max} AMJJAS exhibits a multi-decadal variability at periodicities of ~55 and 25 years, a periodicity of 12.8 years and an interannual variability expressed as broad peaks at 7–8 years and at 5.5 years (Fig. 6a). Our reconstructed temperature is based on a linear regression of latewood tree-ring cellulose δ^{18}O and historical grape harvest dates, without any statistical treatment of the raw records. It is remarkable that the reconstruction captures the general shape of the instrumental temperature power spectrum, with variability expressed in the multi-decadal range (~45 and 25 years), at 12.8 years. The reconstruction however differs significantly from the instrumental record at the inter-annual scale. Although it does capture the relative magnitude of variability in the inter-decadal scale, it exhibits more narrow peaks at 8.2 and 5.9 years than the continuum observed for the instrumental data.

Our initial hope was to discuss the stability of the power spectrum of temperature, just using our best fit reconstruction. This mismatch between the reconstruction and the instrumental record at the inter-annual scale puts clearly a limitation to the use of reconstruction. We have therefore decided to compare the power spectrum of each proxy record.

Both the latewood tree-ring cellulose δ^{18}O and historical grape harvest dates exhibit multi-decadal variability, with a ~25 year peak more strongly marked in the harvest dates. They have similar power expressed at 12.8 years. Both records also have marked periodicities peaking at ~8 years and 5.4–5.9 years. Because they do not have a continuum of spectral power at ~7 years, the reconstruction fails to capture the observed spectral power in this range. The combination of these two records has more similarity and coherency than each individual record, pointing again to the improved reconstruction obtained by combining the two records.

We have then compared the spectral power expressed in the two other tree ring parameters which are not used in the reconstruction. The latewood tree-ring cellulose δ^{13}C and the growth index have little in common with the prior records and with the temperature power spectrum. The carbon power spectrum reflects long term trends and a secondary maximum in the 10 year range. The tree growth index has its maximum power expressed at 13.5 years and a secondary peak at 6.7 years. We have no clear explanation for the discrepancy between the power spectra of the growth, carbon and temperature-sensitive proxies.

We have analysed the auto-correlation of the records. δ^{18}O has almost no auto-correlation with 1 year lag (R=0.34); the grape harvest dates are significantly auto-correlation with 1 year lag (R=0.45). δ^{13}C has a stronger auto-correlation (R=0.57 with 1 year lag) persistent up to a 13 year lag. The growth index shows also a strong auto-correlation (R=0.52 with 1 year lag) but only over up to 2 years. It cannot be excluded that the observed δ^{13}C and tree growth index periodicities may be associated with productivity effects. Some studies have indeed shown that extreme dry/heat wave years may have multi-year effects on *Quercus* sp. growth (E. Dufresnes, personal communication).

We have however tested if the use of the component of tree growth index filtered in the range [0–10 years] could improve the power spectrum of our reconstruction. The inclusion of this filtered growth index does not improve the linear regression model (R^2=0.59) and does not add spectral power at ~7 years in the reconstruction. We have therefore decided to keep the initial regression model using only δ^{18}O and harvest dates.

3.4.2 Evolution of power spectra with time

Within the accuracy of the spectral method, rather similar power spectra are observed for the 122 years of the instrumental period and for the last 148 years of the proxy records (Figs. 6a and d). It can just be observed in grape harvest dates and reconstructed $T_{\max}$ AMJJAS that there is an increase in the power expressed at 5–6 years compared to the power expressed at ~8 years. This could be due to changes in the inter-annual variability in the period from 1853 to 1879. The coherency between δ^{18}O and grape harvest dates is maximum for the multi-decadal variability (25–45 years), for 12–14 years, and for 8.5 years.

The results obtained from 1853 to 2000 (Fig. 6d) are now compared to the results obtained for the period from 1748 to 1895 (Fig. 6c) (two overlapping 148 year long intervals). For this older period, the coherency between δ^{18}O and grape harvest dates decreases at the decadal and multi-decadal scales and increases strongly for the inter-annual scale, with a continuum from 5.5 to 9 years.

The periodicities expressed in the δ^{18}O record are diminished on the multi-decadal scale and 5–6 years but enhanced at 11–14 years and 8–9 years. Those expressed in the historical grape harvest dates remain quite similar on the decadal and multi-decadal scales, shift from 8.1 to 9.4 years and decrease strongly in the 5–6 years range.

The reconstructed T_{max} AMJJAS therefore shows a power spectrum quite similar to the one observed over the last 148 years, but with more power expressed in the range 5.5–9 years, peaking at 5.7 years. This analysis suggests that the 5–6 year interannual variability is more strongly imprinted on T_{max} AMJJAS during the mid-18th to 19th centuries than over the 20th century.

This result must be taken with caution because the reliability of grape harvest dates data decreases back in time. Changes in vine production practices may induce multi-decadal biases. Our multi-proxy approach may on one hand add such specific biases on the reconstruction. On the other hand, the two records combined in the reconstruction do exhibit strong coherency (>0.85) at the inter-annual scale.

The δ^{13}C and tree growth index periodicities obtained over 1748–1895 remain comparable to those observed for the most recent period, with small shifts in spectral peaks. The most striking difference is the appearance of a 5.3 years periodicity in δ^{13}C but with no coherency with the other records.

