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Testing for tree-ring divergence in the European Alps

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Abstract

Evidence for reduced sensitivity of tree growth to temperature has been reported from multiple forests along the high northern latitudes. This alleged circumpolar phenomenon described the apparent inability of temperature-sensitive tree-ring width and density chronologies to parallel increasing instrumental temperature measurements since the mid-20th century. In addition to such low-frequency trend offset, the inability of formerly temperature-sensitive tree growth to reflect high-frequency temperature signals in a warming world is indicated at some boreal sites, mainly in Alaska, the Yukon and Siberia. Here, we refer to both of these findings as the 'divergence problem' (DP), with their causes and scale being debated. If DP is widespread and the result of climatic forcing, the overall reliability of tree-ring-based temperature reconstructions should be questioned. Testing for DP benefits from well-replicated tree-ring and instrumental data spanning from the 19th to the 21st century. Here, we present a network of 124 larch and spruce sites across the European Alpine arc. Tree-ring width chronologies from 40 larch and 24 spruce sites were selected based on their correlation with early (1864–1933) instrumental temperatures to assess their ability of tracking recent (1934–2003) temperature variations. After the tree-ring series of both species were detrended in a manner that allows low-frequency variations to be preserved and scaled against summer temperatures, no unusual late 20th century DP is found. Independent tree-ring width and density evidence for unprecedented late 20th century temperatures with respect to the past millennium further reinforces our results.

Keywords: climate change, conifers, dendroclimatology, global warming, growth responses, temperature reconstructions

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Introduction

Annually resolved reconstructions of millennial-long temperature variations are primarily derived from tree-ring width (TRW) or density chronologies (IPCC, 2007). A potential bias limiting the palaeoclimatic interpretation of these data is often seen as a low-frequency offset between tree growth that does not parallel the increase in summer temperatures. Another bias is a decrease in high-frequency sensitivity (i.e., correlation) of tree growth at some previously temperature-limited sites over the second half of the 20th century. This phenomenon has been recently described as the 'divergence problem' (DP; D'Arrigo *et al*., 2008) and has been reported from multiple conifer sites across the high northern latitudes (Jacoby & D'Arrigo, 1995; Barber *et al*., 2000; Jacoby *et al*., 2000; Lloyd & Fastie, 2002; D'Arrigo *et al*., 2004; Wilmking *et al*., 2004; Driscoll *et al*., 2005; Lloyd & Bunn, 2007; Pisaric *et al*., 2007).

While large-scale evidence for the DP was introduced from a circumpolar TRW and maximum latewood density (MXD) northern latitudinal network since around the 1960s (Briffa *et al*., 1998a, b), data from the European Alps suggest that the DP is more likely to effect TRW than MXD (Büntgen *et al*., 2006b), with greater susceptibility of spruce (*Picea abies* Karst.) than other species (Büntgen *et al*., 2006c). The latter observation is confirmed by circumpolar boreal forest growth (Lloyd & Bunn, 2007). If DP is real and widespread, it would

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question the overall ability of tree-ring-based temperature reconstructions to capture earlier periods of putative warmth, such as during medieval times (Lamb, 1965). The lack of a clear understanding of growth/climate relationships evident in the DP debate also suggests limitations in the ability to model tree growth and hence limitations to estimate future biomass productivity and the role of forest vigor on the global carbon cycle (Kurz *et al*., 2007 and references therein).

Potential causes for DP likely include temperature-induced late summer drought stress (Jacoby & D'Arrigo, 1995; Barber *et al*., 2000; Lloyd & Fastie, 2002; Büntgen *et al*., 2006c), complex nonlinear growth responses to changes in ecological site conditions (Vaganov *et al*., 1999), warming-induced thresholds of tree growth (D'Arrigo *et al*., 2004), specific sensitivity to not parallel maximum, minimum or mean temperature targets in response studies (Wilson & Luckman, 2002, 2003), effects of airborne pollution (Wilson & Elling, 2004; Yonenobu & Eckstein, 2006), changes in stratospheric ozone concentration (Briffa *et al*., 2004), and effects of global dimming and brightening upon photosynthesis rates (D'Arrigo *et al*., 2008).

Additional sources of methodologically induced DP include tree-ring detrending methods and end-effect issues in chronology development (Cook & Peters, 1997; Melvin, 2004), biases emerging from the calibration technique and period used (Esper *et al*., 2005a), and the time-series smoothing practice performed (Mann, 2004). Besides these tree-ring data and analysis related uncertainties are potential sources of instrumental station bias, e.g., the homogenization procedure applied, 'micro-site' effects and influences of the 'urban heat island' (Auer *et al*., 2007). Such limitations of the target data, multivariate growth/climate interactions, and methodological issues can systematically bias inferred relationships with tree growth (Frank *et al*., 2007b).

