

Climatic response of multiple tree-ring parameters from the Spanish Central Pyrenees

U. Büntgen¹, J. Esper¹, A. Verstege¹, D. Nievergelt¹, D.C. Frank¹ & R.J.S. Wilson²

¹Swiss Federal Research Institute WSL, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland

²School of GeoSciences, Grant Institute, Edinburgh University, West Mains Road, Edinburgh EH9 3JW, Scotland
E-mail: buentgen@wsl.ch

Introduction

There are many studies showing that tree-ring data are highly useful for the assessment of past climatic variations. Annually resolved proxy time-series that extend several centuries back in time and reach into the 21st century, are, however, exceptionally rare. Temperature sensitive ring-width datasets of millennial length are restricted to a mere handful of geographic regions at high northern latitudes or higher elevations.

The paucity of long-term temperature sensitive tree-ring records is greatest in the mid to low-latitudes, and there are even less records if additional parameters (e.g., density) besides tree-ring width are demanded. Critical consequences are that (i) too few data exist to distinguish spatial patterns of climatic extremes, particularly prior to AD 1400 (D'Arrigo et al. 2006), (ii) large-scale reconstructions of temperature indicate substantial divergence in their amplitude (Esper et al. 2005), and (iii) the restriction to ring width data complicates benchmarking annual extremes (Büntgen et al. 2006a, b), as ring width measurements reflect only a short portion of high summer conditions with the tendency of containing some information of the previous year (Frank and Esper 2005). For the southern European region, detailed knowledge of the climatic signal preserved in different tree-ring parameters is limited. Previous dendroclimatological studies from the Pyrenees are based on ring width data from living trees only (Camarero et al. 1998; Gutiérrez 1991; Rolland and Schueller 1994; Ruiz-Flaño 1988; Tardif et al. 2003).

Here we seek to understand the potential of multiple tree-ring parameters for palaeoclimatic reconstructions in the western Mediterranean region. We have developed the first tree-ring dataset of living and dry-dead timberline wood from the Central Spanish Pyrenees that both extends into the 21st century and meanwhile reaches back prior to AD 1000 (with 58 series from three sites reaching back to AD1500). Five annualized tree-ring parameters were measured: tree-ring width, maximum latewood density, minimum earlywood density, earlywood width and latewood width, herein abbreviated as TRW, MXD, MID, EWW and LWW. Their climatic signal was assessed by comparison with regional temperature and precipitation data.

Data and methods

Tree-ring data and detrending

Three climatologically and partly ecologically similar high-elevation timberline sites: Gerber, Sobrestivo and Port de Cabus (hereinafter GER, SOB and CAB) were considered. Living and

in situ dry-dead (i.e., preserved on dry ground) pine (*Pinus uncinata* Ram.) trees of all age-classes were sampled. *Pinus uncinata* Ram. is a shade-intolerant species, most dominant within the sub-alpine Central Pyrenees between 1,600-2,500 m asl.

The GER site (42°38'N, 1°06'E) is located in the northern part of the National Park 'd'Aigüestortes I Estany de Sant Maurici' within an altitudinal range of 2,200-2,450 m asl. The SOB site (42°41'N, 0°06'E), ~70 km west of GER is located between the National Park 'de Ordesa y Monte Perdido' and the French border within an altitudinal range of 2,350-2,450 m asl. The CAB site (42°30'N, 1°25'E), ~50 km east of the GER site is located at the border between Spain and Andorra within an altitudinal range of 2,350-2,450 m asl (Figure 1). While GER and SOB are characterized by wide talus-slopes, CAB is less steep and dominated by an open-forest grassland.

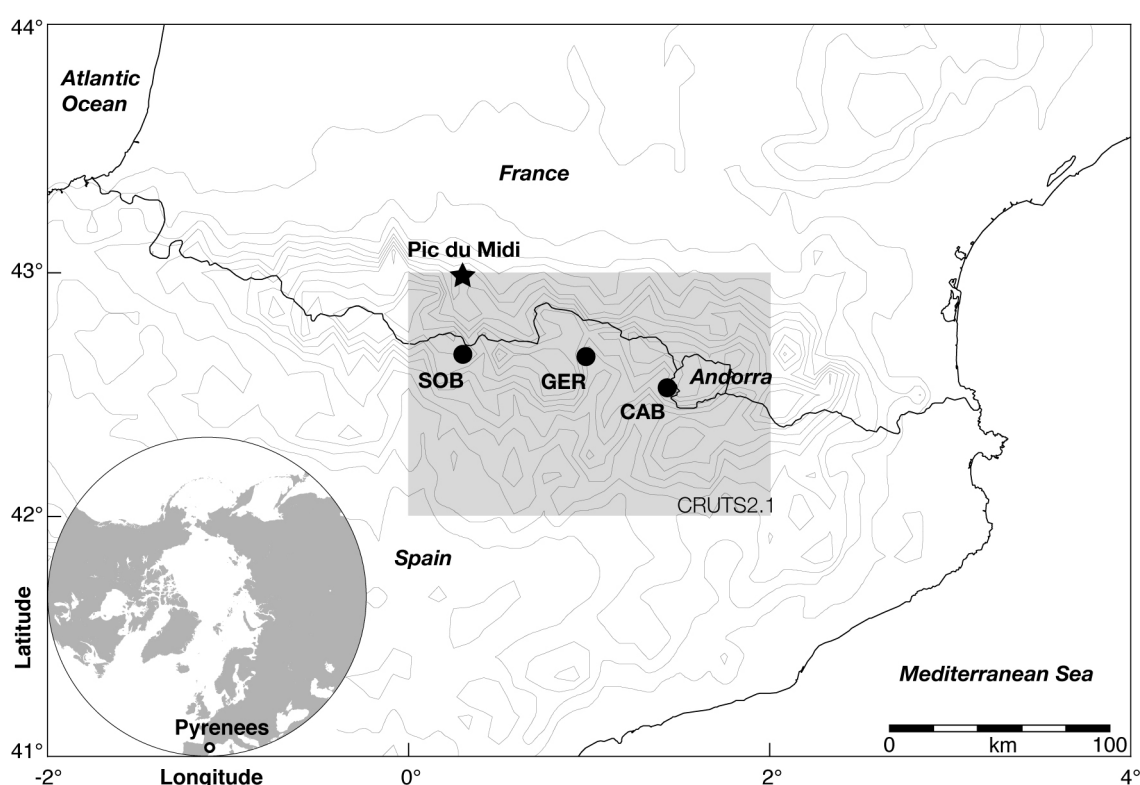


Figure 1: Location of the three timberline sites Gerber (GER), Sobrestivo (SOB), and Port de Cabus (CAB) in the Spanish Central Pyrenees. The inset map shows the location of the Pyrenees in a larger-scale context.