From 1596 to 1743, δ^{18}O and grape harvest data show less coherency (typically up to 0.8), more focused on selected periodicities which appear on the reconstruction at ~22–23 years, 9–11 years, 8.1 years and 6.8 years. At the inter-annual scale, there is therefore a disappearance of 5 year periodicities and a stronger 8.1 year periodicity. The largest difference is observed for the grape harvest data, with much more spectral power in the inter-annual scale (6–8 years) than during the most recent periods. Again, it must be noted that this change of shape may result from vineyard management and less reliable historical archives.

For this oldest time interval, there is no dramatic change in the power spectrum of δ^{13}C. The growth index also shows a shift from periodicities around 5–6 to 6–7 years, coherently with our temperature reconstruction.

This analysis reveals a persistence of decadal (at 8–9) and multi-decadal periodicities in δ^{18}O, grape harvest dates and reconstructed $T_{\max}$ AMJJAS over three intervals spanning each 1.5 century. By contrast, there seems to be significant shifts of the frequency of the inter-annual variability: from 6–7 years (1596–1743), a strong ~6 years component (1748–1895), then 5–6 year component for the last interval over the 20th century.

Earlier studies have related the 5–10 inter-annual variability to modes of atmospheric variability in the north Atlantic sector, including the North Atlantic Oscillation (Appenzeller et al., 1998; Souriau et al., 2001). However, the correlation between NAO index and northern France climate parameters is very weak (the best correlation, R=0.2 is obtained between the measured $T_{\max}$ AMJJAS and April NAO index from 1950 to 2000). However, a relationship is observed between moisture availability in southern Europe and the occurrence of heat waves in Europe (Vautard et al., 2007). There is also a correlation between NAO index and Western Europe precipitation δ^{18}O (G. Hoffmann, personal communication) due to different moisture advection paths. We suggest that these two processes build a link between Fontainebleau cellulose δ^{18}O record and NAO, through the isotopic composition of rainfall and xylem water, and/or through summer extreme warmth imprinted through leaf evaporation processes. Future simulations of tree ring cellulose isotopic composition conducted using inputs from mesoscale atmospheric models equipped with the explicit modelling of water stable isotopes may improve the understanding of these suggested relationships.

4 Conclusion and perspectives

In this paper, we have combined a Burgundy grape harvest date record with new $\delta^{18}O$ measurements conducted on timber wood and living tree cellulose from Fontainebleau castle and Fontainebleau forest. Using these two independent datasets, we have applied a linear calibration method developed and tested against 20th century instrumental data (Etien et al., 2007[1]) to construct a temperature reconstruction for northern France. The originality of our approach lies in the quality of the original proxy records and in their strong relationship with growing season maximum temperature, demonstrated for the 20th century. By contrast with "classical" dendrochronology, we have not deployed sophisticated statistical data treatment to combine different tree sets; and contrary to many other temperature reconstruction methodologies, we have used continuous and homogeneous proxy records. We have not faced homogeneity problems with $\delta^{18}O$ records, while grape harvest dates, tree growth, latewood $\delta^{13}C$ may be affected by anthropogenic effects due to vine production practices, changes in nutriments in soils and changes in atmospheric CO_2 concentration and $\delta^{13}C$ composition. Our reconstruction associated with an analytical uncertainty of ~0.55°C, is expected to provide a reference series for the variability of growing season temperature in western Europe.

Obviously, several uncertainties remain regarding the quality of the reconstruction. First, grape harvest dates may be affected by changes in wine growing practices, inducing artificial trends in the record. Second, changes in wood origin and age may affect $\delta^{18}O$ and its sensitivity to climate parameter (although this has not yet been demonstrated). Spectral analyses conducted on each record and on the reconstruction clearly evidence past changes in their relative spectral properties, with varying weights of frequencies ranging between 6 and 25 years. It is questionable whether we should combine the two records using a simple linear calibration as we have done here, or whether more sophisticated methods should be deployed, for instance by retaining only high frequencies for grape harvest dates. Analyses of spectral properties clearly show different relative weights of different frequencies on the two records. Further comparisons with other δ^{18}O records obtained within the ISONET project in France and in Europe will help to decipher the regional/continental coherency of these new tree ring proxies, at the interannual/decadal/centennial scale. Other uncertainties clearly arise from the calibration target, focused on the maximum temperature averaged over the growing season from April to September. This parameter was selected because it gave the strongest and most persistent correlation coefficients over the 20th century. However, latewood cellulose δ^{18}O and grape harvest dates may reflect more clearly the weather conditions on a different subseason. For instance, 2007 grape harvest dates are now observed to occur exceptionally early, due to extreme warmth during April 2007 in France and despite cool conditions from June to August. Factors other than temperature, such as water stress, do affect grape maturation, precipitation and cellulose isotopic composition. It is possible that combinations of intra-seasonal variability of temperature and precipitation may explain why extreme events cannot be simultaneously identified in grape harvest dates and cellulose δ^{18}O data. The interest of combining the two proxies appears therefore clearly in terms of seasonal temperature signals.

