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Inner Alpine conifer response to 20th century drought swings

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Abstract Tree rings from the Alpine area have been widely used to reconstruct variations in summer temperature. In contrast, estimates of changes in the hydrological cycle are rather scarce. In order to detect altitudinal and species-specific patterns of growth responses to anomalous dry and wet conditions, a large network of 53 tree-ring width site chronologies along the Rhone valley (Valais, Switzerland) covering the 1751–2005 period was compiled and analyzed. A total of 1,605 measurement series from four conifer species—pine, larch, spruce, fir—were detrended to allow inter-annual to multi-decadal scale variability to be preserved. Site chronologies were combined to four altitudinal (colline: <800 m asl, sub-montane: 800–1,000 m asl, montane: 1,000–1,450 m asl, sub-alpine: >1,450 m asl) and species-specific mean time-series. These records were compared with temperature, precipitation, and drought (scPDSI) data. Among the altitudinal records, the colline chronologies showed highest correlation with June precipitation and scPDSI (0.5 and 0.7). Altitudinal effects, via control on climatic conditions, were superimposed upon species-specific characteristics in affecting tree growth and response to moisture variations. In particular, species-specific differences affected the significance level of drought response, with decreasing drought sensitivity towards higher elevations. Growth conditions were found to be optimal at ~1,300 m asl, with precipitation/drought limiting tree growth below and temperature above. Common years of extreme drought and low growth for the colline sites occurred in 1921, 1944, 1976, 1992, and 1998. Our results demonstrate the potential of lower elevation conifers for reconstructing long-term changes in Alpine hydro-climate.

Keywords Alpine drought · Tree-ring width · Hydro-climate · Dendroclimatology

Introduction

Regional- to global-scale climate variability within the past decades is now regarded to exceed natural envelopes of more than the last millennium (IPCC 2007). Particular emphasis has been placed on temperature fluctuations as these are most directly tied to changes in radiative forcing and due to relatively high spatial autocorrelation may be reasonably well reconstructed with a more sparse data network (Esper et al. 2002; Cook et al. 2004). However, in climate change scenarios, not only rising temperatures are projected, but also shifts in the hydrological cycle are expected or even already observed (Huntington 2005; Zhang et al. 2007).

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In this regard, Zhang et al. (2007) estimated that anthropogenic forcing contributed significantly to the observed increase in annual precipitation in the Northern Hemisphere mid-latitudes (e.g., Treydte et al. 2006) and to drying in subtropical regions (e.g., Esper et al. 2007). Due to the local character of precipitation variability, investigations are, however, more complex, and trend predictions remain difficult, particularly on the regional scale (Stott et al. 2006; Matti et al. 2009). As future short- to long-term variations in water availability are arguably much more important to society and ecosystem functioning than temperature variations (IPCC 2007), current research priorities include the quantification of long-term changes in moisture availability from spatially well-distributed locations, as well as the assessment of drought and pluvial conditions on ecosystem functioning (Straile and Stenseth 2007).

Within the greater Alpine region (GAR), well-homogenized instrumental precipitation measurements that provide reliable insight into regional variability are available over the last decades to centuries, with high-elevation measurements being particularly prone to error (e.g., Efthymiadis et al. 2007; Auer and 31 Co-authors 2007 and references therein). Similarly, van der Schrier et al. (2006) introduced the self-calibrating palmer drought severity index (scPDSI) to investigate 20th century variations in soil moisture availability across continental Europe. A revised version including a snow model was released for the Alpine arc (van der Schrier et al. 2007).

Nevertheless, to assess precipitation totals further back in time—and particularly prior to large-scale industrialization—annually resolved information from indirect archives, so-called proxy data is required. Such records can include precipitation indices based on documentary evidence (see Brázdil et al. 2005, for a review; Gimmi et al. 2007) and various precipitation natural archives (Pauling et al. 2006). Tree-ring data, which have been prominently used to reconstruct temperature variations over the GAR (e.g., Frank and Esper 2005b; Büntgen et al. 2005, 2006, 2008, 2009b), can be a useful tool to also obtain information on past drought and/or precipitation changes. The ability for tree rings to capture temperature or moisture variations depends upon the given site ecology (Fritts 1976; Nemani et al. 2003; Neuwirth et al. 2004; Büntgen et al. 2007). That is, measurements from trees growing near their thermal growth limit (upper or latitudinal treeline) reflect temperature variations, and conversely measurements from trees growing under warm and/or arid conditions mirror drought fluctuations.