Generally two cores were taken from each tree using an increment borer. 62 (141) core samples from living (dead) trees were collected at GER, 26 (32) were collected at SOB, and 17 (25) were collected at CAB, respectively. Although full site control of the dry-dead material existed, the coring location (i.e., stem height) within relict trees often remained unclear, as advanced levels of wood decay yielded to sparse stem leftovers. However, as pines growing near the timberline commonly produce large amounts of resin that preserves the wood by hindering the growth of fungi long after a tree has died (e.g., Grudd et al. 2002). Consequently, dry-dead material herein considered, though often not more than small stem remains, has a wide age range, with the oldest germination date being in the AD 920s. For

this study, 303 core samples of all age-classes, i.e., segment length ranges from 11-732 years, were selected for MXD measurements (Figure 2). Wood was processed using a WALESCH 2003 X-ray densitometer with a resolution of 0.01 mm, and brightness variations transferred into g/cm^3 using a calibration wedge (Eschbach et al. 1995). High-resolution density profiles were then utilized to obtain the five tree-ring parameters: TRW, MXD, MID, EWW and LWW (Schweingruber et al. 1978).

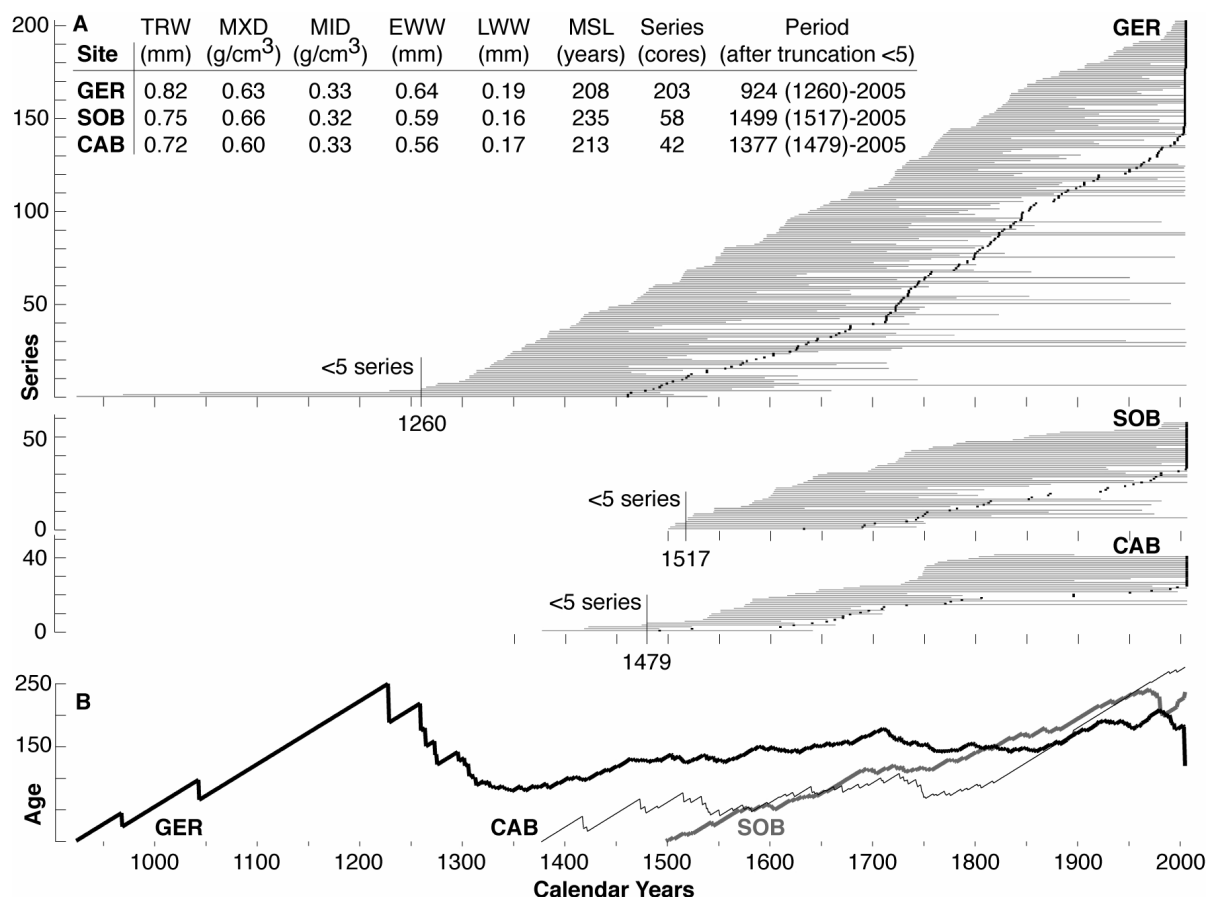


Figure 2: A) Temporal distribution of the 203 Gerber (GER), 58 Sobrestivo (SOB), and 42 Port de Cabus (CAB) core samples. Note the reduction in sample size <5 series prior to AD 1260, 1517 and 1479, respectively. Black dots denote potential sample distribution if series are ordered by their outermost ring. B) Mean cambial age of the GER, SOB and CAB samples for each calendar year. The inset table compares the five individual tree-ring parameters and chronology characteristics on a site-by-site level.