What is the added value of our reconstruction? We have estimated an uncertainty of 0.55°C on individual growing season maximum temperature reconstructions. This uncertainty results from uncertainties on analytical measurements and on the stability of the linear correlations over the 20th century. The good point is that we are able to assess this uncertainty, which is not the case for many documentary sources (diaries etc), and even not the case for early instrumental temperature data. It is possible that thermometer measurements could be biased by up to 1–2°C for maximum summer temperature due to exposure of thermometers issues (P. Jones, personal communication). We have already suggested that homogenised temperature data from Fontainebleau area could be biased and overestimate summer warmth in the early 20th century, a point which has implications for detection/attribution studies and analysis of extreme warmth events.

The comparison between our data and temperature estimates for Europe is highlighting. Increasing correlations from present to past with some of the reconstructions highlight the strong weight of early instrumental records such as the Central England temperature data in many reconstructions, especially prior to ~1750. The construction of this reference "instrumental" record still remains a mystery, and is described by Manley himself as "built up [...] largely by the exercise of judgment on series of observations that are formidably open to doubt [...]". The comparison between our reconstruction and Manley mean growing season temperature data provides an independent control on the quality of CET data. We show that (i) our reconstruction preserves more variance back in time, because it was not distorted/averaged by statistical/homogenisation methods; (ii) the inter-annual correlation remains high even back to the 17th century, therefore providing a strong and independent verification of the quality of the pionneer work of Manley, who did not use grape harvest data (E. Le Roy Ladurie, personal communication). Further works will be conducted to compare the δ^{18}O data from wood cellulose provided by transects of different tree species in Europe obtained within the EC ISONET project, to analyse the spatial and temporal coherency between δ^{18}O records. The decadal variability will be also compared with other precipitation δ^{18}O records such as those obtained from benthic ostracods from deep peri-Alpine lakes, reflecting multi-annual precipitation averaged δ^{18}O values (Von Grafenstein et al., 1998). Precipitation isotopic composition can now be simulated by regional atmospheric models equipped with the modelling of water stable isotopes (Sturm et al., 2005). Such simulations need to be used in order to improve our understanding of the processes relating climate variability, precipitation isotopic composition, and tree ring latewood cellulose isotopic composition.

Acknowledgements. We are grateful to P. Jones and E. Le Roy Ladurie for clarifying comments on Manley (1974) reconstruction and to David Lister for providing European long meteorological records. We are undebted to V. Droguet "Conservateur du Musée Château de Fontainebleau" and P. P. Perraud for counselling and guidance during sampling and historical research. This project was funded by CEA, CNRS (ECLIPSE CAC1000 program) and EC (FP6 ISONET EVK2 CT 2002 00147).

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Table 1. t-values of the correlations between the Fontainebleau chronology and other regional chronologies. The agreement between ring-width curves from Fontainebleau and regional chronologies is backed up by t-values above 7.

t-value	first ring	last ring	local chronology	regional chronologies
7.82	1306	1750	Fontainebleau.05	FontainebleauPilcher
7.31	1306	1750	Fontainebleau.05	Autun.EvD-GL04
6.35	1306	1750	Fontainebleau.05	Compiegne-YT01
6.3	1306	1750	Fontainebleau.05	Cluny-GL51
5.84	1306	1750	Fontainebleau.05	Rouen.ca-LCE11
5.54	1306	1750	Fontainebleau.05	Paris.ND-GL250
5.5	1306	1750	Fontainebleau.05	Dijon.Refg-LCE07a
5.02	1306	1750	Fontainebleau.05	Sens.cath-LCEtr
4.81	1306	1750	Fontainebleau.05	FTVabbayeNef
4.65	1306	1750	Fontainebleau.05	Auxerre.CA-GL126
4.5	1306	1750	Fontainebleau.05	Amiens.F-GL102
4.37	1306	1750	Fontainebleau.05	Nolay.Halles-10b
4.36	1306	1750	Fontainebleau.05	Gray.GAnc-GL13
4.3	1306	1750	Fontainebleau.05	Besançon.Granv-GL02
4.21	1306	1750	Fontainebleau.05	Besançon.Citad-GL12a
4.15	1306	1750	Fontainebleau.05	Beauvais-UlgT4
4.14	1306	1750	Fontainebleau.05	Beaune.HD-09
4.13	1306	1750	Fontainebleau.05	Gray.GAncier-CD11
4.04	1306	1750	Fontainebleau.05	Erquy.01