In a recent review, D'Arrigo *et al*. (2008) concluded that a single cause for DP is implausible, and a combination of reasons varying with location, species, and/or other factors should be considered instead. Additional testing of the ability of TRW or MXD data to track temperatures during the exceptional recent warmth can help to further understand the reliability of long-term climate reconstructions (e.g., Esper *et al*., 2005b; Wilson *et al*., 2007). Such tests are, however, complicated, as a variety of environmental factors including climate, ecology, stand structure and competition, forest history, and human influences simultaneously impact tree growth (Fritts, 1976). Therefore, well-replicated temperature-sensitive tree-ring data and carefully homogenized meteorological target data, which both extend back into the 19th and forward into the 21st century, facilitate a more robust study of the DP. Both conditions, as well as an unprecedented warming trend since the past ~150 years (Auer *et al*., 2007), exist for the European Alps. Accordingly, we compiled a network of the main Alpine conifer species larch and spruce. TRW measurements from 124 sites were aggregated, carefully detrended, and resulting chronologies compared with well-documented and homogenized climate data from high-elevation instrumental stations. The TRW data were first analyzed to emphasize common growth trends and climate responses as a function of site elevation, location, and species. Split period correlations were then used to assess proxy/target relationships over time. Our approach includes the calibration of a subset of TRW chronologies to summer temperatures over the early 1864–1933 period and subsequently assessed their ability to track late 20th century warming. TRW- and MXD-based temperature reconstructions place the proxy/target relationship in a millennium-long context and demonstrate the singularity of the recent warmth. This finding indicates that, as temperatures never approached the current degree of warmth in the past, it is unlikely that warming-induced drought stress was a factor for high-elevation Alpine tree growth back into medieval times.

Material and methods

A dataset of 3069 larch (*Larix decidua* Mill.) and 1600 spruce (*P. abies* Karst.) TRW series from 124 sites (62 per species) distributed across the European Alps was compiled (Fig. 1). This network integrates living trees from Italy, France, Switzerland, Austria, and Slovenia (6–16°E and 44–48°N; 500–2300 m a.s.l.), and also includes some larch series from historical construction timbers (Büntgen *et al*., 2006a).

Raw measurements were statistically re-checked and corrected for dating errors on a site-by-site basis using the software COFECHA (Holmes, 1983). Mean segment length (MSL; the average number of rings per sample) of the larch (spruce) chronologies is 210 (157) years and ranges from 65 to 447 (55–313) years, and the average growth rate is 1.06 (1.46) mm yr^{-1} and ranges from 0.36 to 1.90 (0.69–3.17) mm yr^{-1}. Both metrics portray a close relationship between increasing age and decreasing growth, the so-called age-trend (Fig. 2, insets). On an average, the larch trees grew slower than the spruce trees, were older at the time of sampling, and are generally located at higher elevations. Comparison of the raw TRW data after alignment by cambial age shows that the slower growing larch trees can be described by a negative exponential decrease with increasing age (Fig. 2). A similar, though faster, decline is found for spruce. During the first ~50 cambial years, growth rates in the age-aligned curves deviate markedly – lasting longer (until ~200 years) for

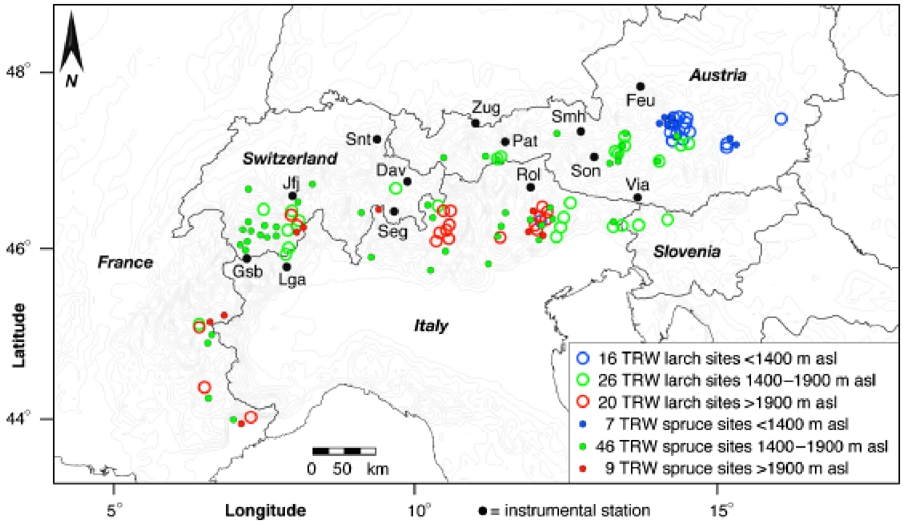

Fig. 1 Location of the 124 larch and spruce tree-ring sites in the European Alps, and the 13 instrumental stations used for comparison. Dav, Davos; Feu, Feuerkogel; Gsb, Gr. St. Bernhard; Jfj, Jungfraujoch; Lga, Lago Gabiet; Pat, Patscherkofel; Rol, Passo di Rolle; Smh, Schmittenhöhe; Seg, Sils/Segl-Maria; Snt, Säntis; Son, Sonnenblick; Via, Villacher Alpe; Zug, Zugspitze.