To remove non-climatic, age-related growth trends from the raw measurement series (Fritts 1976), though allow variations from inter-annual to multi-decadal length to be preserved, individual series standardization was applied using ARSTAN (Cook 1985). Indices were calculated as ratios from relatively stiff 300-year cubic smoothing splines (Cook and Peters 1981). For details see Cook et al. (1995) and Esper et al. (2003), for example. For chronology development, series were averaged using a bi-weight robust mean. The variance in the mean chronology was stabilized using methods described by Osborn et al. (1997). Signal strength of the chronologies was assessed using a 'moving window' approach of the inter-series correlation (R_{bar}), and the expressed population signal (EPS ; Wigley et al.

1984). *Rbar* is a measure of common variance between single series, independent of the number of measurement series. *EPS* is an absolute measure of chronology error that determines how well a chronology, based on a finite number of trees, estimates the theoretical population chronology from which it has been drawn. *EPS* quantifies the degree to which this particular sample record portrays the theoretical population chronology.

Meteorological data

For growth/climate response analyses, records of monthly minimum and maximum temperatures from the Pic du Midi mountain observatory (Pic du Midi de Bigorre: 2,862 m asl, 43°04'N, 0°09'E) were used. See Bücher and Dessens (1991) and Dessens and Bücher (1995, 1997) for details. A dataset of gridded (0.5°x0.5°) monthly temperature means and precipitation sums was further considered (CRUTS2.1; Mitchell and Jones 2005). Mean values from 15 grid-boxes covering the 42-43°N and 0-2°E region were utilized.

Local climate conditions of the GER site were estimated from three nearby high-elevation instrumental station records: *Bonaigua* (2,263 m asl, 42°40'N, 1°06'E), *Sant Maurici* (1,920 m asl, 42°34'N, 1°00'E), *Estany-Gento* (2,120 m asl, 42°30'N, 1°00'E). The mean annual temperature with respect to the 1961-90 period is ~4.3°C, with the lowest (-2.5°C) and highest (13.1°C) monthly values measured in January and July, respectively. The mean annual precipitation is ~1250 mm, evenly distributed throughout the year, which is likely due to the study's location in commonly prevailing air masses of maritime origin, and the existence of convective summer precipitation during periods of persistent high-pressure influence from the Azores-high.

Results

Growth-trends

Raw measurement series of each of the five parameters were age-aligned on a site-by-site basis (considering pith-offset estimation), and their mean growth trends, the so-called regional curves (RCs) estimated (Figure 3). Resulting RCs depict the common growth trend of a given species, parameter and site. Increased variance towards the series outermost ends is induced by low sample replication. While the RCs estimated for TRW, EWW and LWW resemble negative exponential functions, i.e., high values during the juvenile phase (~50 years) followed by an exponential decrease, the RCs derived from MXD describe a somewhat generalized linear decline. After a short juvenile period of high densities until ~25 years, RCs for the MID parameter are nearly horizontal.

Surprisingly, the greatest between site differences are found for MXD, whereas the other parameters show rather similar growth trends at each site. Age-aligned MXD values from the CAB site show almost no juvenile increase following a horizontal line with a relative low mean. Note that the other parameters derived from CAB, though, show a clear juvenile growth pattern, indicating that only little to no pith offset is given. Although MXD values from the GER and SOB sites show a slight juvenile increase, their linear trends are nearly flat, however, characterized by different mean values.