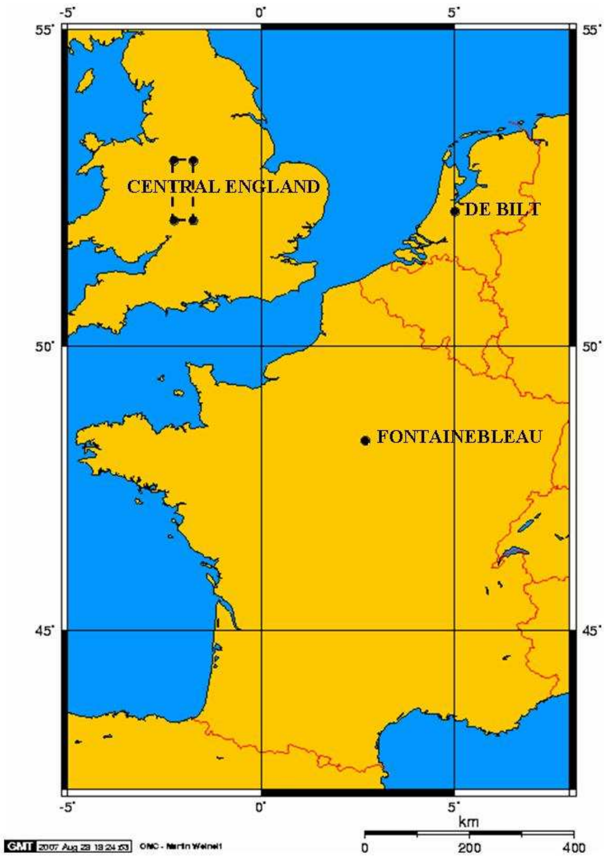

Fig. 1. Location of the Fontainebleau sampling site and ancient instrumental record site of De Bilt (Netherlands) and "Central England" area as defined by Manley (1974) (52°30′ N to 53° N and 1°45′ W to 2°15′ W). Map by: http://www.aquarius.geomar.de.

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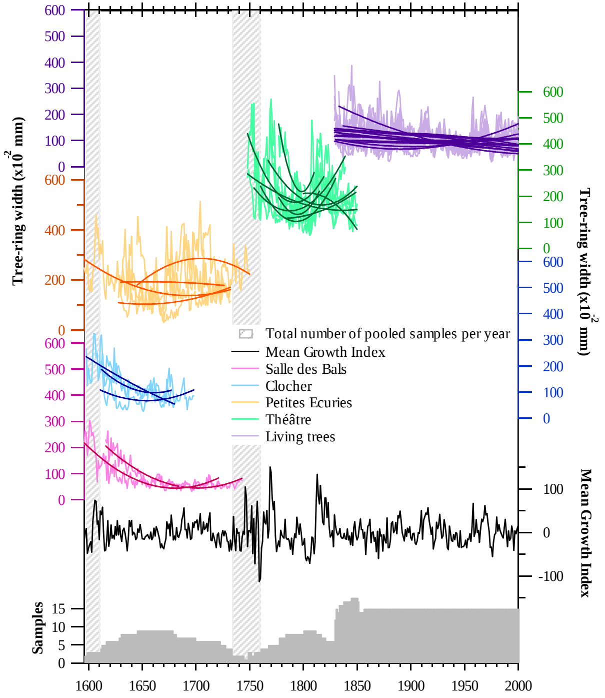

Fig. 2a. From bottom to top, time series of:

- Total number of pooled beam and tree samples per year.
- Mean Growth Index of latewood tree-ring (no unit).
- Individual tree ring width from beams sampled in Salle des Bals, Clocher, Petites Ecuries and Théâtre and from living trees sampled in Fontainebleau forest.

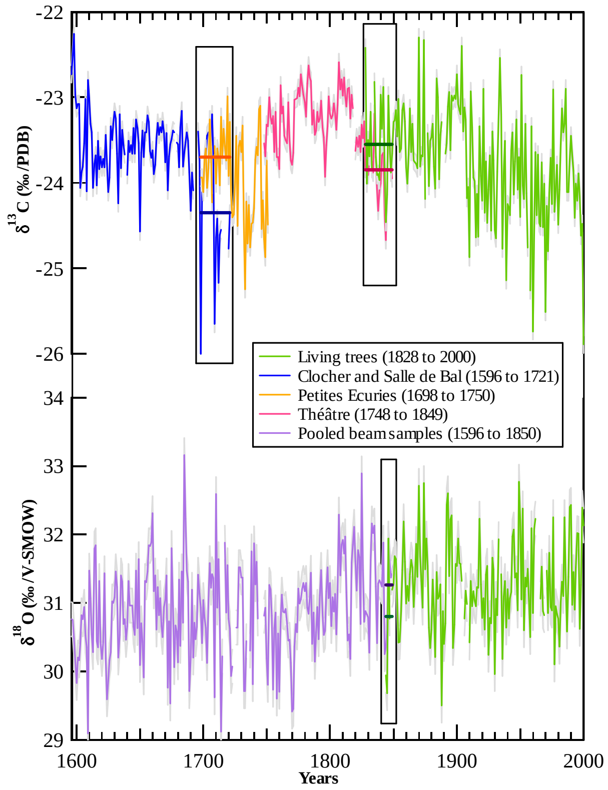

Fig. 2b. Variability of isotopic composition of tree ring cellulose between different sampling sites with their statistical uncertainties (shaded area). Overlap periods are bordered. The segments correspond to the mean values of the isotopic series over the time enclosed.