The only reconstruction that allows inner Alpine precipitation variability to be retained, originates from the Austrian Alps, Tyrol (Oberhuber and Kofler 2002). Other proximal tree ring-based precipitation/drought reconstructions include that from Wilson et al. (2005) for the Bavarian forest and from the Vienna basin (Brázdil et al. 2002; Leal et al. 2008; Strumia et al. 1997 (see Büntgen et al. 2009a) for more information on these studies and an overview of Central European hydro-climatic records). From the spatial distribution of these existing records and considering the short spatial de-correlation length typical for moisture changes, additional locations are necessary to provide a better understanding of European-scale hydro-climatic variability (Pauling et al. 2006; Matti et al. 2009; Büntgen et al. 2009c).

In this regard, tree-ring networks that assess growth response to hydro-climatology are of particular importance. Schweingruber and Nogler (2003) analyzed precipitation signals in a tree-ring network including the southern German Black Forest, the Vosges Mountains (northeastern France), the Central Plateau, Jura, and northern Pre-Alps (both Switzerland). Leal et al. (2008) and Strumia et al. (1997) analyzed the growth sensitivity of numerous low-elevation pine sites in Austria. Other studies focused on climatic forcing of tree growth along various ecological gradients in inner Alpine valleys (Kienast et al. 1987; Oberhuber et al. 1998; Rigling et al. 2001, 2002, 2003; Neuwirth et al. 2004; Eilmann et al. 2006; Weber et al. 2007). More systematic network analyses that would allow the reconstruction of past drought changes are, however, scarce (Büntgen et al. 2009c). Investigations on pine mortality (Bigler et al. 2006; Dobbertin and Rigling 2006) and displacement by oak (Weber et al. 2007, 2008) in the Swiss Valais suggest an increasing effect of drought events to this conifer species. Although an intensification of extreme climate conditions is expected for sensitive regions like the Alps (Wanner et al. 2000), a large-scale assessment of precipitation variability is still missing. The same accounts for a basic assessment of extreme drought events on tree growth.

Here, we present the first step toward reconstructing drought variability in the Swiss Alps. Our study is restricted to the inner Alpine valley of the Valais, as local dry climate conditions suggest precipitation sensitive tree growth. Moreover, an altitudinal gradient can be studied from the valley bottom at 400–600 m asl up to the treeline at ~2,300 m asl. Additional motivation derived from several tree-ring series that are already at disposal. In summary, we (1) develop a unique network of TRW data covering colline to sub-alpine elevations, (2) assess climate signals within this dataset, and (3) discuss altitudinal and species-specific patterns of conifer response to temperature, precipitation and drought.

Materials and methods

We complemented 22 existing TRW site chronologies from the Rhone valley—an inner alpine dry valley in the Swiss Canton Valais (Wanner et al. 2000)—ending in the

1990s with data from 31 new TRW site chronologies continuing until 2005 (Table 1). The resulting network represents a substantial update compared with existing compilations and now covers a longitudinal west–east transect from Martigny to Fiesch spanning from 590 m to 1,570 m asl (Fig. 1). It comprises 1,605 TRW measurement series from four conifer species (Table 1): pine (*Pinus sylvestris* L.), larch (*Larix decidua* Mill.), spruce (*Picea abies* (L.) Karst.), and fir (*Abies alba* Mill.) hereinafter PISY, LADE, PCAB, and ABAL, respectively. The mean number of core samples per site is 28 with a minimum of 5 and a maximum of 135. Mean segment length per site is 96 years with a minimum of 43 and a maximum of 161 years.

Non-climatic biological/geometrical-induced age trends (Fritts 1976) were removed from the raw measurement series (though allowing inter-annual to multi-decadal scale variations to be preserved) using cubic smoothing spline detrending with a 50% cutoff at 150 years (Cook and Peters 1981). Even though longer term growth trends above multi-decadal time-scales are, however, not retained (Cook et al. 1995), Büntgen et al. (2009a) successfully applied this particular spline length on a similar dataset of drought-sensitive pine data from Slovakia. Further, the spectral properties in the TRW chronologies are likely to be similar to variations in the scPDSI due to the extended biological memory of TRW (Frank and Esper 2005a; Frank et al. 2007a, b) and the integration of lower frequency climatic and hydrological parameters in the scPDSI (Esper et al. 2007). For each site, measurement series were averaged to form chronologies based on a bi-weight robust mean, and truncated at a replication of at least five series to mitigate variance artifacts (Frank et al. 2007a, b), as well as noise from poorer representations of the population chronology (Wigley et al. 1984).

