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ORIGINAL ARTICLE

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Growth/climate response shift in a long subalpine spruce chronology

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Abstract A new Norway spruce (*Picea abies* (L.) Karst.) tree-ring width chronology based on living and historic wood spanning the AD 1108–2003 period is developed. This composite record combines 208 high elevation samples from 3 Swiss subalpine valleys, i.e., Lötschental, Goms, and Engadine. To retain potential high- to low-frequency information in this dataset, individual spline detrending and the regional curve standardization are applied. For comparison, 22 high elevation and 6 low-elevation instrumental station records covering the greater Alpine area are used. Previous year August–September precipitation and current year May–July temperatures control spruce ring width back to ∼1930. Decreasing (increasing) moving correlations with monthly mean temperatures (precipitation) indicate instable growth/climate response during the 1760–2002 period. Crucial June–August temperatures before ∼1900 shift towards May-July temperature plus August precipitation sensitivity after ∼1900. Numerous of comparable subalpine spruce chronologies confirm increased late-summer drought stress, coincidently with the recent warming trend. Comparison with regional-, and large-scale millennial-long temperature reconstructions reveal significant similarities prior to ∼1900 (1300–1900 mean r=0.51); however, this study does not fully capture the commonly reported 20th century warming (1900–1980 mean r=−0.17). Due to instable growth/climate response of the new spruce chronology, further dendroclimatic reconstruction is not performed.

Keywords Alps · Dendroclimatology · Growth/climate response · High–low frequency · Standardization

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Introduction

Tree-ring analyses provide empirical evidence on how trees respond to internal (biotic) and external (abiotic) forcings (e.g., Fritts 1976). Identifying high- to low-frequency wavelengths embedded in long, annually resolved ring width series contributes to a better understanding of past terrestrial ecosystem productivity, e.g., mountain regions (Beniston 2003; Keller et al. 2000; Kienast et al. 1998), with high elevation vegetation being particularly sensitive to temperature changes (e.g., Büntgen et al. 2005a; Frank and Esper 2005a; Schweingruber 1996), and low-elevation vegetation being particularly sensitive to precipitation changes (e.g., Cook et al. 2004; Stahle and Cleaveland 1994; Woodhouse and Overpeck 1998). However, due to the interaction of several climatic forcings (e.g., Nemani et al. 2003), and a complex plant physiology (e.g., Tranquillini 1964), the discrimination of growth response to a single controlling parameter often fails (e.g., Fritts 1976; Schweingruber 1996; Tessier 1989). In the upper and northern timberline ecotone, a thermal boundary for tree growth is generally given (e.g., Körner 1998; Esper and Schweingruber 2004). However, when temperatures are already high, water availability during the relatively short vegetation period becomes key for tree growth (e.g., Anfodillo et al. 1998; Carrer et al. 1998; Masson-Delmotte et al. 2005; Tranquillini 1964).

With ∼74% abundance, Norway spruce (*Picea abies* (L.) Karst.) is the dominant tree species in the Alps, commonly found in montane and subalpine forests (Ellenberg 1996). Recent publications describe the growth/climate response of high-elevation Alpine spruce trees from annual extremes (Desplanque et al. 1999; Neuwirth et al. 2004; Rolland et al. 2000), to multi-decadal fluctuations and network analyses (Frank and Esper 2005a; Rolland et al. 1998; Wilson and Topham 2004). Others discuss the annual growth/climate relationship though include samples from elevations <1,000 m asl (Dittmar and Elling 1999; Meyer and Bräker 2001; Vogel and Schweingruber 2001). Attention has also been drawn to the temporal instability in the response of European spruce-growth to climate (Hasenauer et al. 1999; Wilson and Elling 2004; Wilson and Topham 2004), with further studies reporting a reduction in tree sensitivity and/or changing growth/climate response to temperature at differing high northern latitudinal sites (Barber et al. 2000; Briffa et al. 1998b; D'Arrigo et al. 2004, 2005; Davi et al. 2003; Jacoby and D'Arrigo 1995; Lloyd and Fastie 2002; Vaganov et al. 1999; Wilmking et al. 2004).

Here we compile both, long and short tree-ring records, with the former overcoming difficulties of multi-centennial chronology development related to the (i) relatively low tree ages commonly reached in the Alps (Eckstein 1982), (ii) challenge of sampling historic construction timbers (Büntgen et al. 2004, 2005b; Wilson et al. 2004), subfossil and dry-dead wood (Holzhauser 2002; Nicolussi and Patzelt 2000), and (iii) complexity of age-related standardization techniques required (Briffa et al. 1996, 2001; Esper et al. 2003b), and the latter detailing the revealed growth/climate response.

In this paper, data and methods are first introduced, and preserved tree-ring variability after different detrending methods shown. The new spruce ring width chronology (together with numerous additional subalpine chronologies) is then compared with monthly mean temperature and precipitation data back to 1760 and 1858, and with regional- and large-scale temperature reconstructions back to 1600 and 1300, respectively. The growth/climate response is detailed, and discussion is provided regarding possible shifts observed.

Material and methods

Tree-ring data

The primary dataset consists 208 Norway spruce (*Picea abies* (L.) Karst.) ring width series from three Swiss subalpine valleys (Fig. 1) dating from AD 1108–2003 (Fig. 2A). This dataset combines 74 living and 134 historic trees from elevations >1,500 m asl. Samples were collected, processed and cross-dated by B. Neuwirth, K. Treydte, and M. Schmidhalter for the Lötschental/Valais (LOE), by M. Schmidhalter for the Goms/Valais (GOM) and by M. Seifert for the Engadine/Graubünden (ENG). The average growth rate (AGR) is 1.13 mm/year and the mean segment length (MSL)—the average number of rings per core or disc—is 145 years. After data splitting into recent (1636–2003) and historic (1108–1988) subsets, AGR is 1.07 and 1.16 mm/year, and MSL is 194 and 122 years, respectively. AGR and MSL provide information about