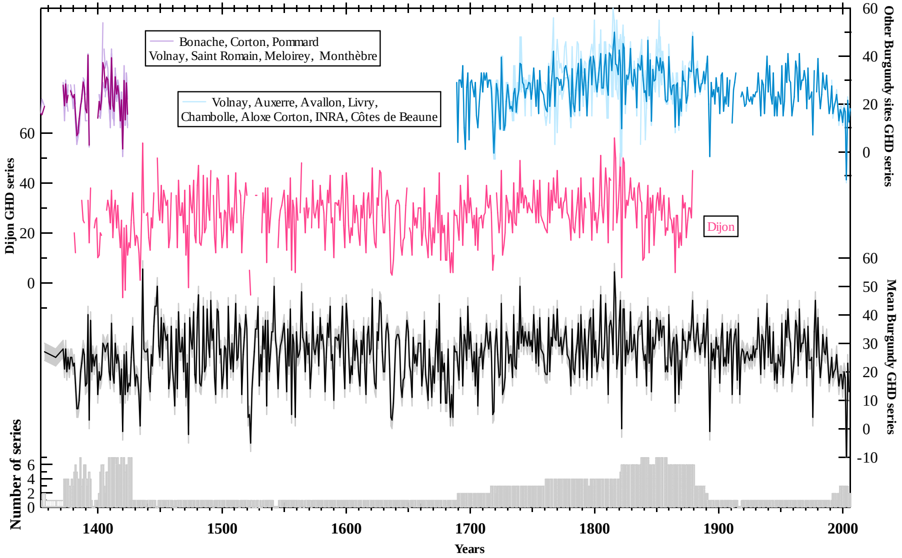

Fig. 2c. From top to bottom:

- Various local series of Burgundy grape harvest dates used to build the Burgundy series.
- Dijon series (the longest Burgundy series).
- Burgundy grape harvest dates series published by Chuine (2004). This record is constructed as the median of the local series shown above. The error shown by the grey area is calculated using the maximum standard deviation between local series.
- Number of local series used to establish the Burgundy grape harvest dates record.

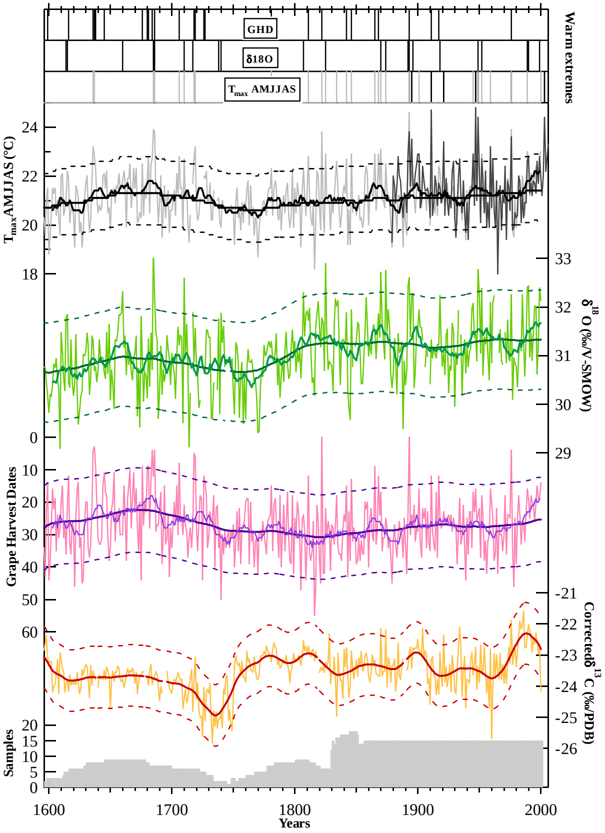
GHD
δ18O
Tmax AMJJAS
Warm extremes
Tmax AMJJAS (°C)
24
22
20
18
δ18O (‰/V-SMOW)
33
32
31
30
29
Grape Harvest Dates
0
10
20
30
40
50
60
Corrected δ13C (‰/PDB)
-21
-22
-23
-24
-25
-26
Samples
20
15
10
5
0
1600
1700
1800
1900
2000
Years

Fig. 3a.

Fig. 3a. From top to bottom, time series of:

- Warm extremes indicated by Grape Harvest Dates, δ^{18}O of latewood cellulose and instrumental and reconstructed T_{max} AMJJAS. Extremes are defined as deviation above or below the average parameter (by more than 1.5 standard deviation). The extreme warm years for δ^{18}O are: 1614, 1615, 1660, 1685, 1686, 1710, 1717, 1738, 1740, 1807, 1825, 1870, 1874, 1892, 1893, 1896, 1918, 1949, 1952, 1989, 1990, 1999. For grape harvest dates: 1599, 1616, 1636, 1637, 1638, 1645,1676, 1680, 1681, 1684, 1686, 1706, 1718, 1719, 1726, 1727, 1781, 1811, 1822, 1842, 1846, 1865, 1868, 1893, 1911, 1917, 1976. For reconstructed T_{max} AMJJAS: 1636, 1637, 1685, 1686, 1706, 1710, 1718, 1719, 1781, 1811, 1822, 1825, 1834, 1842, 1846, 1865, 1868, 1870, 1874, 1893, 1901, 1945, 1949, 1952, 1959, 1976, 1989, 2000. For instrumental T_{max} AMJJAS: 1893, 1895, 1911, 1921, 1947, 1949, 1976.
- Variability and trends of T_{max} AMJJAS records measured from 1879 to 2006 (dark line) and reconstructed from 1596 to 2000 (grey line). Fifteen years running mean (15RM) and century-scale trends (SSA) are also displayed.
- Variability and trends of δ^{18}O records measured from 1596 to 2000 (with 15RM and SSA).
- Variability and trends of Grape Harvest Dates records measured from 1596 to 2000 (with 15RM and SSA).
- Variability and trends of δ^{13}C records measured from 1596 to 2000 (with 15RM and SSA).
- Total number of pooled beam and tree samples per year.

