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LONG-TERM SUMMER TEMPERATURE VARIATIONS IN THE PYRENEES FROM DETRENDED STABLE CARBON ISOTOPES

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Abstract: Substantial effort has recently been put into the development of climate reconstructions from tree-ring stable carbon isotopes, though the interpretation of long-term trends retained in such timeseries remains challenging. Here we use detrended $\delta^{13}C$ measurements in *Pinus uncinata* tree-rings, from the Spanish Pyrenees, to reconstruct decadal variations in summer temperature back to the 13th century. The June-August temperature signal of this reconstruction is attributed using decadally as well as annually resolved, 20th century $\delta^{13}C$ data. Results indicate that late 20th century warming has not been unique within the context of the past 750 years. Our reconstruction contains greater amplitude than previous reconstructions derived from traditional tree-ring density data, and describes particularly cool conditions during the late 19th century. Some of these differences, including early warm periods in the 14th and 17th centuries, have been retained via $\delta^{13}C$ timeseries detrending — a novel approach in tree-ring stable isotope chronology development. The overall reduced variance in earlier studies points to an underestimation of pre-instrumental summer temperature variability derived from traditional tree-ring parameters.

Keywords: Climate change, paleoclimatology, stable isotope geochemistry, tree-rings, Europe.

1. INTRODUCTION

Tree-ring $\delta^{13}C$ records have been used to reconstruct various climate parameters including temperature (Treydte *et al.,* 2009), precipitation (Bale *et al.,* 2011), drought (Kress *et al.,* 2010), relative humidity (Edwards *et al.,* 2008), and cloud cover (Gagen *et al.,* 2011). However, the assessment of potential low frequency trends in these climate parameters, using tree-ring stable isotope data, remains challenging as the isotope records are typically based on *(i)* few trees and *(ii)* pooled wood samples (mixed material from different trees prior to mass spectrometer measurement) (Borella *et al.,* 1998). The pooling procedure limits the ability to analyze varying $\delta^{13}C$ levels among individual trees as well as any potential underlying age-trends that might obscure long-term climate signals (Esper *et al.,* 2010; Dorado Liñán *et al.,* 2011; Hangartner *et al.,* 2012). As a result, climate reconstructions derived from detrended tree-ring $\delta^{13}C$ data, in which $\delta^{13}C$ level differences and age-trends have been analyzed and, if detected, removed, are largely missing from the literature.

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The investigation of between-tree $\delta^{13}C$ level differences and $\delta^{13}C$ age-trends requires processing single trees individually throughout the time-demanding and expensive procedure of sample preparation and mass spectrometry measurement. This can realistically be achieved by reducing the temporal resolution of $\delta^{13}C$ measurement from annual to decadal or even lower time steps (Edwards *et al.,* 2008). Here we present the first such experiment, comprising 31 individual $\delta^{13}C$ measurement series from living and dead *Pinus uncinata* trees, from a high elevation site in the Spanish Pyrenees. All trees were treated individually, at decadal resolution, to develop a dataset containing 1007 $\delta^{13}C$ measurements spanning the past millennium. The 31 decadally resolved $\delta^{13}C$ timeseries (each representing a single tree) cannot be used to reconstruct annual extremes, but permit the analysis and treatment of $\delta^{13}C$ level differences and age-trends to develop a detrended stable isotope chronology containing long-term climate variations back to the 13th century.

Statistical calibration and verification of such a record, however, requires annually resolved $\delta^{13}C$ measurements during the period of overlap with instrumental data. This objective is addressed by combining the decadally resolved $\delta^{13}C$ data with 545 annually resolved $\delta^{13}C$ measurements from a sub-sample of *Pinus uncinata* trees covering the 20th century (Konter *et al.,* 2014). The high frequency climate signals of $\delta^{13}C$ (and $\delta^{18}O$ from the same trees) have been explored in detail in Konter *et al.* (2014) including assessments of the effects of differing $\delta^{13}C$ correction procedures, to account for the Suess effect (Suess, 1955), on the calibration schemes. We here build on these results and develop a millennial-scale reconstruction based on decadally resolved, detrended, $\delta^{13}C$ measurements, with the climate signal attributed to the comparison of annually resolved $\delta^{13}C$ measurements with instrumental data. The reconstruction is compared to extant long-term estimates of warm season temperature variability from the Spanish Pyrenees, based on maximum latewood density (MXD) data.