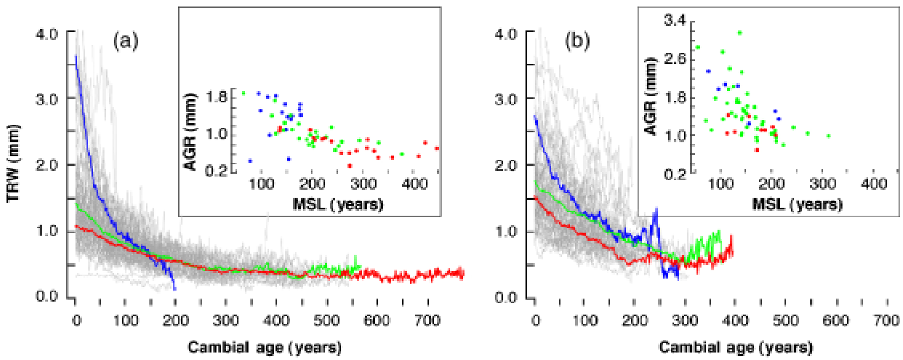

Fig. 2 Regional curves of (a) 62 larch and (b) 62 spruce sites (gray), together with mean records integrating data from <1400 (blue), 1400–1900 (green), and >1900 (red) m a.s.l. Insets show the relationship between average growth rate (AGR) and mean segment length (MSL) at the individual sites.

spruce than larch (until ~100 years). Data separation into <1400, 1400–1900, and >1900 m a.s.l. elevation-zones indicated that lower elevation growth is faster in comparison with higher elevation growth. While mid- and high-elevation larch growth rates and age trends are almost identical, spruce growth rates from these elevations are offset by ~0.3 mm. The geographical distribution of sites from different elevations is, however, not homogeneous across the network (Fig. 1).

To remove nonclimatic, tree-age-related growth trends (Fritts, 1976) from the raw TRW measurement series, two different detrending techniques were applied using the program ARSTAN (http://www.ldgo.columbia.edu/res/fac/trl/public/publicSoftware.html). For the preservation of inter-annual to multi-decadal scale variability, TRW series from each site were individually detrended using 300-year cubic smoothing splines, with 50% frequency-response cutoff equal to 300 years (Cook & Peters, 1981). Indices were calculated as residuals from the estimated growth curves after power transformation (details in Cook & Peters, 1997). For the preservation of inter-annual to centennial-scale variability, the regional curve standardization method (RCS; Esper *et al.*, 2003) was applied. Regional curves were estimated for each species and site. Mean chronologies were calculated using a bi-weight robust mean (Cook, 1985), their variance stabilized (MEANr correction as in Frank *et al.*, 2007a), and records truncated at a minimum replication of five series.

For growth/climate response analyses, we used a homogenized long-term (1864–2003) mean of 13 instrumental stations located >1500 m a.s.l. (Fig. 1). Eight of these stations extend back into the 19th century (Auer *et al.*, 2007). The 124 spline detrended site chronologies were correlated against monthly and seasonal temperature means over the early/late 1864–1933/1934–2003 periods. Correlations to temperature of the two independent intervals were used to assess temporal stability in the network's growth/climate relationships. Calibration/verification trials of two species-specific TRW mean chronologies – considering only those sites that correlate at $r > 0.39$ ($\sim P < 0.001$) with early (1864–1933) temperatures – were computed over the early/late (1864–1933/1934–2003) periods. Emphasis is place on the later period, as this is (1) independent from the screening interval and (2) the time period of greatest warmth and potential vulnerability to drought-related signal degradation. For calibration, we used both ordinary least-square linear regression and scaling (i.e., matching the mean and SD of a proxy time-series to those of the instrumental target data). Pearson's correlation coefficient (*r*), reduction of error (RE), coefficient of efficiency (CE), and Durbin–Watson statistics (DW) were used to assess temporal stability in the calibration models. Both RE and CE are measures of the shared variance between actual and estimated series (CE is a more rigorous verification statistic), with a positive value suggesting that the reconstruction has some skill (Cook *et al.*, 1994). DW tests for lag-1 autocorrelation in the model residuals. A DW value of 2 indicates no first-order autocorrelation in the residuals; values greater (less) than 2 indicate negative (positive) autocorrelation (Durbin & Watson, 1951).

Results

Growth responses to climate

Calibration trials of the 300-year spline chronologies against early 1864–1933 observational data reveal correlations >0.39 for 40 larch and 24 spruce sites to (either monthly or seasonal) summer temperatures (Fig. 3a and b). Average maximum site response is 0.44 for larch and 0.33 for spruce. While 28 out of 40 temperature-sensitive larch sites from elevations >1400 m a.s.l. respond most strongly to the June–July mean, the spruce sites show highest correlations to a greater variety of seasonal windows (Fig. 3c and d). Only 9 out of the 24 spruce chronologies reach maximum correlations with June–July temperatures. During the early 1864–1933 period, average correlation of all larch (spruce) site chronolo-