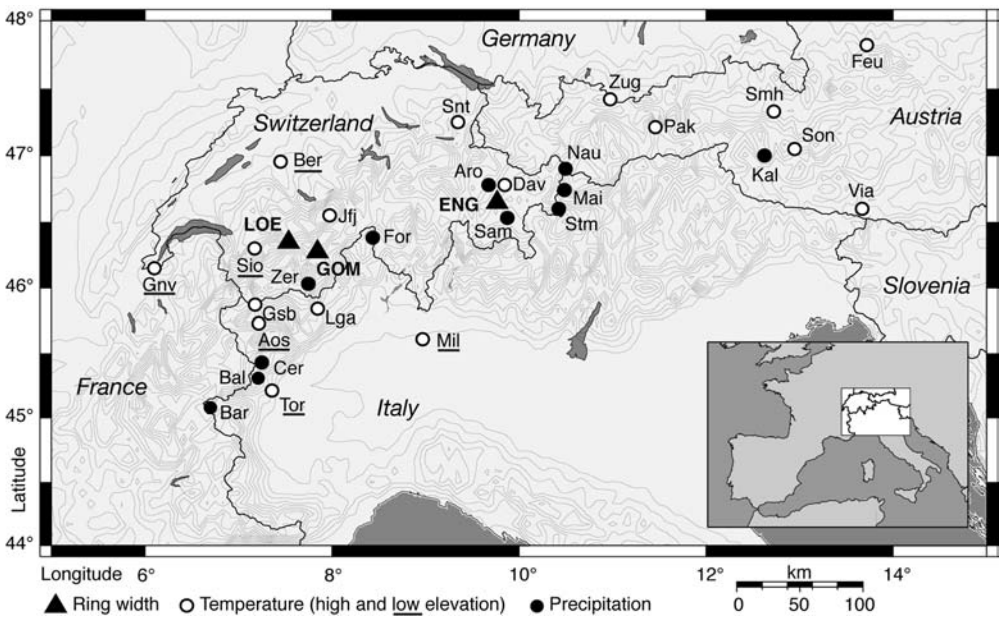

Fig. 1 Location of the 22 high- and 6 low-elevation instrumental stations, and the tree-ring datasets used. Homogenized temperature records (>1,500 m asl): *Dav* Davos (1901), *Feu* Feuerkogel (1930), *Gsb* Gr. St. Bernhard (1818), *Jfj* Jungfraujoch (1933), *Lga* Lago Gabiet (1928), *Pak* Patscherkofel (1931), *Smh* Schmittenhöhe (1880), *Snt* Säntis (1864), *Son* Sonnenblick (1887), *Via* Villacher Alpe (1851), *Zug* Zugspitze (1901), and low-elevation temperature records (<600 m asl, *underlined*): *Aos* Aosta (1841), *Ber* Bern (1864), *Gnv* Geneva (1760), *Mil* Milano (1763), *Sio* Sion (1864), *Tor* Torino (1760). Homogenized precipitation records (>1,300 m asl): *Aro* Arosa (1890), *Bal* Balme (1914), *Bar* Bardonecchia (1914), *Cer* Ceresole Reale (1927), *For* Formazza Ponte (1901), *Kal* Kals (1896), *Mai* Marienberg (1858), *Nau* Nauders (1896), *Sam* Samedan (1861), *Stm* Sta. Maria (1901), *Zer* Zermatt (1892). Parentheses indicate start years of instrumental measurements, ending in 2002. Tree-ring datasets (>1,500 m asl): LOE Lötschental, GOM Goms, ENG Engadine

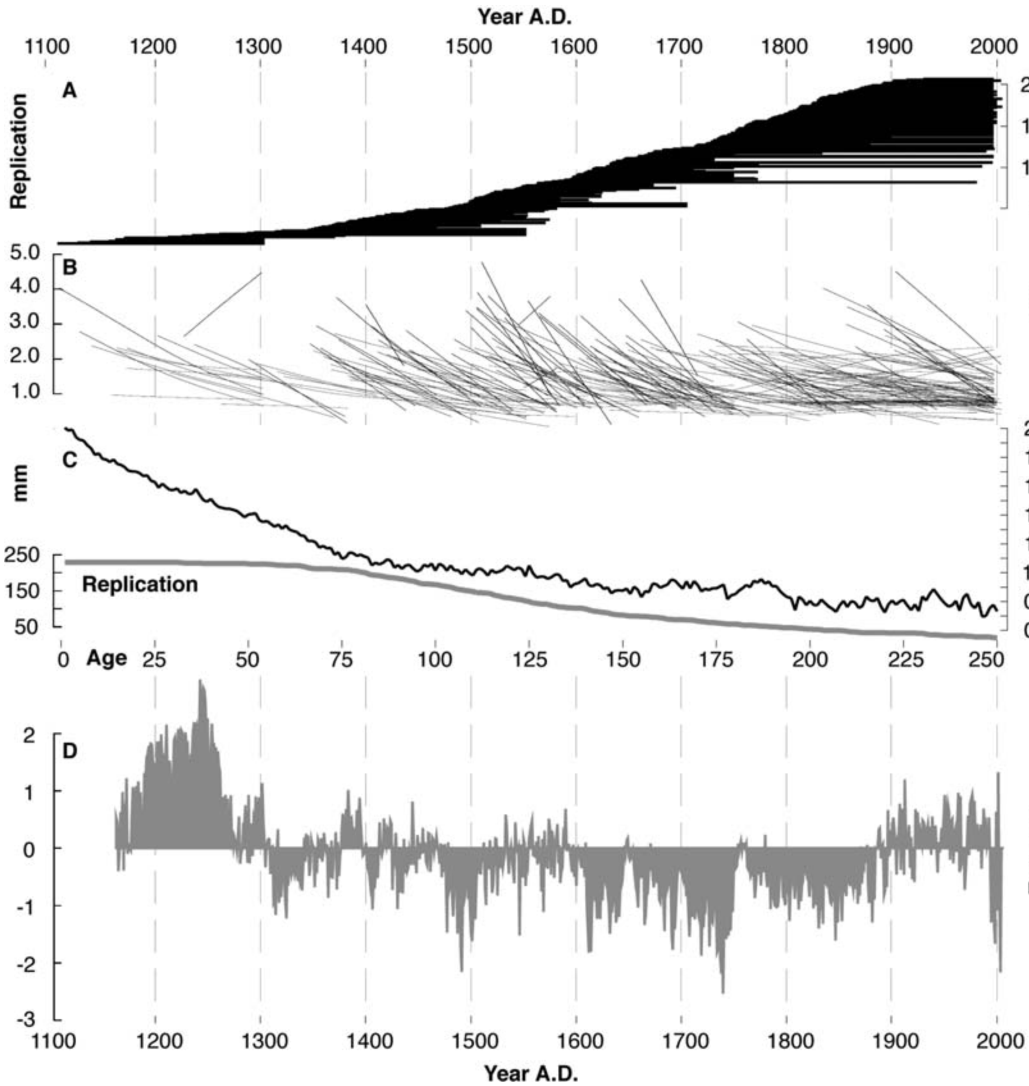

Fig. 2 **A** Temporal distribution of the 208 recent and historic samples. **B** Individual 300 year splines fit to each series. **C** Age-aligned mean curve (*RC, calculated after power-transformation*), and their replication. **D** Residuals between the 300 year spline and RCS chronology

growth characteristics and the ability of preserving longer-term ring width variations after detrending (see tree-ring standardization below).