2. $\delta^{13}C$ DATA, DETRENDING AND CALIBRATION METHODS

Increment cores from living trees and dry-dead wood were collected (**Fig. 1**) to develop a continuous, millennium-length *Pinus uncinata* composite chronology for the Central Pyrenees (Büntgen *et al.,* 2008). The sampling site is located near lake Gerber (42°38'N, 1°06'E) at the upper treeline (2400 m a.s.l.), where traditional tree-ring width (TRW) and MXD data have been shown to contain a summer temperature signal (Büntgen *et al.,* 2010). From a total of several hundred *Pinus uncinata* sampled during several field campaigns, 31 trees were used to develop a stable carbon isotope ratio chronology spanning the past 700+ years with a fairly stable temporal distribution, ranging from 5 trees in 1300 C.E. to 13 in 2000 C.E. (bottom panel of **Fig. 2**).

Increment cores were sectioned into decadal blocks (1991–2000, 1981–1990, ...) using a scalpel and processed individually to quantify the $^{13}C/^{12}C$ ratios in the wood samples (Esper *et al.,* 2010). From five of the 31 trees, this procedure was applied at annual resolution over the 1901–2009 period so that the resulting $\delta^{13}C$ timeseries from this sub-sample is decadally resolved before 1901 and annually resolved thereafter (Konter *et al.,* 2014). We extracted α-cellulose from the wood samples, homogenized and freeze dried the cellulose, and measured the $^{13}C/^{12}C$ ratios using an isotope ratio mass spectrometer, interfaced elemental analyzer, following standard procedures (Boettger *et al.,* 2007; Battipaglia *et al.,* 2008).

The isotope ratios are expressed in the conventional δ notation in parts per thousand (‰) relative to the Vienna Pee Dee Belemnite standard. The resulting $\delta^{13}C$ timeseries were corrected to account for atmospheric changes in $^{13}C/^{12}C$ composition due to combustion of fossil fuels (~1.8‰ from 1850–2009) and discrimination changes under elevated CO_2 concentrations (0.0073‰/ppmv CO_2) (Kürschner, 1996). In addition to this "Kur" correction we also discuss results based on the $^{13}C/^{12}C$ atmospheric correction (Atm), as well as additional plant physiological responses at the leaf level (0.02‰/ppmv CO_2; Fen) (Feng and Epstein, 1995; overview in Treydte *et al.,* 2009). Detailed assessments of the differently corrected $\delta^{13}C$ timeseries and calibration against instrumental climate data are reported in Konter *et al.* (2014).

The $\delta^{13}C$ timeseries were detrended using dendrochronological techniques (Cook and Kairiukstis, 1990) to account for level differences among single trees and age-trends inherent to the timeseries (Esper *et al.,* 2010). A detrended $\delta^{13}C$ chronology was developed by *(i)* aligning the $\delta^{13}C$ measurements prior to 1850 C.E. by biological age (to assess age-trend; **Fig. 2a**), *(ii)* removing $\delta^{13}C$ age-trends over the first 200 years of the trees' lifespans by calculating residuals from fitted exponential functions (**Fig. 2b**), *(iii)* removing additional $\delta^{13}C$ level differences of tree-rings older than 200 years by calculating residuals