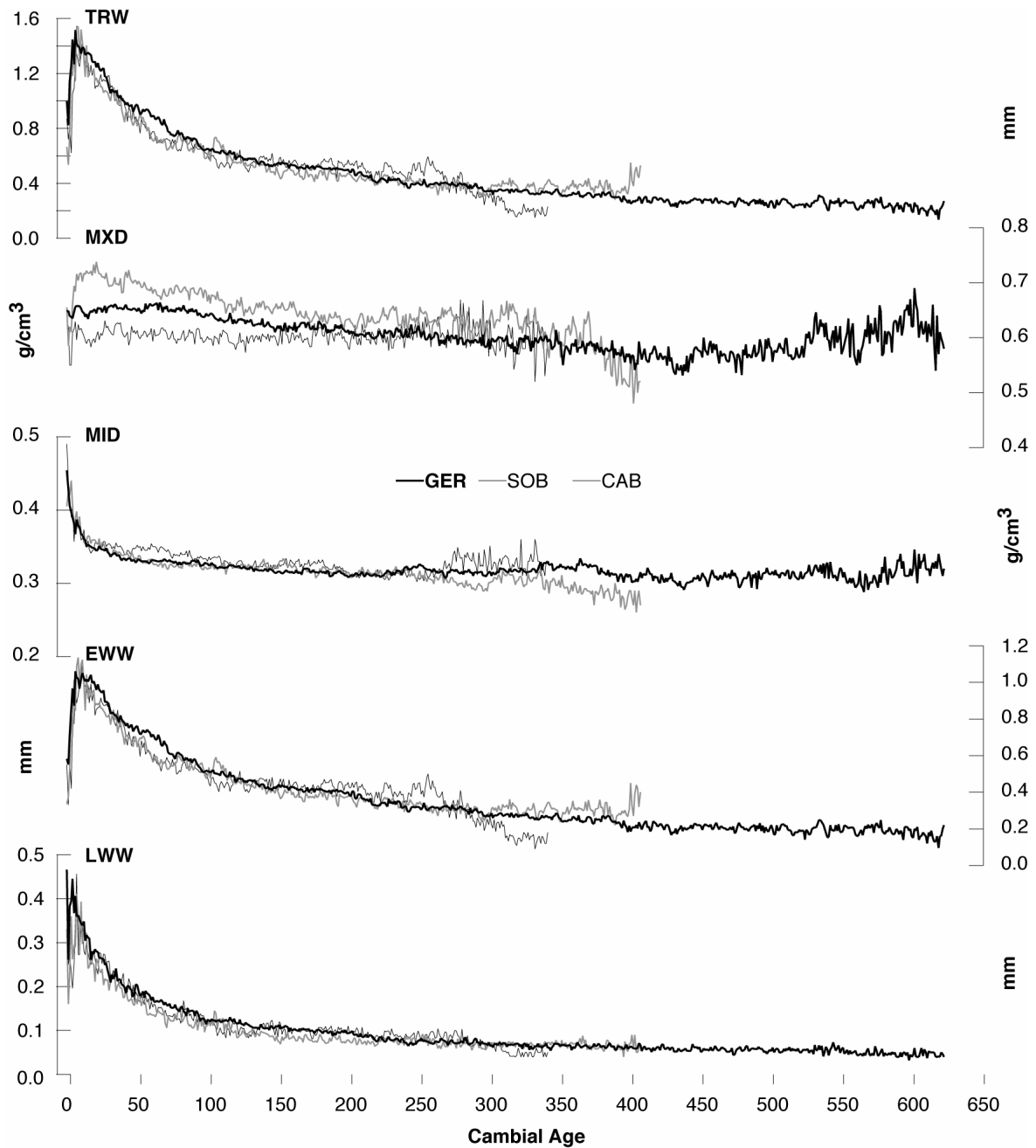


Figure 3: Mean growth trends of the five parameters after age-aligning all series by cambial age (considering pith-offset estimation) on a site-by-site basis. Regional curves are truncated at 5 series.

Chronology characteristics

Visual comparison of the 20-year low-pass filtered site chronologies (using individual 300-year spline detrending) illustrates some common decadal-scale variability in the TRW, MXD, EWW and LWW series, but less agreement with MID chronologies (Figure 4). Distinct decadal-scale depressions are recorded around 1600 AD, 1700, in the 1820s and 1970s in the TRW, MXD, EWW and LWW chronologies that coincide with the timing of solar minima (Luterbacher et al. 2001; Wanner et al. 1995), and/or periods of increased volcanic activity (Oppenheimer 2003). Similar TRW and MXD responses to solar and volcanic forcing are reported from the European Alps (Büntgen et al. 2006a), Tatra Mountains (Büntgen et al.

2006b) and Canadian Rockies (Luckman and Wilson 2005), for example. In contrast, the MID chronologies show increased values during these periods.

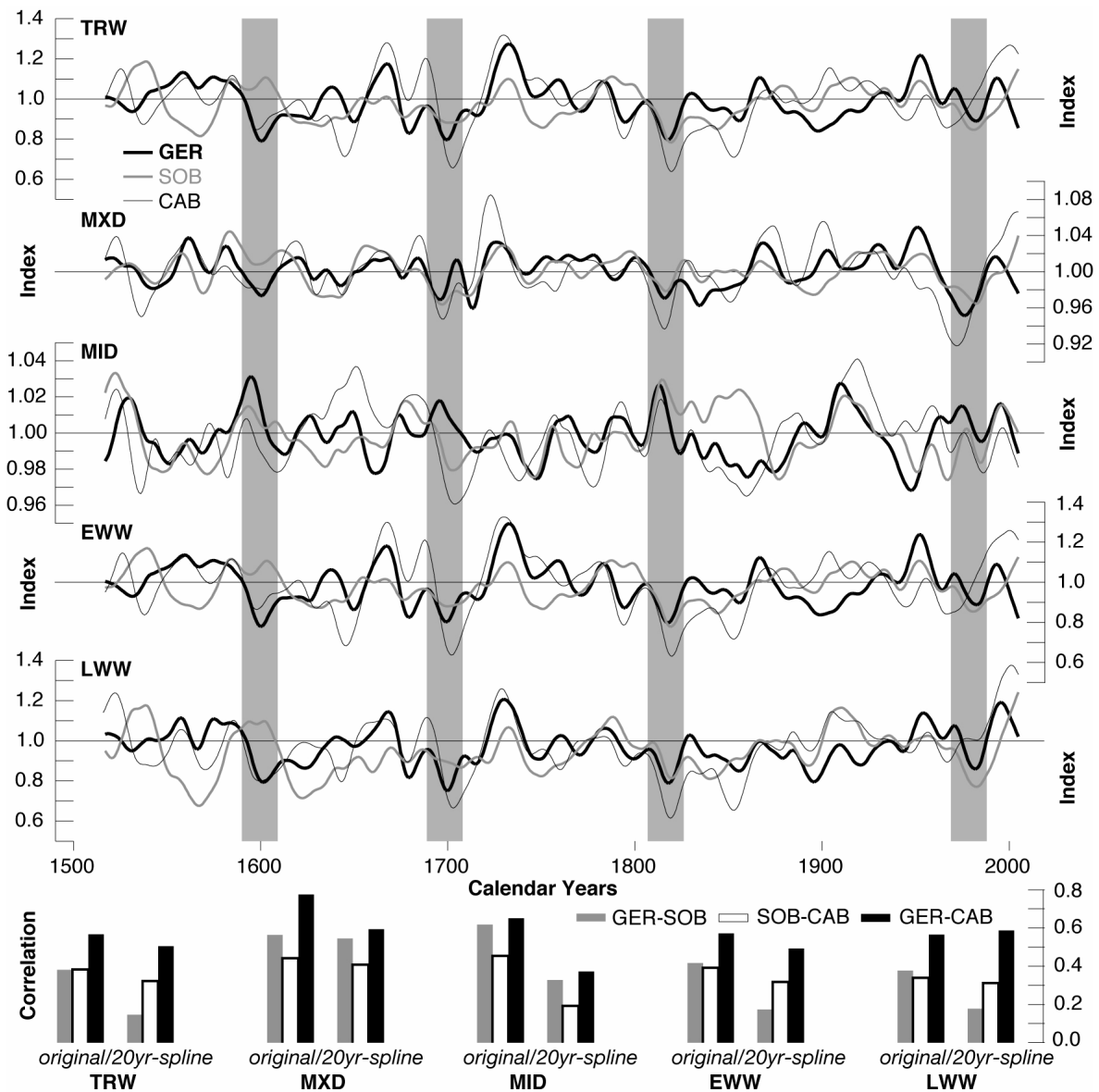


Figure 4: Site chronologies (GER = black; SOB = grey; CAB = light grey) of the five parameters after standardization using fixed 300-year smoothing splines. Series are 20-year low-pass filtered, truncated at <5 series and shown over their common 1517–2005 period. Grey shadings denote periods of common decadal-scale growth depressions in the TRW, MXD, EWW and LWW series. Bar plots denote intra-parameter correlations between the three sites GER, SOB and CAB, using the original (left) and low-pass filtered (right) chronologies.