For comparison and validation, 14 recent spruce chronologies (1532–1995), from elevations >1,500 m asl were downloaded from the International Tree-Ring Data Bank (ITRDB). These data include 151 samples from Switzerland, western Austria, northern Italy, and France. The AGR is 0.88 mm/year and the MSL is 192 years. Further verification was performed by a high elevation (>1,500 m asl) compilation of 53 tree-ring width chronologies used by Frank and Esper (2005a, 2005b) and Frank et al. (2005c), hereafter referred as Frank05. Here we divided this network into 30 spruce (567 series), and 23 non-spruce (795 larch, fir and pine series) chronologies. Note that Frank05 includes ITRDB data also. For detailed data description, e.g., sources, spatio-temporal distribution, site ecology and growth/climate response see Frank and Esper (2005a).

Tree-ring standardization

Prior to detrending, all ring width series were screened for missing rings and dating errors on a site-by-site and recent-historic basis using the program COFECHA (Holmes 1983). For standardization and statistical analyses, a recent version of the program ARSTAN (Cook 1985) was employed. Series were detrended to remove long-term growth trends embedded in the raw tree-ring series, thought to be induced by non-climatic influences, such as aging and/or site ecological effects (Fritts 1976). Tree-ring indices were calculated as residuals from the estimated age-trend after applying an adaptive power transformation (PT) to eliminate heteroscedastic behavior of the originally homoscedastic tree-ring series (Cook and Peters 1997). Since individual series detrending eliminates signals on wavelength longer than the series segment length (details in Cook et al. 1995), two conceptually different standardization methods were performed, (i) individual series standardization (Cook and Peters 1981), hereafter referred as spline detrending and (ii) the regional curve standardization (RCS, Becker et al. 1995; Briffa et al. 1992, 1996; Mitchell 1967; Esper et al. 2003b).

1. To emphasize inter-annual to multi-decadal scale variations, cubic smoothing splines (Cook and Peters 1981) were fit to the power transformed series, and residuals between the measurements and splines calculated. For high to mid frequency verification, data were split into recent and historic subsets, and splines (−67 year) with 50% frequency-response cutoff, equal 2/3 of the individual series length were used (not shown). To retain multi-decadal variability (Fig. 2B), generally stiffer splines (300 year) with 50% frequency-response cutoff, equal 300 years were applied (details in Cook and Peters 1981).
2. To preserve potential low-frequency information and avoid the so-called "segment length curse" in tree-ring chronology development (Cook et al. 1995), RCS was employed (Fig. 2C). RCS first aligns all series by their innermost ring, commonly reflecting the biological and/or cambial age of one. The age-aligned series collectively describe the age-related, biological growth trend, typical for the given species, site and region. The mean growth function from all age-aligned series, the regional curve (RC, smoothed using a cubic spline of 10% the series length) is calculated. Residuals from the RC are taken and then the series are re-aligned by calendar year (details in Esper et al. 2003b).

All detrended series were averaged to form chronologies using the biweight robust mean (Cook 1985). The number of samples per year and the cross-correlation coefficient between all measurements was used for variance stabilization of the chronologies to avoid changes in variance related to changes in sample depth (Osborn et al. 1997). Chronologies were truncated at sample size ≤6 series, and smoothed record ends padded (Mann 2004). For signal strength assessment (Cook and Kairiukstis 1990; Wigley et al. 1984), the inter-series correlation (*Rbar*, [$\bar{r}$]), expressed population signal (*EPS*), standard error (*SE*), and coefficient of variation (*CV*) were computed (Table 1). Correlations were corrected for lag-1 autocorrelation (Trenberth 1984).

Wavelength <10 years, between 10–100 years and >100 years are herein described as high, mid, and low frequency, respectively.

Instrumental data

For comparison and calibration of the proxy data, 11 "rural" temperature (precipitation) stations from elevations >1,500 m asl (>1,300 m) were used (Auer et al. 2005; Böhm et al. 2001) (Fig. 1). The common periods of the homogenized temperature and precipitation series are 1933–2002 and 1927–2002, respectively. For temporal extension of the temperature data, six "urban" low-elevation stations, with two reaching back to 1760 (Geneva, Torino) were employed. Instrumental stations cover approximately the 45°–48°N and 6°–14°E greater Alpine region. Monthly mean values were transformed to anomalies with respect to the 1961–90 period. For detailed data description, e.g., sources, homogenization, and clustering see Auer et al. (2005) for the precipitation, and Böhm et al. (2001) for the temperature data.

Results

High- to low-frequency variations

After detrending using −67 year splines equal 2/3 of the individual series length, recent (74 series, mainly Lötschental) and historic (134 series, mainly Goms and Engadine) chronologies show common inter-annual to decadal scale variations, however, a clear limitation in their low-frequency domain exists (not shown). During the 1714–1940 period of overlap, the correlation between the recent and historic chronologies is 0.50, and range from 0.45–0.61 after splitting into four 56 year sections. Shared common growth variations include depressions ~1750, 1820, and 1860, and high values ~1740, 1790, and 1880. *Rbar* values are 0.24 and 0.18 for the recent and historic data, and *EPS* values are 0.88 and 0.76, respectively (Table 1). *EPS* values are stable during the chronologies mid section, and decrease toward their ends, however, range about the commonly cited values of 0.80–0.85 (Briffa and Jones 1990; Cook et al. 2000; Esper et al. 2003a). Comparison with the ITRDB data verifies the Alpine signal within the 208 new samples. Correlation between this study and the ITRDB chronology is 0.54 for the 1578–1995 period of overlap, and ranges from 0.39–0.72 after splitting into four 104 year sections. Based on shared high frequency variability, recent and historic data were merged.