Fig. 1. *Increment borers used to sample 5 mm diameter cores from living (left) and dead (right) Pinus uncinata near the timberline in the Spanish Pyrenees.*
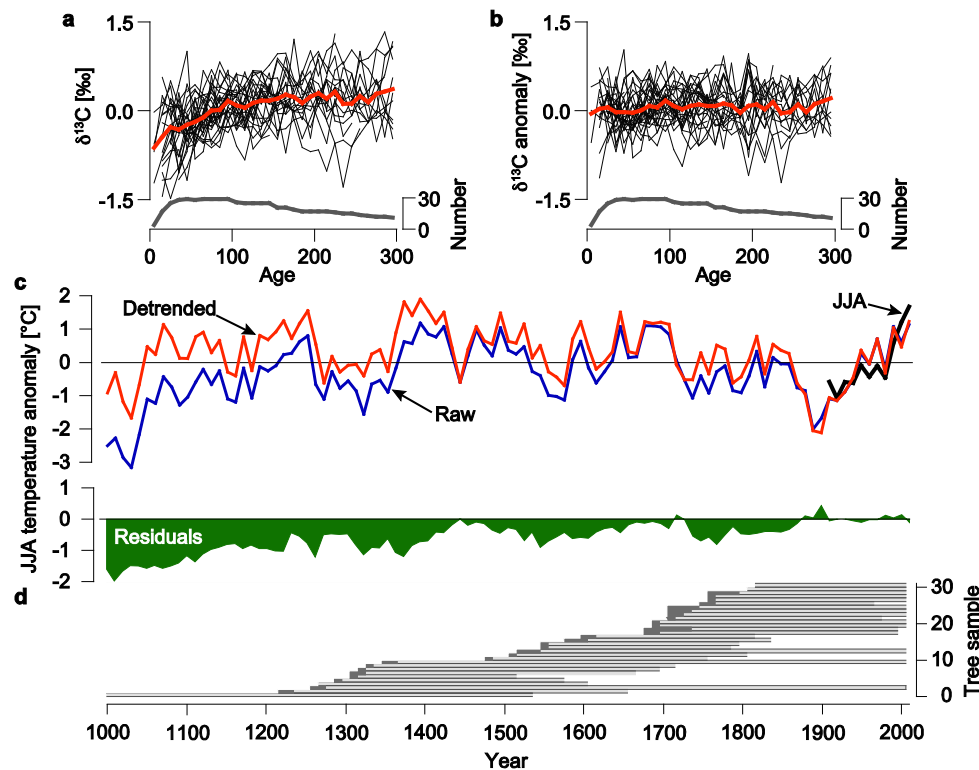
Fig. 2. *δ¹³C age-trend detection, correction, and chronology characteristics. (**a**) The raw δ¹³C measurement series of 31 trees (black) and their mean (red) after alignment by cambial age. The data prior to 1850 C.E. are shown to avoid biases due to modern δ¹³C correction procedures. Measurement series are expressed as anomalies with respect to the mean values over the years 1–200. Bottom panel shows the replication of the age-aligned data, including an initial increase up to cambial ages of ~30 years due to missing juvenile rings in core samples. (**b**) Same as in (**a**), but for the exponential and straight line detrended data. (**c**) Raw and detrended arithmetic mean chronologies after regression against regional JJA temperatures. Post-1850 data were Kur corrected, and chronology variance changes stabilized to remove effects due to replication changes (see Methods). Bottom panel shows the residual timeseries between the raw and detrended chronologies. (**d**) Temporal coverage of individual trees throughout the past millennium. Dark grey indicates the number of missing innermost rings on core samples.*

from the mean δ¹³C values of these mature rings, and *(iv)* calculating arithmetic means of the detrended δ¹³C timeseries. Temporal variance changes in the resulting chronology, due to replication changes from n = 13 trees in the 20th century to n < 5 trees in the 13th century, were removed by calculating ratios from running, 110-year (11 decadal values) standard deviations, derived from the first-differenced δ¹³C chronology (details in Frank *et al.,* 2007).