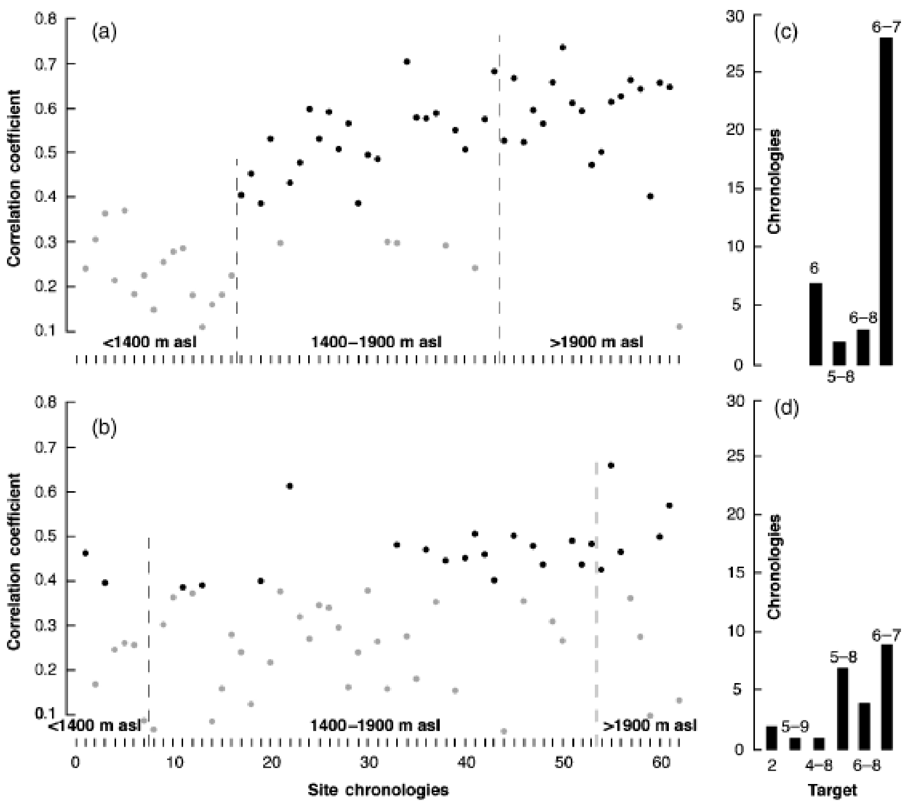

Fig. 3 Maximum response of the spline detrended (a) 62 larch and (b) 62 spruce site chronologies (ordered by elevation) to current year monthly and seasonal temperature targets computed over the early 1864–1933 period. Black dots indicate correlations >0.39. Histogram shows the amount of (c) larch and (d) spruce chronologies that have maximum correlation with certain temperature targets (6–8: June–August).

gies with June–July temperatures is 0.34 (0.20), and slightly decreases to 0.33 (0.19) for the period 1934–2003. Average correlations over the early and late periods increase to 0.53 (0.37) and 0.44 (0.29) when considering the 40 (24) sensitive larch (spruce) records. In contrast, average correlations over the early and late periods significantly decrease to −0.01 (0.10) and 0.14 (0.13) when considering the 22 (38) insensitive larch (spruce) records, respectively. These results clearly stress the importance of careful site selection, and an overall lower temperature sensitivity of Alpine spruce growth.

To assess temporal change in species-specific maximum growth responses to temperatures of the vegetation period, we compared results from the early (1864–1933) and late (1934–2003) calibration periods. Scatter diagrams of optimal growth/temperature relationships of all (62 larch/62 spruce) sites, the sensitive (40/24), and insensitive (22/38) subsets (as defined in Fig. 3) were computed (Fig. 4). While 62 larch sites explain >50% of temporal variance, this value is below 20% for the 62 spruce sites. Generally less variance is explained when regressing smaller subsets of the sensitive and insensitive sites from both species. During the early, late, and full period of instrumental overlap, spruce TRW appears to show a less robust temperature signal compared with larch.

Tracking recent warming

The 40 larch and 24 spruce chronologies of both the 300-year spline and RCS detrended data that correlate >0.39 to early 1864–1933 temperatures were averaged (using their simple mean) to species-specific chronologies and then regressed against June–July temperatures over the full 1864–2003 instrumental period (Fig. 5). Correlation between the larch RCS chronology and June–July temperatures over this period is 0.70 and 0.65 when using the 300-year spline chronology. With the spruce RCS and spline chronology, correlations are 0.65 and 0.53, respectively. The tree-ring and instrumental records reflect cooler conditions at the end of the 19th century, initial warming from the 1910s to ∼1950, subsequent cooling until 1980, and increasing temperatures peaking in 2003.

Moving 31-year correlations between target temperatures and proxy estimates indicate nearly similar results for both species and the different detrending methods applied (see dots in Fig. 5). The overall significant ($P<0.05$) correlations range from ∼0.85 to 0.40 and show a decline from ∼1900-present, but with a slight recent increase for larch (Fig. 5). Results indicate enhanced model skill for the spruce RCS chronology compared with the spline version, whereas both larch chronologies robustly match the instrumental target data. Residuals between the RCS chronologies and summer temperatures highlight inter-annual disagreement. Decadal-scale trends are emphasized with a low-pass filter (Fig. 5). While larch shows negative residuals from ∼1900 to 1930, and positive ones in the 1950s, and 1970s, spruce residuals are negative from ∼1910 to 1930 and in the 1970s, and positive over the last ∼15 years of overlap (Fig. 5). The mean of the 10 strongest positive annual residuals between the larch (spruce) RCS chronology and June–July temperatures is 1.63 (1.79), indicating an overall better coherency between growth and summer temperatures for larch than spruce. Figure 6 summarizes all annual residuals ordered by size. Using the RCS detrended data, 3 out of the 10 and 6 out of the 20 strongest positive residuals for both species occur after 1980. Post-1980 results are quite similar for the spline detrended larch data (4/10 and