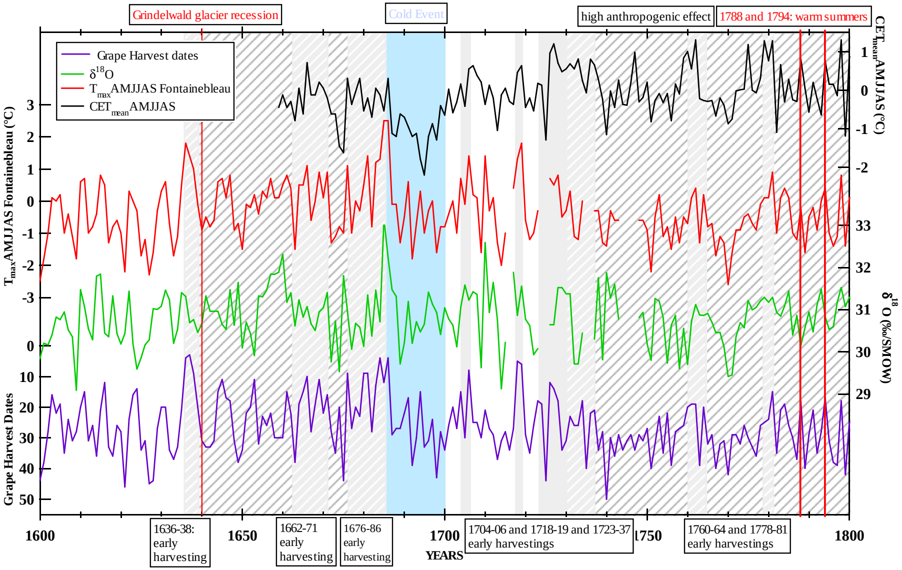

Fig. 3b. Comparison between instrumental Central England T_{mean} AMJJAS, reconstructed Fontainebleau $T_{\max}$ AMJJAS, cellulose δ^{18}O and Burgundy Grape Harvest Dates. Vertical grey bars correspond to historical early harvesting (Le Roy Ladurie et al., 2006). Dashed vertical bars correspond to a time period where anthropogenic effects on grape harvest dates were undershot over climatic factors. Vertical red lines highlight warm event. Vertical blue bar displays the coldest episode up to now.

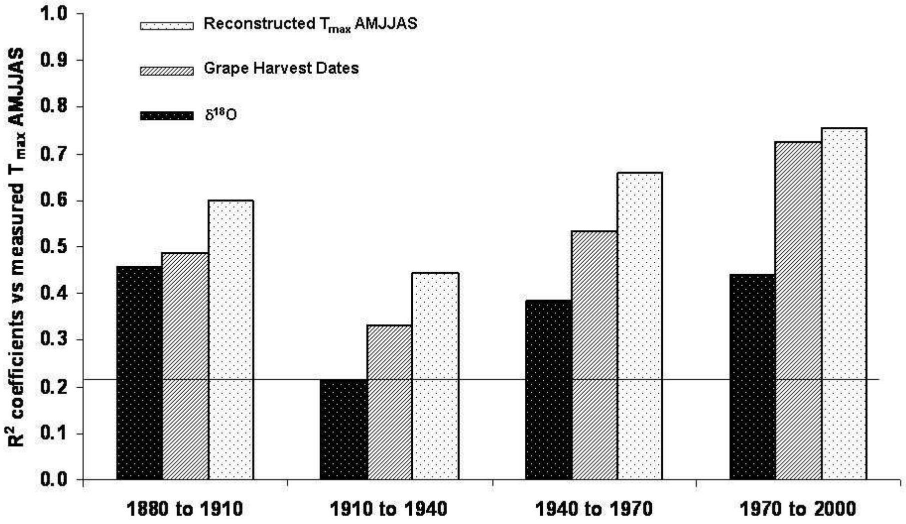

Fig. 4. R^2 coefficients of proxy records (δ^{18}O, grape harvest dates) and reconstructed $T_{\max}$ AMJJAS with measured $T_{\max}$ AMJJAS considered for the instrumental period.

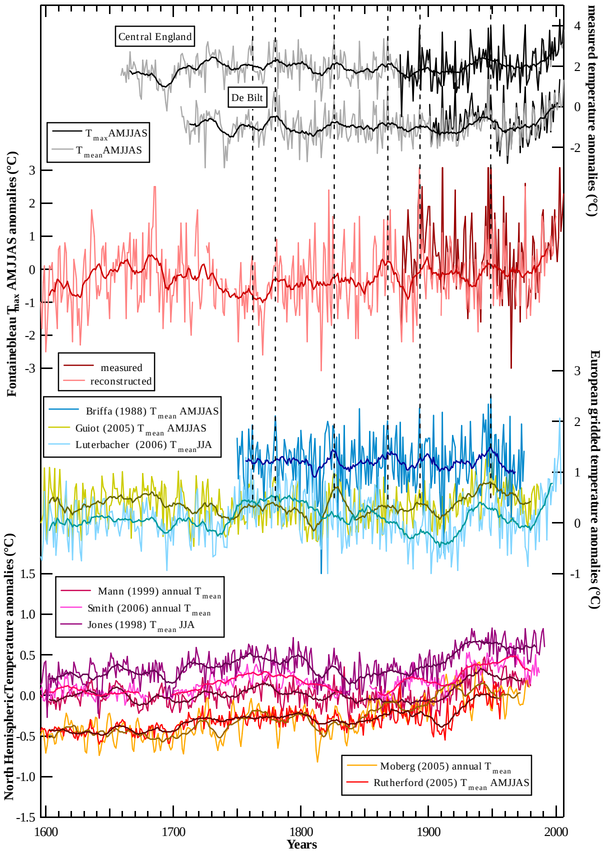
Central England
De Bilt
T_{max} AMJJAS
T_{mean} AMJJAS
measured temperature anomalies (°C)
4
2
0
-2
Fontainebleau T_{max} AMJJAS anomalies (°C)
3
2
1
0
-1
-2
-3
measured
reconstructed
Briffa (1988) T_{mean} AMJJAS
Guiot (2005) T_{mean} AMJJAS
Luterbacher (2006) T_{mean} JJA
European gridded temperature anomalies (°C)
3
2
1
0
-1
Mann (1999) annual T_{mean}
Smith (2006) annual T_{mean}
Jones (1998) T_{mean} JJA
North Hemispheric Temperature anomalies (°C)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
Moberg (2005) annual T_{mean}
Rutherford (2005) T_{mean} AMJJAS
1600
1700
1800
1900
2000
Years