Key feature of the 300 year splines used for detrending (Fig. 2B) is their systematic decline, ideally reflecting the biotic age-trend, however, some splines show increasing values with increasing age, likely caused by abiotic factors. Splines are shaped close to straight-line functions and emphasize mid frequency variability in the resulting chronology. Six main population generations are observed during the past 900 years, likely an artifact of periodic felling for construction and dendrochronological investigations.

The mean growth function (RC) of the RCS method is shaped close to a negative exponential function and describes the collective age-related growth behavior of the trees used (Fig. 2C). The declining RC and corresponding replication explain a reasonably systematic and simple way of growth *versus* age (Bräker 1981). The ability of RCS is increased by the tree's resembling growth trend and even temporal sample distribution (Briffa et al. 1992, 1996; Esper et al. 2003b). For verification, the ITRDB data were included to the primary 208 series dataset, and the two RCS chronologies—with and without additional ITRDB data—correlate at 0.74 over the 1578–1995 period of modification. This was done, as the ITRDB data alone do not possess adequate temporal dispersion for robust RCS detrending.

Table 1 Chronology characteristics

Chronology	Data	Series no	Period	Rbar[a]	EPS[a]	SE	CV
−67 year spline	Recent	74	1636–2003	0.24	0.88	0.33	0.16
−67 year spline	Relict	134	1108–1908	0.18	0.76	0.05	0.17
−67 year spline	ITRDB	151	1532–1995	0.19	0.82	0.06	0.25
300 year spline	Recent/relict	208	1108–2003	0.17	0.82	0.05	0.21
RCS	Recent/relict	208	1108–2003	0.15	0.80	0.09	0.40
RCS	Recent/relict/ITRDB	359	1108–2003	0.17	0.85	0.09	0.40

[a]Calculated over 50 years, lagged by 25 years

After 300 year spline and RCS detrending, a long-term limitation in the spline chronology and rich low-frequency behavior in the RCS counterpart are obtained (Fig. 2D). Deviations prior to ∼1300 refer to superior tree growth preserved in the RCS chronology, potentially caused by the extension of the putative Medieval Warm Period (Lamb 1965). Caution is, however advised, as this early period, as well as the most recent end, are characterized by lower sample replication (Fig. 2A). Discrepancies between the two chronologies during ∼1300–1900, likely reflect the Little Ice Age (Grove 1988), which is more pronounced by the RCS method. Five depressions associated with the Little-Ice-Age-Type-Events described by Wanner et al. (2000) are pronounced in the RCS chronology. The 20th century warming, however, is poorly captured (Fig. 2D).

Although statistics are more convincing after spline detrending and additionally ITRDB data (Table 1), herein, we use the RCS chronology without data inclusion, as the more 'noisy' but 'comprehensive' RCS method maximizes low-frequency information, and solely new data are compiled. The primary dataset of 208 spruce series in combination with RCS hereafter serves as a case study, with the additional data providing validation, only.

Growth/climate response

Unlike the more uniform temperature variability, precipitation variability across the greater Alpine region shows considerable spatial variation on high- to low-frequency

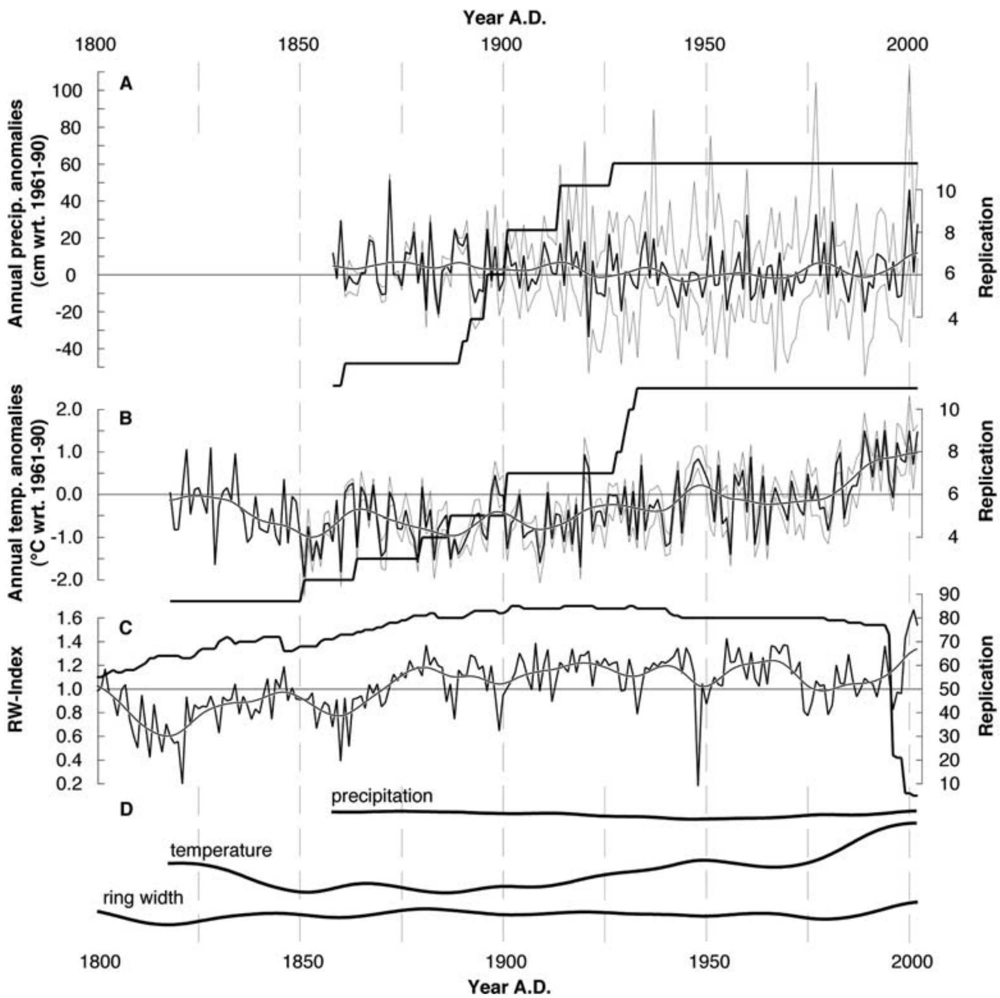

Fig. 3 Comparison between annual mean (*black*), minimum, and maximum (*grey*) **A** precipitation, **B** temperature, and **C** the RCS ring width records, with replication at the right hand axes. Means were 20 year and **D** 40 year low-pass filtered for trend illustration

scale (Auer et al. 2005; Böhm et al. 2001) (Fig. 3A–B). Inter-series correlations of the individual temperature and precipitation series are 0.92 and 0.55, for the 1933–2002 common period. The covariance between temperature and precipitation is expressed by correlations of −0.01, −0.08, and 0.10 for their annual, June–August, and December–February means.