The final, detrended and variance stabilized, δ¹³C chronology was calibrated over the 1901–2009 period against gridded (CRU3.1) June-August (JJA) temperature data averaged over 0–3°E/38–43°N (Mitchell and Jones, 2005; Konter *et al.,* 2014). Calibration was performed using both the annually resolved proxy and instrumental data, as well as the decadally resolved data — with the JJA temperatures averaged to meet the decadal resolution of the δ¹³C timeseries. Split calibration/verification trials were performed over the 1951–2009 and 1901–1950 intervals, and the reduction of error (RE) and coefficient of efficiency (CE) calculated to estimate statistical skill of the proxy/climate association (Cook *et al.,* 1994). For

temperature reconstruction, the δ¹³C chronology was regressed against the decadally resolved JJA temperature data (Esper *et al.,* 2005). Reconstruction uncertainties were estimated by calculating the standard error (SE) from repeated (> 100 times) calibration trials using differently replicated (n = 13, n = 12, ..., n = 3) δ¹³C chronologies over the 20th century to account for the replication decline back in time. Finally, the δ¹³C based JJA temperature reconstruction is compared to a MXD based reconstruction that was originally calibrated against JJA maximum temperatures (Büntgen *et al.,* 2008) and a multi-site MXD based reconstruction calibrated against May-September mean temperatures (Dorado Liñán *et al.,* 2012). In this comparison, the temporal resolution of the MXD timeseries was reduced to match the decadally resolved δ¹³C record presented here.

3. RESULTS AND DISCUSSION

The removal of δ¹³C level differences and age-trends resulted in a millennium-long record indicating higher chronology levels back in time, compared to its non-

detrended "raw" counterpart (**Fig. 2**). The detrending procedure corrected the systematically lower $\delta^{13}C$ values of biologically younger rings likely triggered by the *(i)* uptake of CO_2 enriched ambient air from soil respiration (Francey and Farquhar, 1982), and *(ii)* decreased hydraulic resistances and higher stomatal conductance of smaller trees (McDowell *et al.,* 2002). As a consequence, the residual timeseries, between the raw and detrended chronologies, increases from –0.26°C in the 17th century to –0.74°C in the 13th century. However, it is important to note, the early periods of the chronology are represented by fewer trees (one before 1230 C.E.). The detrended $\delta^{13}C$ chronology produces higher values during late 15th, late 14th and early 13th centuries, compared to the late 20th century.

Calibration of the annually resolved 20th century $\delta^{13}C$ data against instrumental temperatures revealed a clear seasonal pattern including highest correlations with June, July, and August temperatures (**Fig. 3a**). The correlation against mean JJA temperatures is $r = 0.56$, though split-period calibration/verification trials indicate a weakening of this association back over the 20th century (**Fig. 3b**; $r_{1951-2009} = 0.47$ to $r_{1901-1950} = 0.28$), a finding that is likely related to a loss of skill in the meteorological network during the first half of the 20th century (see Konter *et al.,* 2014 for more detail on climate responses and effects of $\delta^{13}C$ correction procedures).

The JJA temperature signal is stronger at the decadal scale ($R^2 = 0.70$; $p < 0.05$), compared to the annual data ($R^2 = 0.32$; $p < 0.001$) (**Fig. 4**). However, the low-resolution calibration is based on much fewer degrees of freedom (~4) compared to the high-resolution approach (~64), owing to the reduced number of correlation pairs (11 decades compared to 109 annual values over 1901–

2009) and an increased lag-1 autocorrelation (0.56 compared to 0.46). The RE (0.66 for decadal and 0.62 for annual) and CE results (0.64 and 0.28) indicate the $\delta^{13}C$ timeseries match the JJA target data reasonably well, so