Correlations between chronologies of the same parameter, but from different sites, show highest agreement between the GER and CAB data. Such inter-site correlations are most significant for MXD, followed by MID, and generally lower for all three ‘width’ parameters (Figure 4). While inter-site coherency of the ‘density’ chronologies is strongest between the original chronologies and tends to decrease after 20-year low-pass filtering, coherency of the ‘width’ chronologies is equally distributed amongst inter-annual and multi-decadal frequency.

Interestingly, lowest correlations are obtained between the smoothed TRW, EWW and LWW chronologies from GER and SOB, most likely reflecting the parameters high degree of unexplained mid-frequency variability, in comparison to MXD.

First order autocorrelation is lowest for MXD, followed by slightly higher values for MID (Table 1). LWW, EWW and particularly TRW, however, show significant first order autocorrelation, reflecting biological persistence in radial growth (Frank and Esper 2005a). Hence, there is a tendency of overestimating decadal-scale variability when using TRW measurements for reconstructing past environmental conditions, as the 'target's' autocorrelation is lower. Out of all five parameters, the lowest autocorrelation is derived from GER, whereas increased values obtained from SOB and CAB are fairly similar. *Rbar* and *EPS* statistics of the SOB site are generally lower than those of the GER and CAB sites. Robust *EPS* statistics for the GER chronology most likely result from the high sample depth, whereas stable *EPS* statistics for the CAB chronology most likely result from open forest-grassland site conditions, which result in less between tree competition and physical stress (e.g., rock fall). Signal strength of the SOB chronology, however, possibly suffers from low replication and the severe talus-slope site condition (e.g., increased rock fall activity). Such indicators of chronology signal strength are relatively high for the MXD, TRW and EWW records, compared to lower values obtained for the MID and LWW chronologies.

Table 1: Chronology characteristics of the five parameters on a site-by-site basis using the 1517-2005 common period. AC_1 refers to the records autocorrelation lagged by one year. Rbar and EPS are mean value statistics from using 30-year windows lagged by 50%.

	TRW			MXD			MID			EWW			LWW		
	GER	SOB	CAB	GER	SOB	CAB	GER	SOB	CAB	GER	SOB	CAB	GER	SOB	CAB
AC_1	0.41	0.54	0.63	0.00	0.22	0.19	0.12	0.28	0.28	0.38	0.48	0.61	0.25	0.48	0.48
Rbar	0.26	0.21	0.32	0.29	0.15	0.35	0.14	0.13	0.16	0.26	0.21	0.32	0.17	0.17	0.22
EPS	0.95	0.86	0.87	0.96	0.80	0.89	0.91	0.76	0.72	0.96	0.86	0.87	0.93	0.83	0.80

With respect to the common signal reported from the three site chronologies and to provide a more comprehensive regional-scale approach, five records (TRW, MXD, MID, EWW, LWW) were averaged using all 303 measurement-series available. These resulting mean parameter chronologies reflect growth patterns of the Central Pyrenees, and thus are most suitable for the comparison with climate data. For the 20th century where maximum proxy replication is given and instrumental measurements of monthly temperature means and precipitation sums are most reliable, a detailed examination on inter-annual growth variations of the five parameters was conducted (Figure 5).

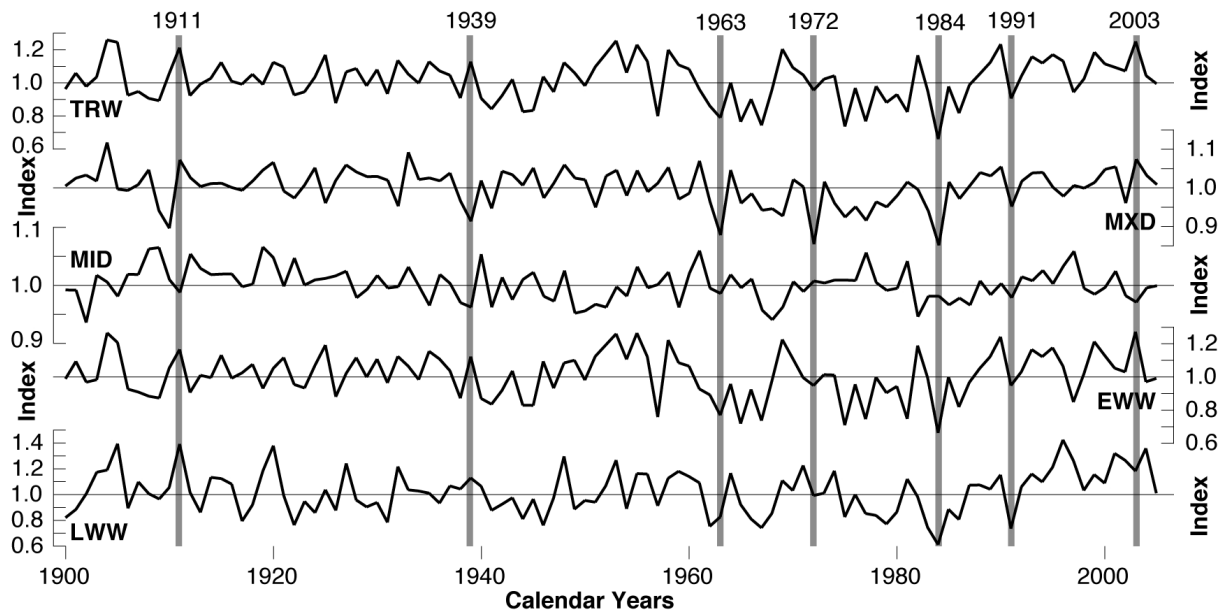


Figure 5: Mean series of the five parameters after averaging the three sites chronologies standardized using fixed 300-year smoothing splines. Grey shadings denote common extremes in annual growth variations.