For growth/climate response analyses, the site chronologies were divided into four altitudinal master chronologies: colline (<800 m asl, mean *Rbar* of site chronologies = 0.64), sub-montane (800–1,000 m asl, *Rbar* = 0.69), montane (1,000–1,450 m asl, *Rbar* = 0.67), and sub-alpine (>1,450 m asl, *Rbar* = 0.61). Moreover, the site chronologies were divided into four species-specific master chronologies: PISY, LADE, PCAB, and ABAL for which intercorrelation *Rbar* is 0.63, 0.66, 0.71 and 0.73, respectively. The low-elevation colline chronology consists of four site chronologies (97 PISY series) covering the 1901–2002 period, whereas the sub-montane chronology includes 21 site chronologies (674 series, all species) covering the 1824–2005 period. The montane chronology combines 19 site chronologies (488 series, all species) over the period 1751–2005 and the sub-alpine chronology combines nine site chronologies (255 series, all species) over 1796–2005.

For climate response analysis, datasets of gridded (0.5° × 0.5°) monthly temperature and precipitation (CRUTS 2.1; Mitchell and Jones 2005) and scPDSI (van der Schrier et al. 2007) were used. Data from one grid point nearby Sierre (46°18′N/7°31′E) were considered for comparison over the 20th century and expressed as anomalies with respect to the 1961–1990 climatology. The altitudinal and species-specific chronologies were correlated against monthly climate data over the common 1932–1979 period and using an 18-month window from May of the year prior to tree growth until October of the vegetation period. Correlation coefficients were calculated along with the corresponding 95% significance levels corrected for *lag-1* autocorrelation of each dataset (Trenberth 1984).

Results

Low- and mid-elevation chronologies showed significant ($P < 0.05$) negative relationships with temperature of previous year August and September (Fig. 2a). The colline chronology correlated negatively with current year April–May and July–August temperatures, whereas the mid-elevation chronologies indicated slightly negative correlations to current year May (sub-montane and montane) and August (sub-montane) temperatures. The high-elevation sub-alpine chronology revealed non-significant ($P > 0.05$) correlations with temperature, although a certain tendency toward positive values from current August to October was indicated.

For precipitation, significant TRW responses were found by the sub-montane chronology to previous year July–August and by the sub-alpine chronology to August (Fig. 2b). The low-elevation colline chronology correlated slightly positive with January and highly positive with June–July precipitation in the year of ring formation. Moreover, the sub-montane and the montane chronology indicated good agreement with June precipitation.

Comparison of the altitudinal master chronologies with scPDSI data (Fig. 2c) resulted in highest coefficients and a reduced monthly difference due to increased autocorrelation of the scPDSI metric. Low- to mid-elevation chronologies correlated positively with previous year July–December scPDSI. The sub-montane and the montane chronologies showed decreasing correlations with scPDSI in the current year, with non-significant coefficients obtained for the montane chronology in February, March, and August and for both chronologies in October. With June scPDSI, however, they both still showed high correlations (0.59 and 0.48). The colline chronology indicated a strong relationship to current year scPDSI data with highest coefficients in the summer months June and July (0.73 and 0.72). The