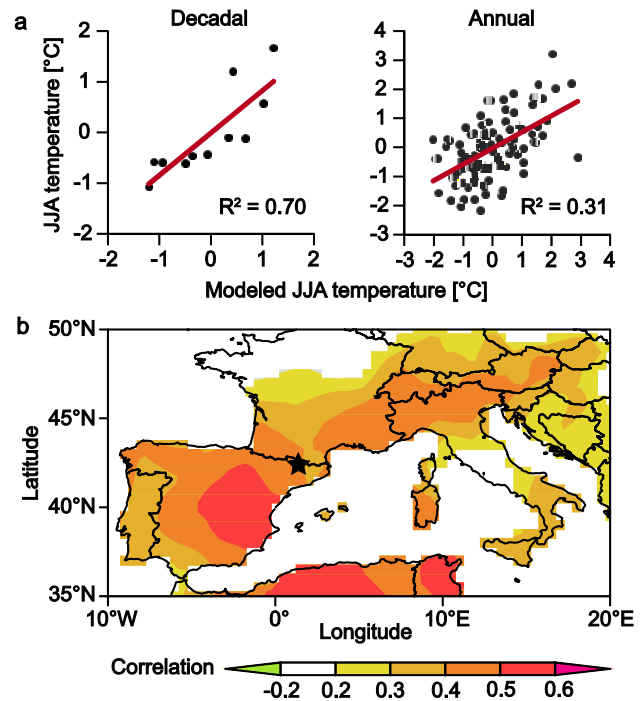**Fig. 4.** *$\delta^{13}C$ calibration against regional JJA temperatures. (**a**) Distribution and linear trends of the decadally (11 values) and annually resolved (109 values) $\delta^{13}C$ and JJA temperature data over the 1901–2009 period. (**b**) JJA temperature correlation field of the annually resolved $\delta^{13}C$ data. Star indicates the location of the sampling site.*
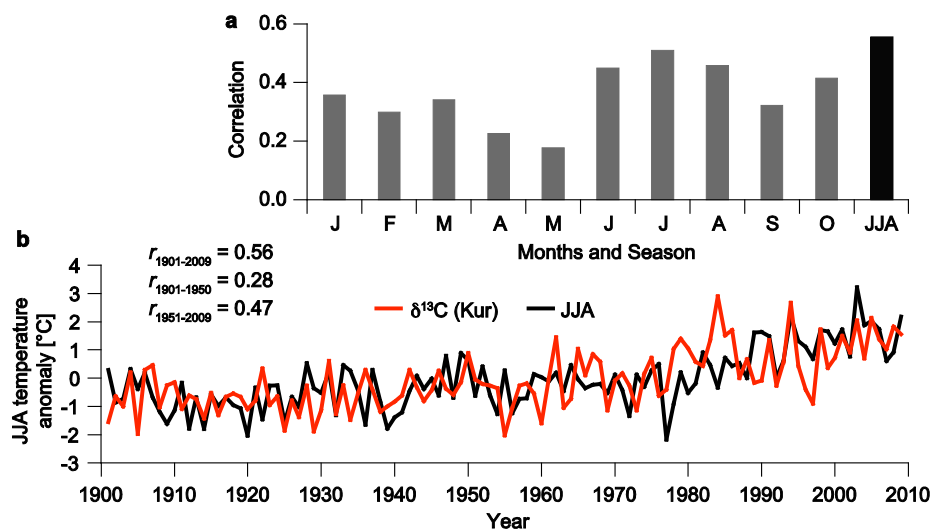

Fig. 3. *Calibration of the annually resolved $\delta^{13}C$ data. (**a**) Correlation results between the monthly (January to October) and seasonal (JJA) temperature (CRU3.1) and the Kur corrected $\delta^{13}C$ data over the 1901–2009 period. (**b**) The annually resolved $\delta^{13}C$ timeseries (red) scaled to match the mean and variance of the JJA temperature timeseries (black).*

that a reconstruction based on this proxy would have statistical skill. The spatial pattern of the signal ($r > 0.4$) indicates a predominating influence of Mediterranean synoptic systems on the pine isotopic composition, extending from Northern Africa into the Iberian Peninsula and eastwards over the European Alps (**Fig. 4b**).