Annual temperature, precipitation, and RCS ring width records reveal different variations and trends (Fig. 3). After 20 year smoothing, precipitation shows quasi-periodic decadal variability with higher values ∼1870, ∼1920, and ∼1980, and no trend (Fig. 3A). Twenty year smoothed temperature shows decadal variability with high values ∼1860, ∼1900, ∼1950, and ∼1980–present, and a superimposed long-term warming starting ∼1880 (Fig. 3B). The RCS chronology shows decadal variability with depressions ∼1820, ∼1860, ∼1950, and ∼1970–90, and again no trend (Fig. 3C). After 40 year smoothing, no longer-term trend is preserved in the precipitation record, however, temperatures increase from ∼1880–present. After 40 year smoothing, no longer-term trend remains from the tree-ring RCS chronology, but slight decadal-scale fluctuations before ∼1880 and after ∼1960 persist. (Fig. 3D). Low ring width values coincide with high temperatures, e.g., ∼1860, ∼1900, and ∼1950. The growth depression from ∼1970–90 matches increasing temperatures and generally low precipitation.

Monthly growth/climate response patterns of the spruce RCS chronology are obtained after correlations with high-elevation temperatures and precipitation of the previous and current year, over the 1933–2002 and 1927–2002 maximum periods of overlap are performed, respectively (Fig. 4). Negative (positive) correlations with previous year July–September temperatures (precipitation), and positive correlations with current year May–July temperatures, and negative correlations with December–January precipitation are obtained. Correlations with individual stations reveal homogeneous temperatures, and heterogeneous precipitation patterns for the Alps (Fig. 4A and B), also reported by Auer et al. (2005), and Böhm et al. (2001).

Maximum response to June–July mean temperatures confirms the importance of high summer temperatures, however indicates the generally curtness of the subalpine vegetation period, triggered by elevation and exposition (e.g., Carrer et al. 1998; Körner 1998). Monthly correlations reveal the importance of May climate and irrelevant August conditions for radial tree growth vigor, back to ∼1930. Neuwirth et al. (2004) showed that May temperatures and precipitation are crucial for 20th century ring width pointer years in the Lötschental. Positive correlations with February precipitation of the current year likely reflect the importance of sufficient snow cover. The interaction of May precipitation and spring snow-cover serves as water supply during the early vegetation period (e.g., Vaganov et al. 1999).

Resulting growth/climate response patterns denote the interaction of previous year June–September precipitation, and current year summer temperatures, for subalpine spruce growth vigor, as already reported for 20th century conditions (Lingg 1986; Tranquillini 1964; Vogel and Schweingruber 2001). Ring width variations result from the persistence of various effects into subsequent years through changes in nutrients and biological preconditioning of growth. For most conifers, photosynthetic gain from the previous growing season has major impact on current year radial growth behavior (Kozlowski and Pallardy 1997). For the trees used, the carry-over effect (Cook and Kairiukstis 1990; Fritts 1976; Jacoby and D'Arrigo 1989), such as storing assimilates is most significant for water supply. As a general feature of evergreen species, growth variations are significantly affected by the biological persistence, expressed by the 0.74 lag-1 autocorrelation (1163–2002, RCS chronology). Temperatures during the first part of the growing season, as well as the water supply of the previous year are key for the production of earlywood, which dominates the total ring width. Results show that the

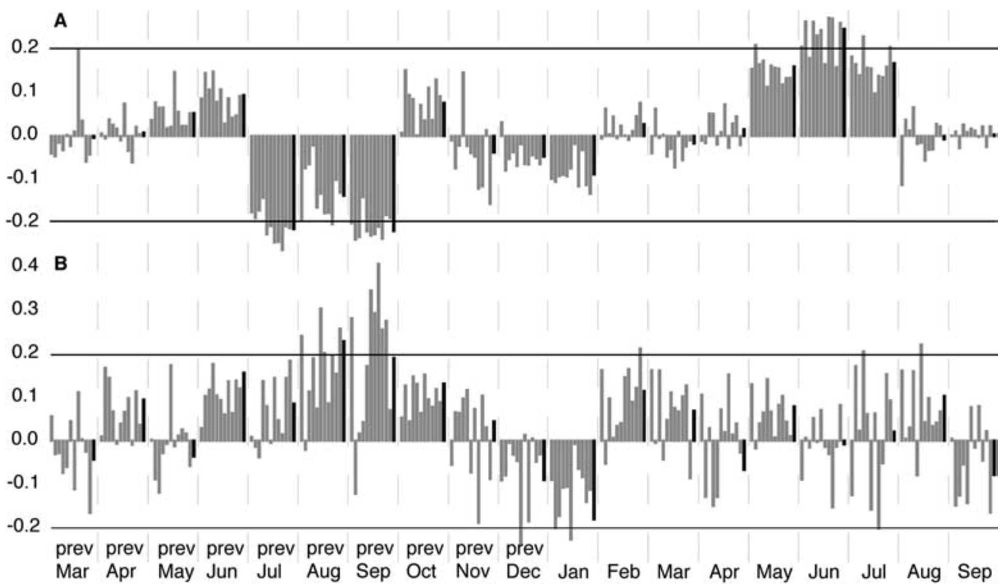

Fig. 4 Monthly growth response to **A** temperature (1933–2002) and **B** precipitation (1927–2002) of the previous and current year (*maximum common periods*). *Grey bars* show correlations with individual stations, and *black bars* denote correlations with the mean of these stations. *Horizontal lines* indicate 90% significance levels, corrected for lag-1 autocorrelation

definition of a single growth controlling parameter is not suitable.