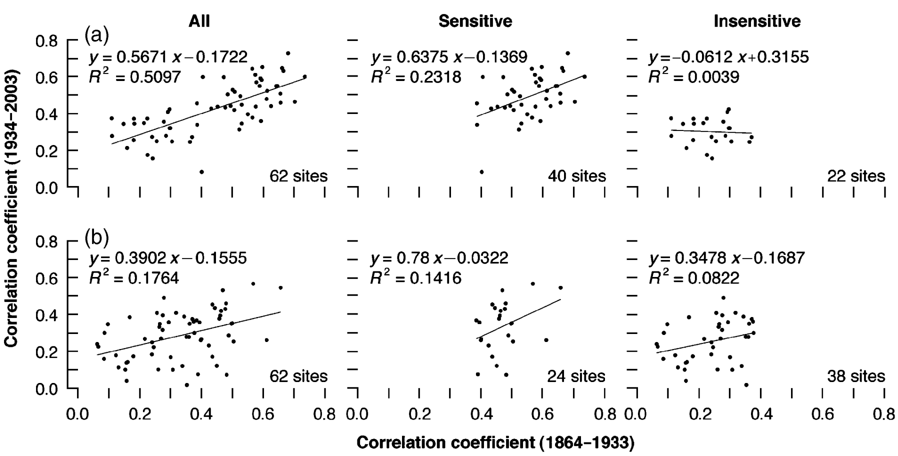

Fig. 4 Scatter plots of the early (1864–1933) vs. late (1934–2003) period maximum growth/temperature response for (a) larch and (b) spruce. Results are shown for all (left), the sensitive (mid), and insensitive (right) sites, as introduced in Fig. 3.

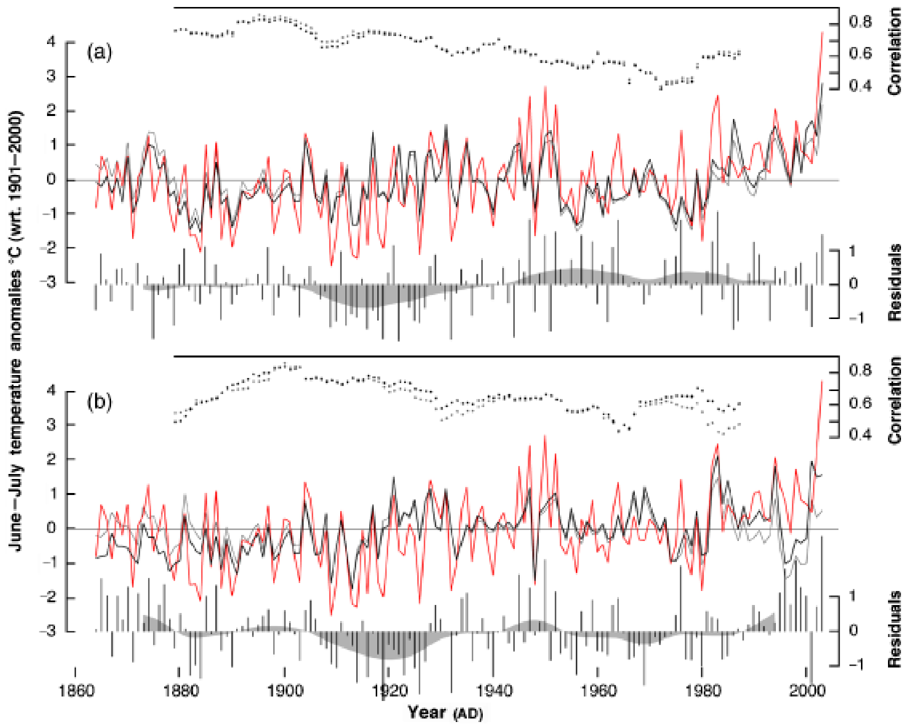

Fig. 5 Mean (a) larch and (b) spruce RCS (black) and 300-year spline (gray) chronologies that integrate 40 larch and 24 spruce sites, respectively. Records are regressed (1864–2003) against June–July temperatures (red). Dots (black and gray) indicate 31-year moving correlations between the chronologies (RCS and spline) and temperature. Bottom panels show residuals between the RCS records and instrumental measurements, and their 20-year low-pass filters (gray areas).