Fig. 5a.

Fig. 5a. Ancient instrumental records and reconstructions of temperature.

From top to bottom:

- Ancient instrumental records of Central England and De Bilt (Netherlands) AMJJAS mean (grey lines) and max (dark lines) temperature. Fifteen years running mean is also displayed.
- Homogenised instrumental record of Fontainebleau Tmax AMJJAS anomalies (dark red) and reconstructed Tmax AMJJAS anomalies (light red) with its 15 years running curve.
- Briffa (1988), Guiot (2005) and Luterbacher (2006) reconstructions of European mean temperature anomalies and their 15 years running curve.
- Jones (1998), Mann (1999), Moberg (2005), Rutherford (2005) and Smith (2006) reconstructions of North Hemispheric temperature anomalies and their 15 years running curve.

Dotted lines correspond to years of common signal on ancient instrumental records and gridded reconstructions of temperature.

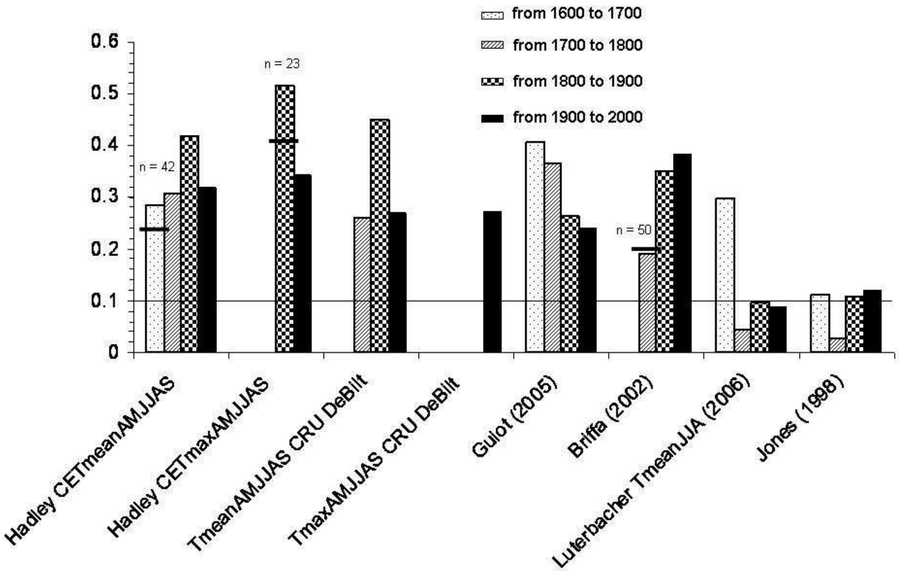

Fig. 5b. Significant correlation coefficients (R^2) obtained with some of the series: instrumental Central England and De Bilt mean and maximum temperature, Tmean AMJJAS of Western Europe (Guiot, 2005) and Europe (Briffa, 1988). Multi proxy reconstruction of European Tmean JJA (Luterbacher, 2004) and multi proxy reconstruction of Northern Hemisphere temperature from Jones (1998). R^2 coefficients are represented over four century-long time periods: 1600 to 1700, 1700 to 1800, 1800 to 1900 and 1900 to 2000.

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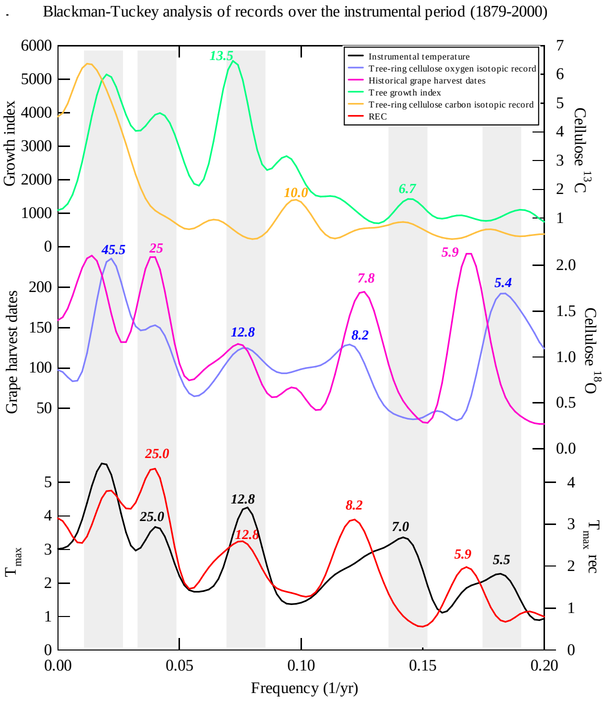