Due to the applied individual spline detrending, vital inter-annual to multi-decadal scale variability was preserved, whereas potential longer-term trends were consequently removed. Indices are relatively stable from 1900 to ~1940, followed by a slight increase until ~1955 and small depressions ~1965 and ~1975. An increase is observed over the last 30 years with a peak in 2003. These decadal-scale fluctuations are distinct in the ‘width’ chronologies, but less pronounced in the ‘density’ records. A positive pointer year in 1911 is reported from all parameters with the exception of MID, which shows a negative anomaly. A similar pattern occurs in 2003 where all parameters show a positive pointer year, but a low value is found for MID, and also for LWW. Annual growth depressions common to all five parameters are found in 1963 and 1991 (most likely due to volcanic eruptions), whereas MID shows relatively stable values in 1972 and 1984, and all other parameters indicate negative anomalies. In 1939 the three ‘width’ parameters show a positive value, whereas the two ‘density’ parameters show a negative anomaly.

Correlations between the mean TRW, EWW, LWW and also the MXD chronologies are significant ($p < 0.01$), whereas no significant correlations are found for the MID chronology (Table 2). Correlations between the five parameters computed over the 1901-2002 period (which is used for comparison with meteorological data) remain stable even if the full period 1517-2005 is used.

Table 2: Correlation matrix of the five mean parameter chronologies as introduced in figure 5. Correlations in the upper right part of the matrix refer to the 1901-2002 period of overlap with the instrumental data, while correlations in the lower left derive from the full 1517-2005 period common to all chronologies after truncation <5 series.

		1901-2002			
		TRW	MXD	MID	LWW
1517-2005	TRW		0.44	-0.10	0.98
	MXD	0.36		0.26	0.39
	MID	-0.18	0.06		-0.18
	EWV	0.98	0.36	-0.25	
	LWW	0.73	0.30	0.13	0.59

Growth/climate response

Growth/climate response analysis between the five mean parameter chronologies and minimum, mean, and maximum temperature and precipitation data was undertaken (Figure 6). Correlations were computed over the common period 1901-2002, using an 18-month window from May of the year prior to tree growth until current year October, along with various seasonal means.

MXD revealed generally significant ($p < 0.01$) response to monthly March, May and August, and various seasonal temperature means of the current year. May-September temperatures yielded the highest correlation. MXD correlations with current year June and July temperatures, along with those of the previous year and precipitation sums of all target windows were found to be not significant ($p < 0.01$). Even though, this generally derived response pattern (monthly May and August, seasonal May-September) of the MXD parameter exists for all temperature records, highest correlations are gained from maximum, and lowest correlations from minimum temperatures. Detailed information on the potential of reconstructing regional-scale maximum summer temperatures back into medieval times using MXD data is provided in Büntgen et al. (in review). A nearly similar MXD response to maximum growing season temperatures is further reported from the Canadian Rocky Mountains (Luckman and Wilson 2005; Wilson and Luckman 2003). A comparable pattern of MXD formation, i.e., during the early and late vegetation period with less vitality in between, is reported from a larch network from nearby timberline sites in the Swiss Alps (Büntgen et al. 2006a), from a multi-species network across the Alpine arc (Frank and Esper 2005), the Tatra Mountains in the northwestern Carpathian region (Büntgen et al. 2006b), and from hundreds of sites along the northern latitudinal timberline (Briffa et al. 2002). An altitudinal/latitudinal modification of the absolute growing season length, however, must be considered, when comparing results from different geographical settings.

MID revealed a somewhat similar monthly response pattern as described for MXD, with lower significance, though. Remarkable differences, however, are the significant ($p < 0.01$) negative response of MID to July and all high summer seasonal temperature means, complimenting the inverted correlation results as described above.

TRW, EWW and LWW correlations with minimum, mean and maximum temperatures and precipitation sums are not significant, or show only slightly coherence. The first month that shows significant, and at the same time highest correlations ($p < 0.01$), independent of the parameter and temperature data considered, is May. A similar relationship between radial growth and May temperatures of several high-elevation *Pinus uncinata* TRW sites from the Central Spanish Pyrenees has been observed by Tardif et al. (2003), however, they also describe some effect of previous November temperatures on tree growth.