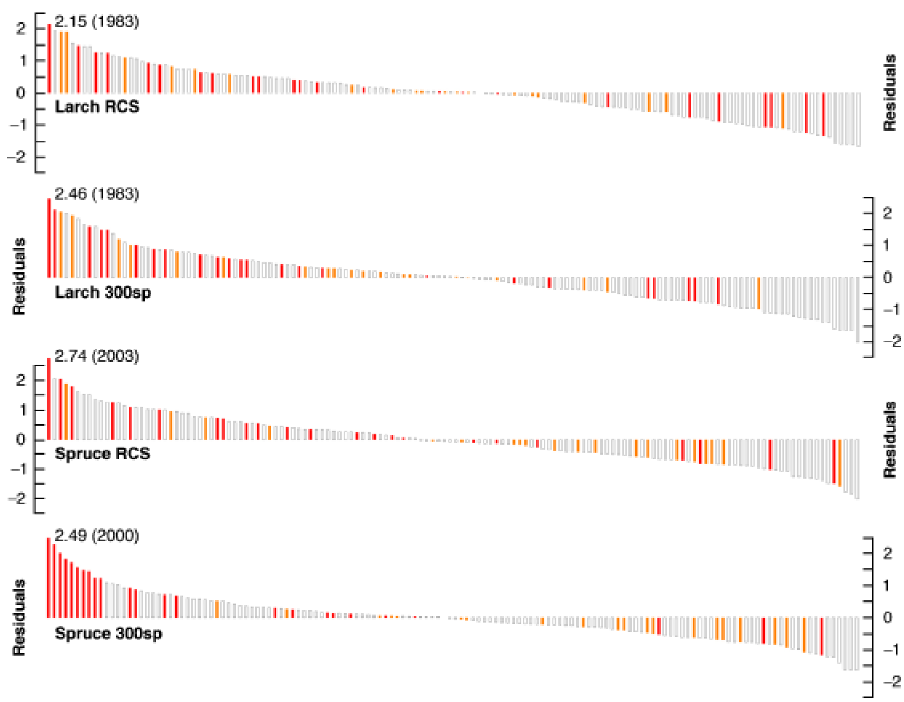

Fig. 6 Residuals (ordered by size) between the larch and spruce chronologies (after RCS and 300-year spline detrending) and June–July temperatures (1864–2003). Orange and red bars indicate annual residuals of the late 20th century that occurred between 1960–1979 and 1980–2003, respectively.

7/20), but increase noticeably for the spline detrended spruce data (10/10 and 12/20), indicating effects of tree species and detrending method. Residual sizes are evenly distributed over time and describe no systematic difference between the early/late calibration periods. Indication for an unusual late 20th century DP is thus not found.

Calibration/verification statistics further demonstrate the impact of the tree-ring detrending, with most significant effects observed for the spruce data (Table 1). Correlations of the 300-year spline and RCS larch chronologies against temperature generally decrease after 10-year high-pass filtering, but increase when using the corresponding low-pass fractions. In contrast, 300-year spline detrended spruce data show higher coherency on the inter-annual and lower coherency on the decadal time-scale. Because DW statistics are consistently better for the RCS compared with the spline chronologies and also for larch than spruce, agreement depends on both the species and detrending used. Overall poorer DW statistics are obtained from scaling compared with regression, with this being more noticeable for spruce. A distinct difference between higher RE and CE values after RCS in comparison with 300-year spline detrending, however, is species independent (Table 1). Even though lower values are obtained from scaling in comparison with regression, positive RE and CE values indicate some skill for all RCS chronologies. In contrast, lower RE and negative CE statistics are obtained for the spline chronologies. Comparison of the RCS chronologies and the instrumental June–July temperatures reveals enhanced long-term agreement after scaling than regressing – variance reduction after regressing (noisy) proxy data is visually emphasized in the DP when the target data have end values well above the mean of the calibration period (Fig. 7).

In summary, no indication for an unusual 20th century DP is found for either species after scaling the RCS chronologies, even though larch tracks summer temperatures generally better than spruce.

Millennial-long comparison

To place the proxy/target relationship in a long-term climatic perspective, demonstrating that our Alpine findings on late 20th century DP derive not only from an area of recent warmth (Auer *et al.*, 2007) but also from an era of unprecedented temperatures with respect to the last millennium (Büntgen *et al.*, 2006b), we utilized a selection of 2610 living and relict larch TRW series from 40 sites based on their correlations over the early 1864–1933 period (Fig. 3a). This composite dataset is characterized by evenly distributed series start dates from the mid-10th century until the early 20th century and was processed by RCS. After regression against instrumental June–July temperatures (1864–2003), the new reconstruction was compared with two existing temperature histories – a hybrid of ~1500 larch and pine TRW series from the Swiss and Austrian Alps (Büntgen *et al.*, 2005), plus a collection of 180 larch MXD measurements from the Central Swiss Alps (Büntgen *et al.*, 2006b). These records are methodologically not independent and some data overlap between the TRW records exists. The compilation indicates that the modern time period, corresponding to that where most concerns about the DP exist, is the warmest episode over the past millennium (Fig. 8). Five out of the 10 warmest decades are identified to fall in the 20th

Table 1 Calibration and verification statistics of the (a) larch and (b) spruce 300-year spline and RCS chronologies using regression (scaling)