Moving 51 year correlations between ring width series and summer temperatures of the previous and current year back to 1760 show decreasing growth/temperature response in recent time (Fig. 5A–C), whereas the Frank05 subset of 23 non-spruce chronologies (larch, fir, and pine) does not possess this trend (Fig. 5D). To avoid the potential bias of unrepresentative ring width data and age-related detrending methods, data from the ITRDB and Frank05 were included, and spline detrending performed. In each case, with the exception of the non-spruce data, correlations were higher in the earlier portion. Instable growth/temperature response is most evident for this study, which becomes more stable when including the ITRDB. Instable growth/temperature response also derives from the Frank05 subset of 30 spruce chronologies. These changes are most evident in correlations with the previous year climate. However, one must know, that individual treatment of the Frank05 subset chronologies reveals distinct site differences in growth/climate response, and that their original reconstruction obtains stable calibration and verification skills with instrumental data back in time (Frank and Esper 2005b). Only correlations with May temperature increase during the 20th century and potentially indicate a slight extension and/or forward shift of the vegetation period (not shown). Comparable growth/climate response shifts are shown by numerous low-elevation European spruce chronologies (Neuwirth 2005).

In contrast, moving 51 year correlations between the different spruce datasets outlined above, and previous year June–September precipitation show increasing growth/precipitation response over the 1858–2002 period, with the non-spruce data confirming this trend (Fig. 6A–D). Increasing growth/precipitation response is most evident for August. Periods of high (low) temperatures, such as ~1950 (~1910) coincide with periods of positive (negative) lag-1 growth/precipitation response, thus emphasize the coherency between rising temperatures and induced drought stress (Masson-Delmotte et al. 2005).

Regional- to large-scale comparison

Figure 7A compares the new RCS chronology, scaled to May–July mean temperatures (1864–2002), with regional instrumental (Böhm et al. 2001), and proxy (Frank and Esper 2005b) data.

The 208 series RCS chronology and the Frank and Esper (2005b) network reconstruction using 53 chronologies correlate at 0.45 (0.59), and after 40 year smoothing at 0.32 (0.56) (1600–1989 common period). Values in parentheses indicate correlations using the Frank05 average of the 30 spruce chronologies only. When splitting into the 1600–1900 and 1901–1989 period, correlations are 0.48 (0.40) and 0.39 (0.84). After 40 year smoothing, correlations decrease to 0.30 (0.21) and 0.07 (0.45), respectively. Similarity in the timing of inter-decadal variations and discrepancy in the low-frequency domain are obtained (Fig. 7A). The spruce RCS chronology increases from 1820–1880, then describes a plateau with high values ~1915 and 1960 and a depression ~1970, followed by the most recent increase, whereas the original Frank05 reconstruction shows little long-term warming over the past 400 years. Common inter-decadal features are higher values ~1610, 1790, and 1840 and the prominent depression ~1820. During the period of instrumental measurements, the RCS chronology shows significant

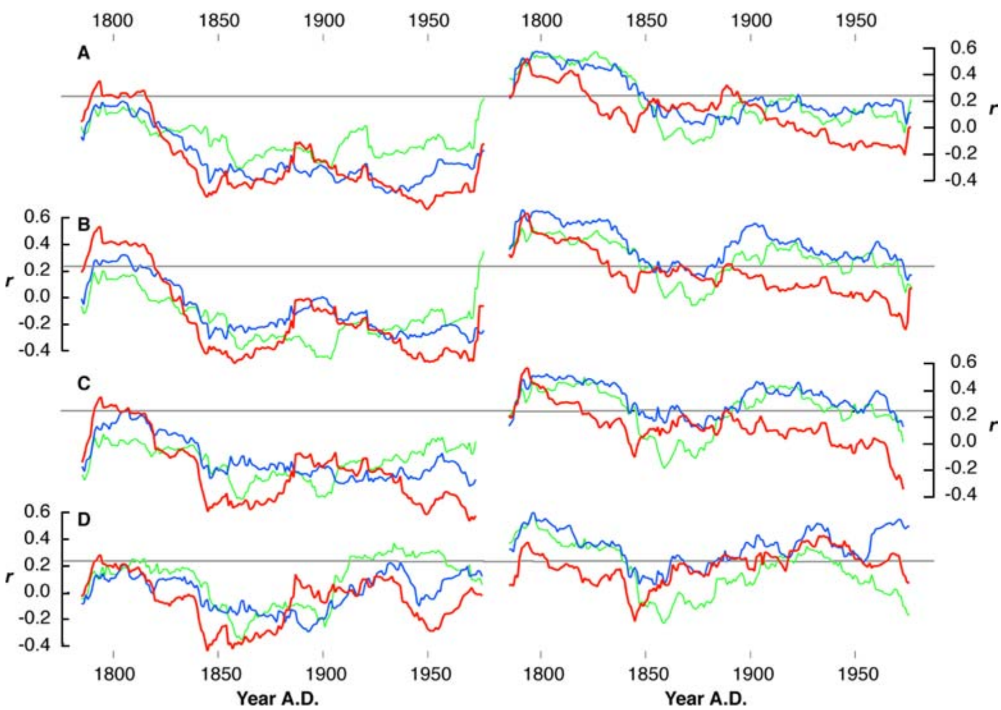

Fig. 5 Moving 51 year correlations between RCS detrended ring width data from **A** this study, **B** this study plus ITRDB, **C** Frank05 (30 spruce series) and **D** Frank05 (23 non-spruce series), and previous year (*left*) and current year (*right*) June (*green*), July (*blue*), and August (*red*) temperatures. Horizontal lines indicate 90% significance levels, corrected for lag-1 autocorrelation