The detrended $\delta^{13}C$ reconstruction exhibits decadal scale summer temperature variations ranging from +1.57°C in the 1390s C.E. to −1.83°C in the 1890s C.E. (**Fig. 5a**). The uncertainty band accompanying this reconstruction back to ~1260 C.E., the first decade represented by three trees, shows most of the temperature variations over the past 750 years did not deviate significantly from the 1961–1990 mean, however. The uncertainty band is increasing back in time as a function of the reduced replication of earlier chronology periods. Whereas more recently reconstructed temperatures (+1.01°C from 2001–2009) have been cooler than the late 14th and 15th centuries, the difference between these periods is insignificant.

The new $\delta^{13}C$ based reconstruction shares some characteristics of existing reconstructions derived from MXD data, including a long-term cooling trend from the late 14th to the mid 19th centuries (**Fig. 5b**). However, the high decadal scale summer temperature variance recorded in our $\delta^{13}C$ based record exceeds the variance retained in the MXD reconstructions that were originally calibrated against maximum temperatures (Büntgen *et al.*, 2008) and extended growing season temperatures (Dorado Liñán *et al.*, 2012). The reduced variability of the existing records likely arises from the application of detrending procedures to MXD datasets obtained from predominately living trees (Esper *et al.*, 2003). Consequently, the MXD based reconstructions do not pick up the cool late 19th/early 20th century conditions reflected in the early instrumental record (see black curves in **Fig. 5b**).

Our new $\delta^{13}C$ based reconstruction seems to capture 20th century temperature trends better than the existing MXD records. The performance improvement is largely determined by the applied atmospheric CO_2 correction. We considered the Kur, Fen, and Atm corrections in our reconstruction attempts, choosing the annually resolved reconstruction containing the least trend in residuals after calibration against instrumental summer temperatures (−0.01°C/decade for Kur, +0.06°C/decade for Fen, and −0.10°/decade for Atm; **Fig. 6**). However, the decision to favor one $\delta^{13}C$ correction scheme over another is generally not well justified (Treydte *et al.*, 2009), and perhaps represents the most significant constraint of the new summer temperature reconstruction presented here.
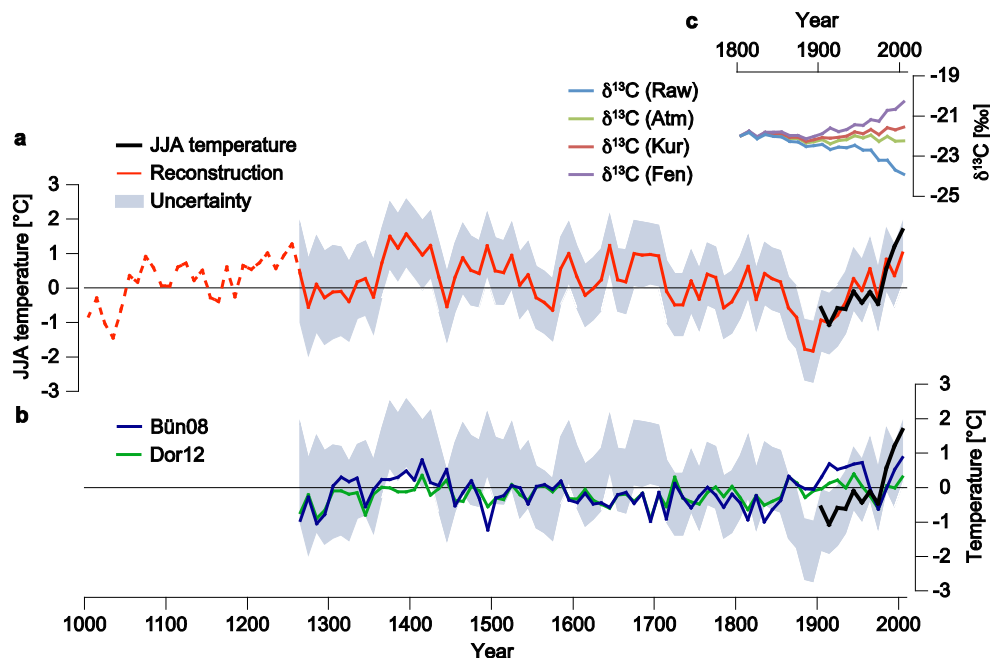