	(a)						(b)					
	Calibration			Verification			Calibration			Verification		
	r (ori)	*r* (hp)	*r* (lp)	DW	RE	CE	*r* (ori)	*r* (hp)	*r* (lp)	DW	RE	CE
1864–1933												
SPL	0.74	0.72	0.86	1.19 (1.18)	0.26 (0.17)	−0.14 (−0.27)	0.67	0.70	0.62	1.24 (0.91)	0.43 (0.00)	0.12 (−0.53)
RCS	0.71	0.71	0.78	1.68 (1.65)	0.51 (0.22)	0.25 (0.14)	0.61	0.72	0.37	1.51 (1.35)	0.53 (0.43)	0.29 (0.12)
1934–2003												
SPL	0.66	0.50	0.89	1.62 (1.56)	0.32 (0.27)	−0.10 (−0.17)	0.43	0.56	0.20	1.22 (0.99)	0.29 (0.29)	−0.15 (−0.14)
RCS	0.66	0.47	0.93	1.77 (1.70)	0.53 (0.59)	0.25 (0.35)	0.58	0.55	0.68	1.47 (1.42)	0.56 (0.51)	0.29 (0.21)
1864–2003												
SPL	0.65	0.63	0.69	1.63 (1.48)			0.53	0.63	0.33	1.31 (1.17)		
RCS	0.70	0.61	0.86	1.89 (1.73)			0.65	0.63	0.70	1.60 (1.42)		

Correlations were computed using unfiltered (ori), and 10-year high-pass and low-pass filtered (hp and lp) time-series.
DW, Durbin–Watson statistics; CE, coefficient of efficiency; RE, reduction of error; RCS, regional curve standardization method.

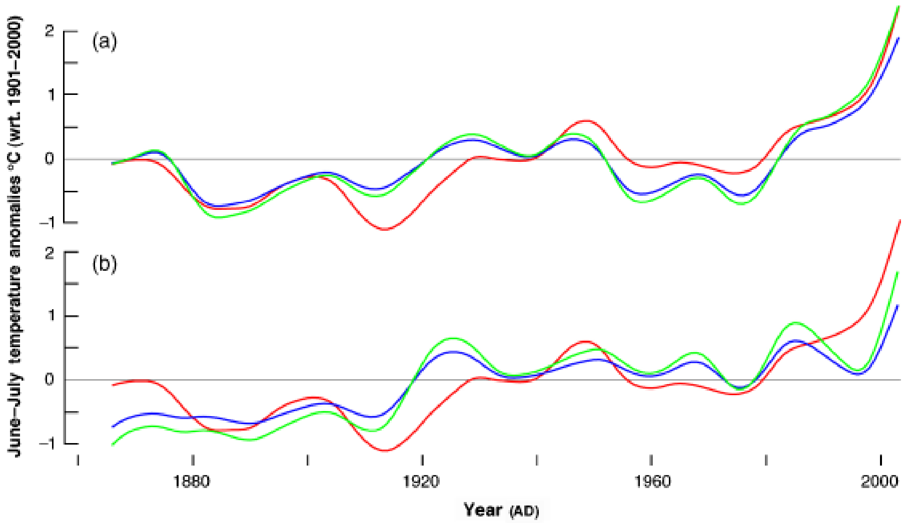

Fig. 7 Twenty-year low-pass filtered (a) larch and (b) spruce chronologies regressed (blue) or scaled (green) against June–July temperatures (red) over the 1864–2003 period.

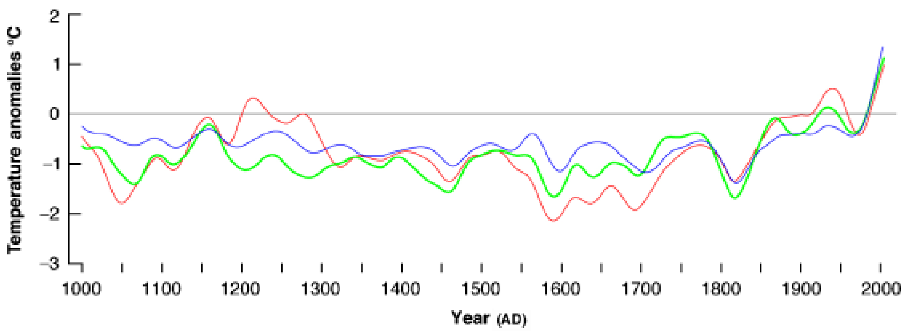

Fig. 8 Millennium-long comparison between this study (green), the TRW-based (blue; Büntgen *et al.*, 2005), and MXD-based (red; Büntgen *et al.*, 2006b) reconstructions of summer temperature variations in the greater Alpine region using 60-year low-pass filters. Data are expressed as anomalies with respect to the 1901–2000 period.

century, with three decades (1920s, 1930s, 1990s) in common between all three records. Based on this picture, we suggest that as summer temperatures never approached this level of warmth in the past, it is most unlikely that temperature-induced drought stress was ever a factor at higher elevation Alpine sites. This, however, would assume that the transition from living to relict material and other potential biases, including those related to the tree-ring detrending, have not significantly affected the reconstructed values.