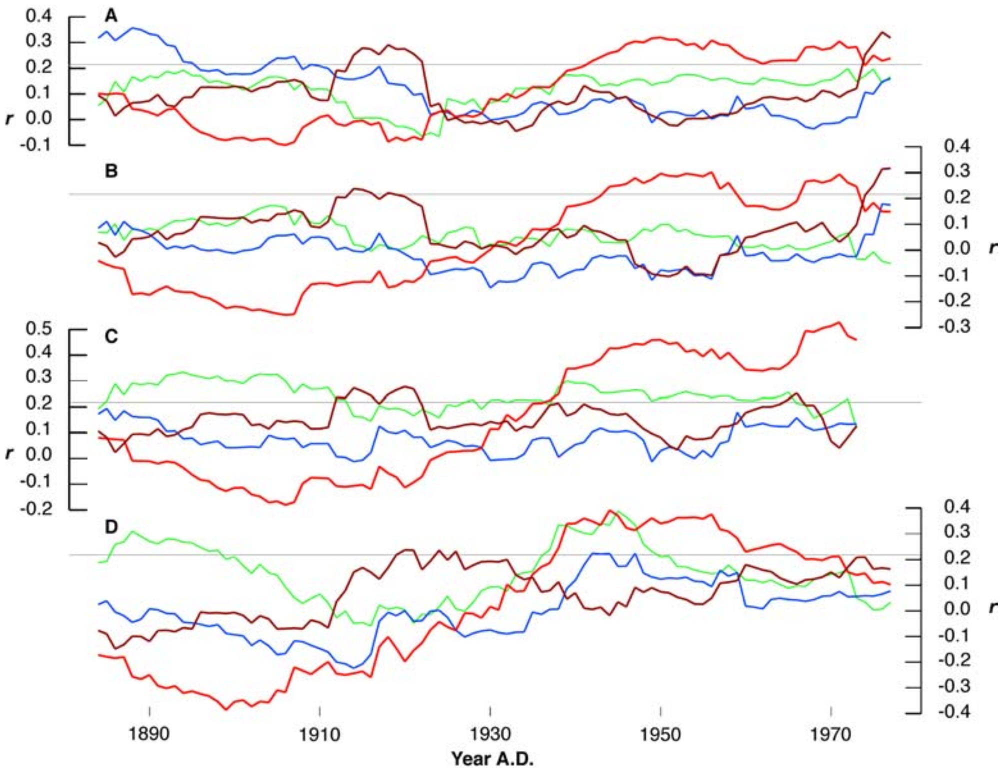

Fig. 6 Moving 51 year correlations between RCS detrended ring width data from **A** this study, **B** this study plus ITRDB, **C** Frank05 (*spruce*), and **D** Frank05 (*non-spruce*), and previous year June (*green*), July (*blue*), August (*red*), and September (*dark red*) precipitation. *Horizontal lines* indicate 90% significance levels, corrected for lag-1 autocorrelation

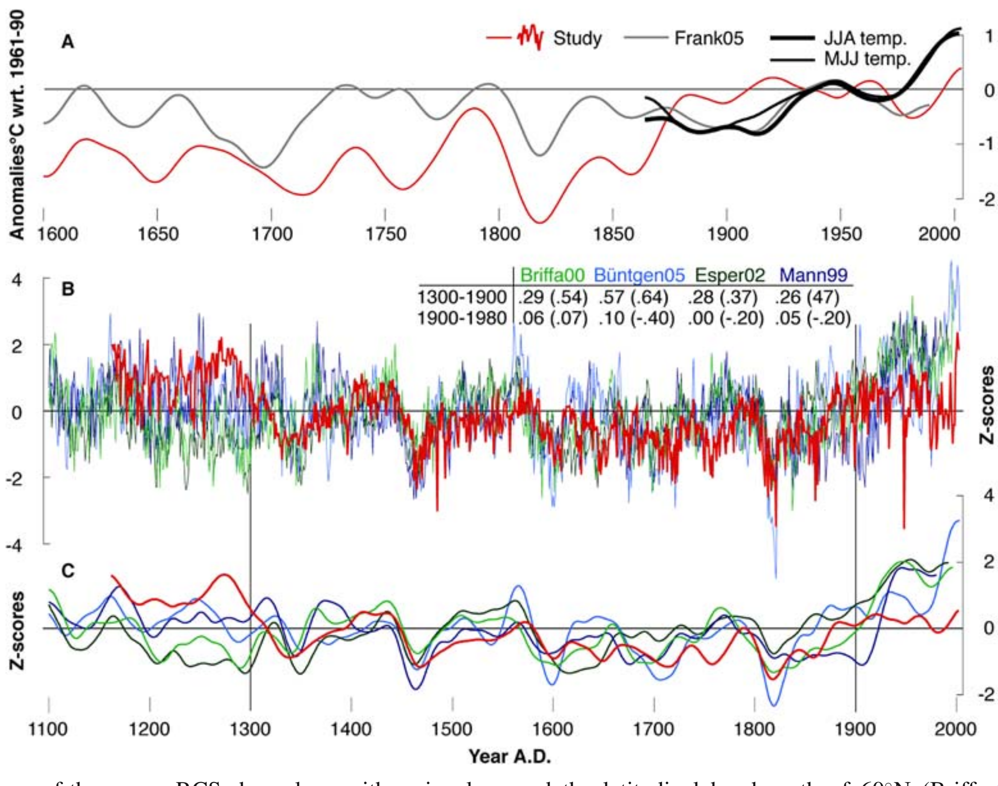

Fig. 7 Comparison of the spruce RCS chronology with regional-, and large-scale temperature reconstructions. **A** This study, Frank05, and May-July and June–August high elevation mean temperatures (Böhm et al. 2001), after 40 year low-pass filtering. **B** This study and temperature reconstructions for the Alps (Büntgen et al. 2005a, tree-rings), Northern Hemisphere (Mann et al. 1999, multi-proxy), Northern Hemisphere extra-tropics (Esper et al. 2002, tree-rings), and the latitudinal band north of 60°N (Briffa 2000, tree-rings). Mann99 is likely weighted towards annual, and Büntgen05, Esper02 and Briffa00 towards warm season temperatures. Records were normalized over the 1108–1980 period of overlap and **C** 40 year low-pass filtered. Inset table shows correlations computed before and after 1900, with values in parentheses deriving after 40 year low-pass filtering

divergence with the original Frank05 reconstruction, which correlates much better with the target instrumental data. Possible reasons are manifold, e.g., tree-ring data, species, detrending methods and instrumental data used, calibration techniques applied, the climatic signal recorded, and/or the screening of the tree-ring data in Frank and Esper (2005b).