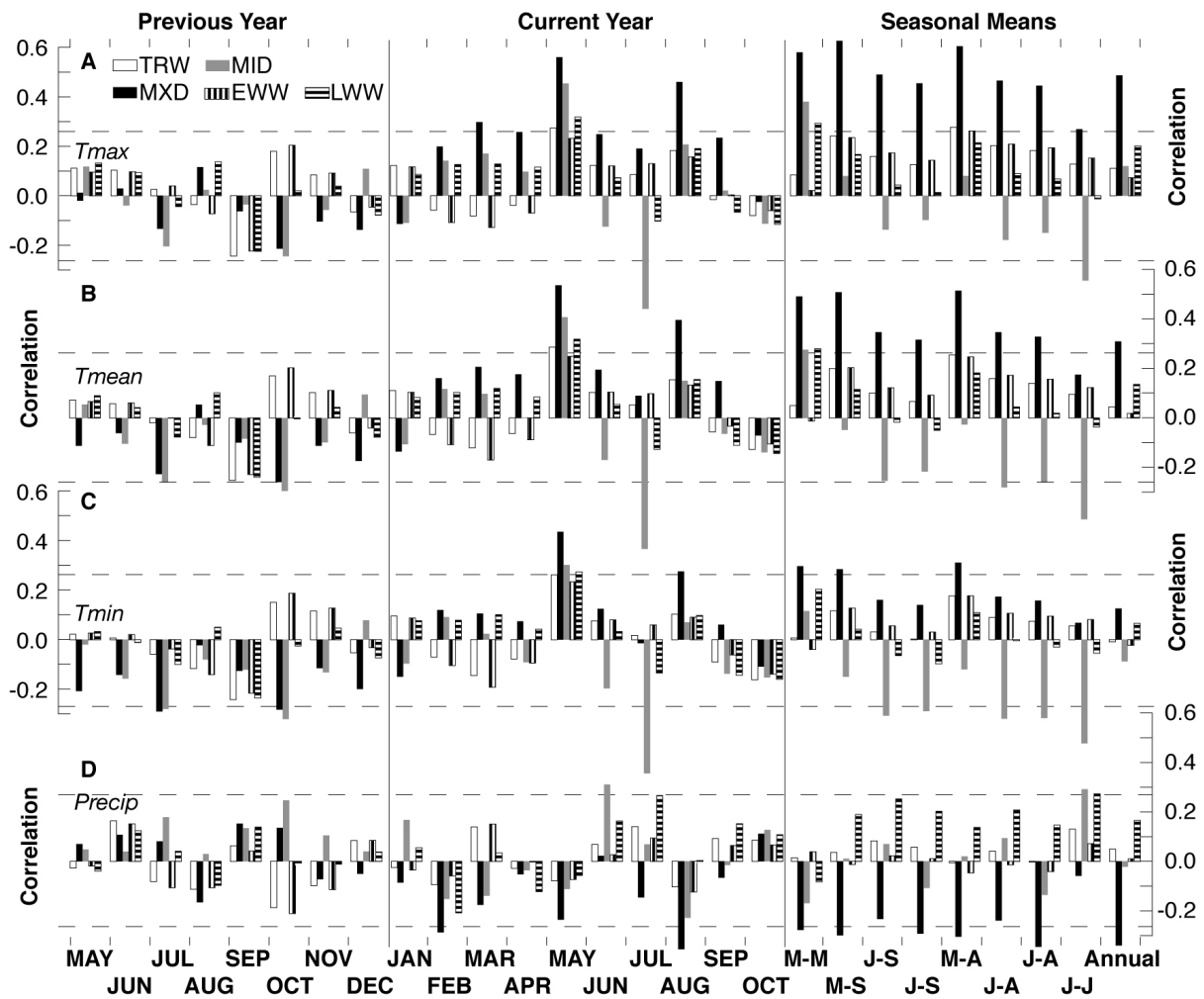


Figure 6: Growth/climate response of the five parameters using A maximum temperatures, B mean temperatures, C minimum temperatures, and D precipitation sums. Correlations are computed from previous year May to current year October over the 1901-2002 common period. Horizontal dashed lines denote the 99% significance levels, corrected for lag-1 autocorrelation. Temperature data derive from the Pic du Midi station, and precipitation data from the CRUTS2.1 gridded dataset, using the mean of 15 grid-boxes that cover the 0-2°E and 42-43°N region. Seasonal abbreviations refer to March-May, May-September, June-September, July-September, May-August, June-August, July-August, June-July, respectively.

Discussion and conclusions

We have presented a new collection of living and dry-dead wood from three timberline sites in the Central Spanish Pyrenees resulting in a composite dataset spanning the AD 924-2005

period. For each site chronology five parameters were measured and compared with regional-scale climate data. While MXD revealed a distinct positive response to May-September temperatures, MID showed a distinct negative response to July and June-July mean temperatures. All other parameters showed no or little response. Even though the dataset utilized, the methods applied and the climate response derived demonstrate the capability of high-elevation *Pinus uncinata* MXD data to robustly reconstruct variations in maximum summer temperatures, several limitations remain.

Even though, all relict material from the three sampling sites is compiled, robust replication still ceases to exist before AD 1500. When sampling dry-dead material, variable degrees of wood decay complicate knowing the stem's coring location. Sometimes samples were collected far from the base of a tree or at unknown heights, hindering the exact dating of the tree's germination date, and potentially introducing some bias in the climatic signal preserved. The individual spline detrending applied, restricts the final chronologies to reflect inter-annual to multi-decadal variations and eliminates potential lower frequency information. To gain a somewhat distinct summer temperature signal, capable for the assessment of past variations, extensive measurements of MXD are required, as TRW revealed a diminished growth/climate response. It appears that only trees growing under severe timberline conditions maintain a temperature signal, whereas radial growth at lower elevation reflects a mixed signal likely to be dominated by changes in precipitation. A reduced number of long and homogenized instrumental station data reflecting climate conditions of the high-elevation sampling sites, further hinders comparison, calibration and verification over longer periods.

Our analysis demonstrates that MXD is the strongest proxy for the reconstruction of past summer temperature variations in the Central Spanish Pyrenees, whereas all other parameters expressed only a weak signal at best. This study, however, also showed that differences independent of the parameter exist between the three sites. To gain insight into such local-scale variability and at the same time allow regional-scale conclusions to be drawn, future research will need to consider (i) the update of existing and (ii) development of new MXD chronologies covering the entire Pyrenees from the Mediterranean Sea in the east to the Atlantic Ocean in the west. New samplings should be focused at (iii) high-elevations and possible compile (iv) dry-dead and sub-fossil wood.

Acknowledgements

We thank F.H. Schweingruber for site selection, the National Park d'Aigüestortes i Estany de Sant Maurici (Jordi Vicente i Canillas) for sampling permission and logistic support. J. Dessens kindly provided instrumental data from the Pic du Midi, and the National Institute of Meteorology (Centre Meteorològic Territorial a Catalunya) made their data available. Supported by the SNSF project Euro-Trans (#200021-105663) and the EU project Millennium (#017008).