Discussion and conclusions

We compiled 124 larch and spruce TRW site chronologies from the European Alps. This network is exceptional in terms of temporal coverage, sample replication, and location. Growth trends and climate responses mainly reveal site elevation as chronologies from ~>1400 m a.s.l. reflect variations in June–July temperatures, with a stronger relationship being found for larch. These findings parallel the generally observed tendency of weaker temperature controls on spruce growth in the Alps (Frank & Esper, 2005a; Büntgen *et al.*, 2006c) and the boreal forest (Lloyd & Bunn, 2007). Interestingly, both species captured mid-20th century (1940–1950s) summer warmth very well, whereas spruce did not fully track the high temperatures in the 1990s, but increased again from 2000 onwards. Using this Alpine-wide compilation, an overall response shift from temperature to precipitation (drought) sensitivity is not observed, because temperatures remain the most dominant factor controlling radial growth from the mid-19th to 21st century. Other network compilations including spruce TRW and MXD measurements from various sites across the Alpine arc (Frank & Esper, 2005b), and Western Carpathian

Mountains (Büntgen *et al*., 2007) also demonstrated their ability to successfully reconstruct variations in regional-scale summer temperatures. Nevertheless, indication for temporal instability in the growth/temperature relationship is reported from smaller subsets of larch (Carrer & Urbinati, 2006) and spruce sites (Büntgen *et al*., 2006c), mainly depending upon site selection (as demonstrated in Figs 3 and 4).

Even though, data selection based on early 1864–1933 correlations with temperature allowed independent verification of species-specific mean chronologies over the late 1934–2003 period, our results may contain bias originating from temporal changes in sample replication of the mean chronologies, their imbalance in the total number of series used, and differences in site elevation and location. This argument is particularly valid for the spruce record, which is characterized by a slight sample reduction in the post-1980s that may account for some recent uncertainties. The Alpine spruce mean chronology integrates 602 series from 24 sites. Replication of these sites ranges from 5 to 79 samples and 15 chronologies have end dates between 1986 and 2003, from which 11 chronologies extend after 1997. In contrast, 2610 series (including historic material) are shared by the 40 temperature-sensitive larch chronologies, with their individual replication ranging from 7 to 372 samples. Thirty-six chronologies have end dates between 1986 and 2004, from which 31 extend after 1997. In short, results from 24 spruce sites are compared with results from 40 larch sites, with mean elevations of 1745 and 1910 m a.s.l., and mean correlation of 0.37 and 0.53 with June–July temperatures, respectively.

Additional splitting of the larch data into young (<250 years) and old (>250 years) trees indicated robust growth/climate response ($r = 0.70$ for both age classes). Because a more local study based on less data found a maximum climate response in larch trees >200 years (Carrer & Urbinati, 2004), our findings show that high sample size most likely compensates for young tree age-induced noise, in line with the results of Esper *et al*. (2008). The heterogeneous distribution of the sample sites throughout the Alpine arc – the network displays research strategies of the various groups rather than an optimal coverage – introduces further uncertainty. All of the lower elevation sites are located in the Austrian Alps and most of the higher elevation ones were sampled in the Italian Alps. Only mid-elevation sites are evenly spread across the study area. Such altitudinal heterogeneity is critical, as there is a tendency for stronger temperature signals to be preserved at higher elevations, resulting in a composite proxy series to be less representative for the eastern Alpine region.

Superimposed on data-related issues are methodological uncertainties due to the challenge of choosing the proper detrending method (e.g., Esper *et al*., 2007; Frank *et al*., 2007b). This is particularly difficult when relying upon simple statistics from rather short calibration windows (D'Arrigo *et al*., 2006). Nonetheless, our results indicate that RCS chronologies best model interannual to multi-decadal variations in Alpine June–July temperatures. Because of the overall lower temperature response of spruce, the remaining limitation of this species is a poorer estimation of temperature fluctuations, in line with previous results from Europe (Frank & Esper, 2005a; Wilson *et al*., 2005; Büntgen *et al*., 2006c) and the boreal forest (Lloyd & Bunn, 2007). Significant trends in the residuals between target data and both RCS chronologies are, however, not observed.

Further bias in the proxy/target relationship possibly emerges from the calibration technique (scaling/regression) applied and period (early/late) used (Esper *et al*., 2005a). Less DP results from scaling instead of regressing, although calibration/verification statistics are poorer after scaling. Regression becomes always critical when the target data have values well above or below the mean of the calibration period. Further accentuation can result from potential end-effect problems due to the smoothing technique applied (Mann, 2004). As a methodological side point, approaches of simple site deviation into 'responders' and 'nonresponders' (those data that do or do not correlate with climate), without taking independent screening (calibration/verification) periods into account (Wilmking *et al*., 2004, 2005; Pisaric *et al*., 2007), can result in a circular reasoning.

Our study, together with the work by Wilson *et al*. (2007), demonstrates that DP is not a systematic issue at temperature-sensitive conifer sites and is therefore not caused by one causal mechanism superimposed on the relationship between late 20th century temperature increase and tree growth. Our results indicate that the DP – including high-frequency loss in climate sensitivity and/or low-frequency trend offset – must be addressed at the local to regional level, before conclusions can be drawn for larger scales. However, future dendroclimatic research cannot ignore potential complex and nonlinear growth responses to a changing climate, which may challenge the principle of uniformity, as well as methodological uncertainties that emerge from the (1) tree-ring detrending, (2) chronology development, and (3) proxy/target calibration methods applied.

In an attempt to test for DP, we therefore suggest to perform careful site selection over split periods of long instrumental measurements, validate the obtained signal over independent periods, and use appropriate detrending techniques that retain high- to low-frequency variability in the resulting chronologies.

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