The comparison with millennial-long regional- (Büntgen et al. 2005a), and large-scale temperature reconstructions (Briffa 2000; Esper et al. 2002; Mann et al. 1999) reveals substantial mid- to low-frequency similarities over most of the time span, with a divergence after ~1900 (Fig. 7B–C). For the 1300–1900 period, correlations after 40 year smoothing range from 0.37 with Esper02 to 0.64 with Büntgen05. For the 1900–1980 period, correlations, however, decrease to 0.07 with Briffa99 and −0.40 with Büntgen05 (Fig. 7C). Key trends within all records are high growth values associated with the putative Medieval Warm Period, several growth depression reflecting the Little-Ice-Age-Type-Events, and increasing values starting ~1820. Most pronounced similarities occur on decadal scale, with all records reflecting low growth values in the 1340s, 1460s, ~1600, 1700, and 1820, likely forced by the interaction of the volcanic eruptions of Kuwae (1452), Huaynaputina (1600), and Tambora (1815) (e.g., Briffa et al. 1998a; Simkin and Siebert 1994), and the Wolf (1280–1340), Spörer (1420–1530), Maunder (1650–1710) and Dalton (1795–1825) solar minima (e.g., Eddy 1977; Usoskin et al. 2003). Between these periods of relatively low growth, higher values occur in all chronologies during the 1440s, 1570s, and 1790s.

Substantial differences between the records are found before 1300, ~1700, and after 1900. Offset within the earlier portion likely reflects decreasing sample size of the spruce chronology. Discord ~1700 is potentially related to the spatial heterogeneity (Camuffo and Enzi 1994; Luterbacher et al. 2001) and seasonality (Pfister 1999; Wanner et al. 1995) of the Late Maunder Minimum (1675–1715). Most significant differences, however, remain in the 20th century, as the spruce chronology does not capture the recent warming trend, clearly reproduced by all other records. Possible reasons for this deviation are discussed below.

Discussion and conclusions

The compilation of 208 (recent/historic) subalpine spruce ring width series, and the application of RCS, resulted in an 896 year long chronology, with reasonable replication and signal strength back to at least 1300. Even though, this new chronology is noisier than its counterpart after spline detrending (Table 1)—a general feature of RCS (Briffa et al. 1992, 1996; Esper et al. 2003b)—it preserves low-frequency information, and retains similarities with regional-, and large-scale temperature reconstructions. Deviations from large-scale growth variations are likely regional expressions. Discrepancies before ~1300 are related to this study's sample reduction and the inclusion of primary juvenile wood. Recent differences are potentially caused by the spruce growth/climate response shift. The 20th century offset between increasing temperatures and constant ring width and precipitation values is distinct after smoothing. Periods of high (low) temperatures and relatively low (high) precipitation match periods of low (high) ring width, such as ~1860, ~1900, ~1950, and ~1970 (Fig. 3).

Evidence of potential anthropogenic forcing (e.g., SO_2 emission) on recent spruce growth (Eckstein and Saas 1989; Elling 1990; Sander et al. 1995; Wilson and Elling 2004) is not assumed, as trees originate from different and remote subalpine sites, and the loss of temperature sensitivity does not coincide with increasing greenhouse gases (Bauer et al. 2003; Etheridge et al. 1996). Also, the response shift is likely not related to a transition between recent and historic tree-ring samples, as the majority of living trees (no. 74) stretch the 1990s, and most of the historic wood (no. 106) ends before 1760. However, cloud cover changes, and trend differences in minimum, maximum and mean temperatures could affect tree growth, as decreased irradiance reduces photosynthetic capacity (e.g., Tranquillini 1964; Körner and Paulsen 2004), and growth responds to different climatic parameters (e.g., Wilson and Luckman 2002).

The idealized "linear" temperature response of subalpine spruce may break down above some threshold, and temperature-induced drought stress likely affects ring width. Above a threshold of ~13°C, subalpine pine and spruce trees seem unable to take full advantage of warm/sunny days (Carrer et al. 1998). With an equivalent threshold ~16°C, larch trees at commonly higher elevations are less affected. Even though, these thresholds are not representative for different site ecologies (M. Carrer, personal communication), larch has a better ability to cope with drought. As deciduous trees, larch maintain the highest photosynthetic capacity during the short growing season despite any variation in water availability, and develop a deep root system, which provides water access to the deepest and wettest soil layers (Tranquillini 1964; Valentini et al. 1994). Figures 5D and 7B–C depict that larch likely possess advantages in competition against spruce when summer temperatures increase, and soil moisture decreases with lowest values towards the end of the vegetation period (D'Arrigo et al. 2004; Wilmking et al. 2004). Since spruce tend to favor water storage instead of water uptake, a reduction in high summer soil moisture seems to result in a shift in balance from August to May temperatures during the 20th century (Figs. 4 and 5). The combination of high temperatures and adequate water availability only stimulate positive radial growth below a critical threshold, as any drought-induced break in the tree's assimilation processes likely stresses radial growth (Anfodillo et al. 1998). However, a slight extension of the vegetation period should compensate for some of the drought-induced growth decline.

To not restrict this study to particular data and detrending methods only, chronologies from the ITRDB and the network developed by Frank and Esper (2005a) were included, and spline detrending performed. Moving 51-year correlations prove our results (Fig. 5A–C); however, individual treatment of the 30 spruce chronologies used by Frank and Esper (2005a) indicates strong site differences in growth/climate relationships (not shown). Non-spruce chronologies generally show more stable correlations during the 20th century (Fig. 5D). Note that results are based on ring width data only, and are not confirmed by maximum latewood density data, commonly used as warm season proxy (Briffa and Schweingruber 1988). Even though different detrending methods were performed, further uncertainty potentially derives from the so-called "end-effect" problem in tree-ring standardization (Cook and Peters 1997).

Our results resemble the temporal instability in growth/climate response, reported from other European spruce sites (Hasenauer et al. 1999; Wilson and Elling 2004; Wilson and Topham 2004), and are perhaps somewhat similarly to the "reduced sensitivity" and increasing drought stress of recent high latitudinal tree growth to temperature (Barber et al. 2000; Briffa et al. 1998b; D'Arrigo et al. 2004, 2005; Davi et al. 2003; Jacoby and D'Arrigo 1995; Lloyd and Fastie 2002; Vaganov et al. 1999; Wilmking et al. 2004). Here we show evidence for increasing drought stress on Alpine high elevation tree-sites which has shifted the balance from a more current growing season summer temperature signal towards a more mixed signal, including positive response to precipitation of the previous year, and negative response to temperatures of the previous and current year.

We here seek to the importance of carefully selected tree-ring data, adequate detrending methods, sufficient sample size and distribution, as well as time-dependent growth/climate response analyses, prior to climatic interpretations. Although our new spruce chronology is prior to the 20th century in scope with commonly reported Alpine temperature variations, we refrain from developing a dendroclimatic reconstruction.

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