Fig. 6a. Spectral power (vertical axes) versus frequency (1/yr) calculated with the Analyseries software (Paillard, 1996) using a Blackman-Tuckey method with Bartlett windows and a resolution adjusted for 50% of variance, calculated over the period from 1879 to 2000. From top to bottom: results for Fontainebleau tree-ring latewood cellulose δ^{13}C (orange), Fontainebleau tree growth index (green), Fontainebleau tree-ring latewood cellulose δ^{18}O (blue), historical Burgundy grape harvest dates (purple), homogenised instrumental April–September maximum temperature (black) and reconstructed April–September maximum temperature based on a linear regression model using the latter two proxy records (red). Periods associated with maxima in spectral power are displayed. Grey rectangles highlight the major periodicities found in the instrumental record.

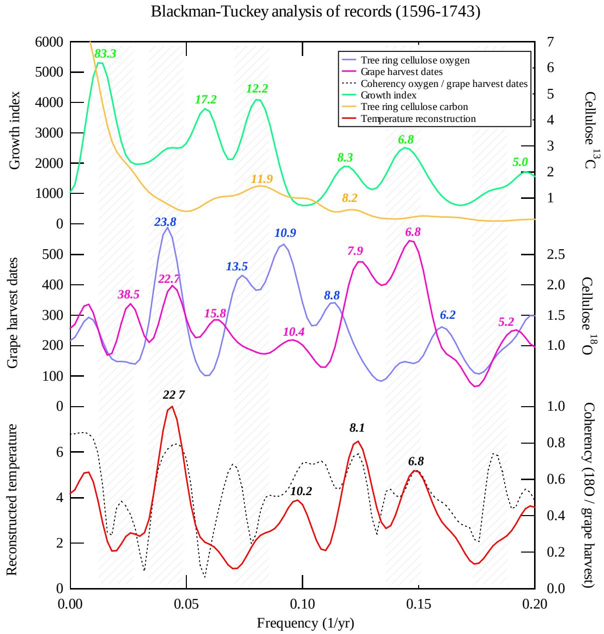

Fig. 6b. Same as Fig. 1a but for the period from 1596 to 1743. The dotted black line displays the coherency between latewood cellulose δ^{18}O and historical grape harvest date records.

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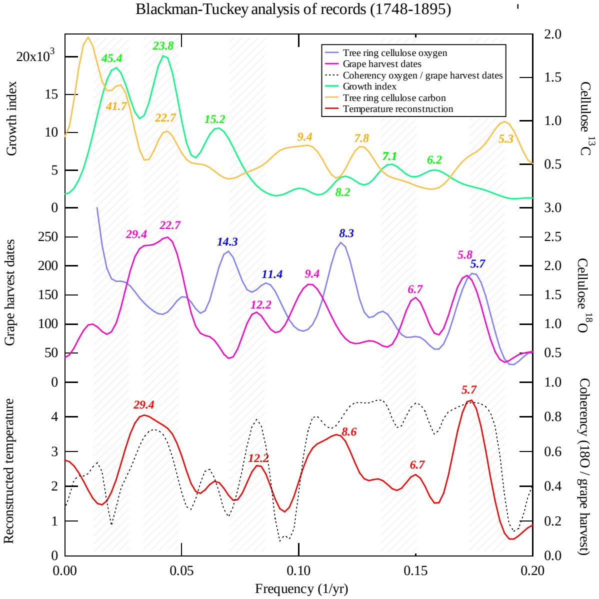

Fig. 6c. Same as Fig. 1b but for the period from 1748 to 1895.

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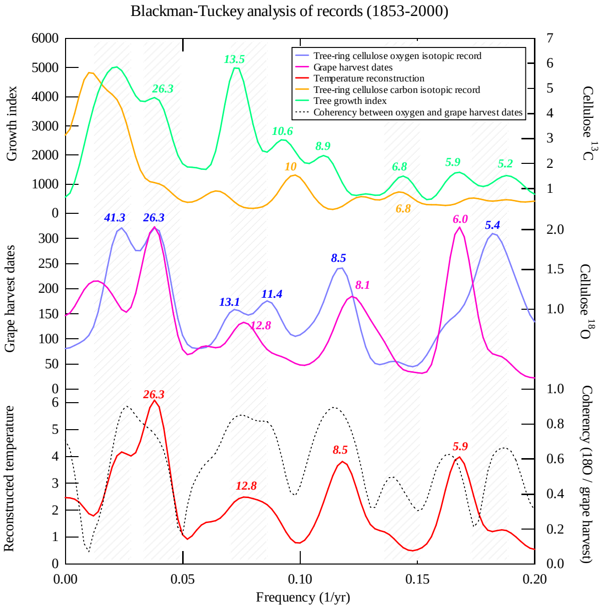

Fig. 6d. Same as Fig. 1c but for the period from 1853 to 2000.