Fig. 5. *$\delta^{13}C$ based JJA temperature reconstruction and comparison with existing estimates. (**a**) Decadally resolved temperature reconstruction back to the 13th century derived from regression against JJA temperatures. Dashed curve indicates the period prior to 1260 C.E. when sample replication falls below three trees. The SE uncertainty band is derived from calibration trials against JJA temperatures using less-replicated chronologies to assess climate signal strengths during earlier chronology periods (see Methods). (**b**) MXD based JJA maximum (Büntgen et al., 2008) and May-September mean temperature (Dorado Liñán et al., 2012) reconstructions, plotted together with the regional JJA temperatures and uncertainty band from (**a**). All timeseries expressed as anomalies with respect to 1961–90. (**c**) Recent $\delta^{13}C$ chronology tails for the raw data and data after application of the Atm, Kur, and Fen corrections to account for atmospheric $^{13}C/^{12}C$ ratio and tree physiological effects.*
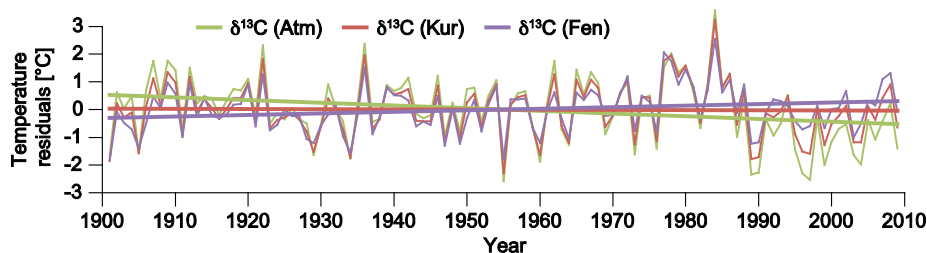
Fig. 6. *Proxy/climate residuals. Annual residuals between the scaled Atm, Kur, and Fen corrected $\delta^{13}C$ timeseries and the target JJA temperature timeseries (thin curves) shown together with the linear regression lines (bold curves) over the 1901–2009 period. Linear trends range from -0.10°/decade for the Atm, +0.06°C/decade for the Fen, to –0.01°C/decade for the Kur corrected data.*

4. CONCLUSIONS

The Spanish Pyrenees $\delta^{13}C$ based reconstruction presented here shows warmer and more variable growing season temperatures during the Little Ice Age than previously described (Büntgen *et al.,* 2008; Dorado Liñán *et al.,* 2012). Developing this reconstruction required systematically removing lower $\delta^{13}C$ values inherent to tree-rings younger than 200 years, that would otherwise lower the mean chronology levels during earlier periods of the past millennium, where these younger rings dominate the reconstruction. As a consequence, earlier warm periods during the late 14th and 15th centuries appear warmer, though not statistically significant, compared to the late 20th century.

A major constraint of the new reconstruction is the substantial difference in recent temperature trends caused by post-1850 $\delta^{13}C$ correction procedures. The correction applied here, accounting for atmospheric $^{13}C/^{12}C$ ratio and plant physiological effects, appeared most suitable as it produced a timeseries without any trend in residuals after regressing against instrumental temperatures. However, developing objective criteria for post-1850 correction, independent of the goodness of fit with instrumental target data, are needed to establish $\delta^{13}C$ based reconstructions as an additional proxy for studying climate variations over past millennia.

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