References

- Briffa, K.R., Osborn, T.J., Schweingruber, F.H., Jones, P.D., Shiyatov, S.G., Vaganov, E.A. (2002): Tree-ring width and density around the Northern Hemisphere: Part 1, local and regional climate signals. *The Holocene* 12:737-757.
- Bücher, A., Dessens, J. (1991): Secular trend of surface temperature at an elevated observatory in the Pyrenees. *Journal of Climate* 4:859-868.
- Büntgen, U., Frank, D.C., Nievergelt, D., Esper, J. (2006a): Summer temperature variations in the European Alps, AD 755-2004. *Journal of Climate* 19:5606-5623.
- Büntgen, U., Frank, D.C., Kaczka, R.J., Verstege, A., Zwijacz-Kozica, T., Esper, J. (2006b): Growth/climate response of a multi-species tree-ring network in the Western Carpathian Tatra Mountains, Poland and Slovakia. *Tree Physiology* (in press).
- Büntgen, U., Frank, D.C., Grudd, H., Verstege, A., Nievergelt, D., Esper, J. (in review): Eight centuries of Pyrenees summer temperatures from tree-ring density. *Climate Dynamics*.
- Camarero, J.J., Guerrero-Campo, J., Gutiérrez, E. (1998): Tree-ring growth and structure of *Pinus uncinata* and *Pinus sylvestris* in the Central Spanish Pyrenees. *Arctic and Alpine Research* 30:1-10.
- Cook, E.R. (1985): A time series analysis approach to tree-ring standardization. Ph.D. Thesis, University of Arizona pp 171.
- Cook, E.R., Peters, K. (1981): The smoothing spline: A new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. *Tree-Ring Bulletin* 41:45-53.
- Cook, E.R., Briffa, K.R., Meko, D.M., Graybill, D.A., Funkhouser, G. (1995): The 'segment length curse' in long tree-ring chronology development for palaeoclimatic studies. *The Holocene* 5:229-237.
- D'Arrigo, R., Wilson, R.J.S., Jacoby, G.C. (2006): On the long-term context for late 20th century warming. *Journal of Geophysical Research* 111, D03103, doi:10.1029/2005JD006352.
- Dessens, J., Bücher, A. (1995): Changes in minimum and maximum temperatures at the Pic du Midi in relation with humidity and cloudiness, 1882-1984. *Atmospheric Research* 37:147-162.
- Dessens, J., Bücher, A. (1997): A critical examination of the precipitation records at the Pic du Midi observatory, Pyrenees, France. *Climatic Change* 36:345-353.
- Eschbach, W., Nogler, P., Schär, E., Schweingruber, F.H. (1995): Technical advances in the radiodensitometrical determination of wood density. *Dendrochronologia* 13:155-168.
- Esper, J., Cook, E.R., Krusic, P.J., Peters, K., Schweingruber, F.H. (2003): Tests of the RCS method for preserving low-frequency variability in long tree-ring chronologies. *Tree-Ring Research* 59:81-98.
- Esper, J., Wilson, R.J.S., Frank, D.C., Moberg, A., Wanner, H., Luterbacher, J. (2005): Climate: Past Ranges and Future Changes. *Quaternary Science Reviews* 24:2164-2166.
- Frank, D.C., Esper, J. (2005): Characterization and climate response patterns of a high elevation, multi species tree-ring network for the European Alps. *Dendrochronologia* 22:107-121.
- Fritts, H.C. (1976): Tree rings and climate. Academic Press, London, pp 567.

- Grudd, H., Briffa, K.R., Karlén, W., Bartholin, T.S., Jones, P.D., Kromer, B. (2002): A 7400-year tree-ring chronology in northern Swedish Lapland: natural climatic variability expressed on annual to millennial timescales. *The Holocene* 12:657-665.
- Gutiérrez, E. (1991): Climatic tree growth relationships for *Pinus uncinata* Ram. in the Spanish pre-Pyrenees. *Acta Oecologia* 12/2:213-225.
- Luckman, B.H., Wilson, R.J.S. (2005): Summer temperatures in the Canadian Rockies during the last millennium: a revised record. *Climate Dynamics* 24:131-144.
- Luterbacher, J., Rickli, R., Xoplaki, E., Tinguely, C., Beck, C., Pfister, C., Wanner, H. (2001): The Late Maunder Minimum (1675-1715) – A key period for studying decadal scale climate change in Europe. *Climatic Change* 49:441-462.
- Mitchell, T.D., Jones, P.D. (2005): An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology* 25:693-712.
- Oppenheimer, C. (2003): Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815. *Progress of Physical Geography* 27/2:230-259.
- Osborn, T.J., Briffa, K.R., Jones, P.D. (1997): Adjusting variance for sample-size in tree-ring chronologies and other regional-mean time-series. *Dendrochronologia* 15:89-99.
- Rolland, C., Schueller, F. (1994): Relationships between mountain pine and climate in the French Pyrenees (Font-Romeu) studied using the radiodensitometrical method. *Pirineos* 143/144:55-70.
- Ruiz-Flaño, P. (1988): Dendroclimatic series of *Pinus uncinata* R. in the Central Pyrenees and in the Iberian System. A comparative study. *Pirineos* 132:49-64.
- Schweingruber, F.H., Fritts, H.C., Bräker, O.U., Drew, L.G., Schär, E. (1978): The X-ray technique as applied to dendroclimatology. *Tree-Ring Bulletin* 38:61-91.
- Tardif, J., Camarero, J.J., Ribas, M., Gutiérrez, E. (2003): Spatiotemporal variability in tree growth in the Central Pyrenees: Climatic and site influences. *Ecological Monographs* 73:241-257.
- Wanner, H., Pfister, C., Brázdil, R., Frich, P., Frydendahl, K., Jónsson, T., Kington, J., Rosenørn, S., Wishman, E. (1995): Wintertime European circulation patterns during the Late Maunder Minimum cooling period (1675–1704). *Theoretical and Applied Climatology* 51:167-175.
- Wigley, T.M.L., Briffa, K.R., Jones, P.D. (1984): On the average of value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Climatology and Applied Meteorology* 23:201-213.
- Wilson, R.J.S., Luckman, B.H. (2003): Dendroclimatic Reconstruction of Maximum Summer Temperatures from Upper Tree-Line Sites in Interior British Columbia. *The Holocene* 13:853-863.