Table 1 Characteristics of the site chronologies ordered by altitude

	Site location	m asl	Series	Period > 5	Species	Rbar	MSL	Source
<800 m asl (colline)	Lens A	695	18	1911–2001	PISY	0.643	63.9	Weber
	LWF Visp 627	704	20	1932–1996	PISY	0.649	43.3	Cherubini
	Eschwald A	710	39	1928–2001	PISY	0.477	61.2	Weber
	Bramois B	735	20	1901–2001	PISY	0.728	83.2	Weber
800–1,000 m asl (sub-montane)	Salgesch A	825	19	1846–2001	PISY	0.593	82.8	Weber
	Les Arbepins 257	840	18	1846–1979	PISY	0.704	103.6	Kienast
	Susten Zänd 469	840	38	1773–1980	PCAB	0.827	92.9	Schweingruber
	Susten Zänd 470	840	6	1847–1980	ABAL	0.798	84.5	Schweingruber
	Susten Zänd 471	840	17	1824–1980	ABAL	0.871	112.3	Schweingruber
	Riddes	860	28	1892–2005	PISY	0.717	89.3	Affolter
	Riddes	860	30	1887–2005	LADE	0.703	101.3	Affolter
	Eschwald B	865	26	1909–2001	PISY	0.658	55.2	Weber
	Stalden	880	135	1838–2003	PISY	0.600	88.2	Rigling
	Boutieu 66	880	32	1886–1979	PISY	0.550	76.5	Kienast
	Eponde 136	880	5	1854–1979	PISY	0.685	118.4	Kienast
	Crete 117	890	26	1839–1979	PCAB	0.733	103.0	Kienast
	Hopflsteig	900	36	1796–2005	LADE	0.705	117.3	Affolter
	Hopflsteig	900	24	1882–2005	PCAB	0.727	76.2	Affolter
	Hopflsteig	900	18	1816–2005	LADE	0.686	127.7	Affolter
	Salgesch	900	22	1793–2001	PISY	0.590	105.3	Eilmann
	Salgesch	910	111	1834–2003	PISY	0.701	117.1	Rigling
	Bramois C	930	20	1892–2001	PISY	0.647	83.2	Weber
	Eggerberg A	950	20	1867–2001	PISY	0.606	75.8	Weber
	Eschwald C	960	20	1910–2001	PISY	0.644	56.0	Weber
	Salgesch B	980	23	1851–2001	PISY	0.718	97.3	Weber
>1,000–1,450 m asl (montane)	LWF Lens 621	1,064	20	1821–1997	PISY	0.719	106.0	Cherubini
	Eggerberg B	1,075	22	1868–2001	PISY	0.524	57.1	Weber
	Deischbach	1,080	52	1841–2005	PISY	0.621	109.3	Affolter
	Salgesch C	1,120	16	1899–2001	PISY	0.608	58.2	Weber
	Lens C	1,150	18	1819–2001	PISY	0.690	106.6	Weber
	Eggerberg C	1,200	18	1911–2001	PISY	0.518	74.5	Weber
	Creux du Dailley mittel	1,200	9	1855–1979	PCAB	0.791	115.0	Kienast
	Pres des Champs 380	1,220	27	1884–1979	PCAB	0.692	71.8	Kienast
	Bannwald Süd 47	1,230	28	1814–1980	PCAB	0.829	125.2	Schweingruber
	Bannwaid Süd 48	1,230	27	1810–1981	ABAL	0.770	101.3	Schweingruber
	Bannwald Süd 49	1,230	25	1878–1980	ABAL	0.797	84.8	Schweingruber
	Bannwald Nord 45	1,240	7	1798–1980	PCAB	0.704	88.0	Schweingruber
	Bannwald Nord 45	1,240	24	1874–1980	ABAL	0.741	87.5	Schweingruber
	Creux du Dailley 119	1,240	15	1751–1979	PISY	0.709	160.7	Kienast
	Ritena	1,260	34	1820–2005	PISY	0.651	139.6	Affolter
	Ritena	1,260	36	1874–2005	LADE	0.744	109.4	Affolter
	Savièse	1,440	32	1820–2005	PISY	0.485	98.8	Affolter
	Savièse	1,440	32	1906–2005	PCAB	0.602	48.6	Affolter
	Scheni Biela	1,450	46	1757–2005	PISY	0.447	157.8	Affolter
>1,450 m asl (sub-alpine)	Jeizinen	1,500	56	1848–2005	LADE	0.566	92.5	Affolter
	Ovronnaz	1,500	11	1829–2005	LADE	0.632	100.5	Affolter
	Ovronnaz	1,500	12	1843–2005	ABAL	0.483	85.1	Affolter
	Ovronnaz	1,500	43	1832–2005	LADE	0.611	90.5	Affolter

Table 1 continued

	Site location	m asl	Series	Period > 5	Species	Rbar	MSL	Source
	Mittleri Hellalawald 294	1,510	27	1796–1980	PCAB	0.619	134.9	Schweingruber
	Mittleri Hellalawald 294	1,510	30	1818–1980	ABAL	0.637	108.8	Schweingruber
	Chable des Trois Besses	1,520	28	1816–1719	PCAB	0.587	129.6	Kienast
	Torrent des Croix 491	1,540	18	1835–1979	PISY	0.655	122.0	Kienast
	Bisse de Saxon 59	1,570	30	1861–1979	PCAB	0.699	104.9	Kienast

Period time-span covered by at least 5 series, *Rbar* inter-series correlation, *MSL* mean segment length

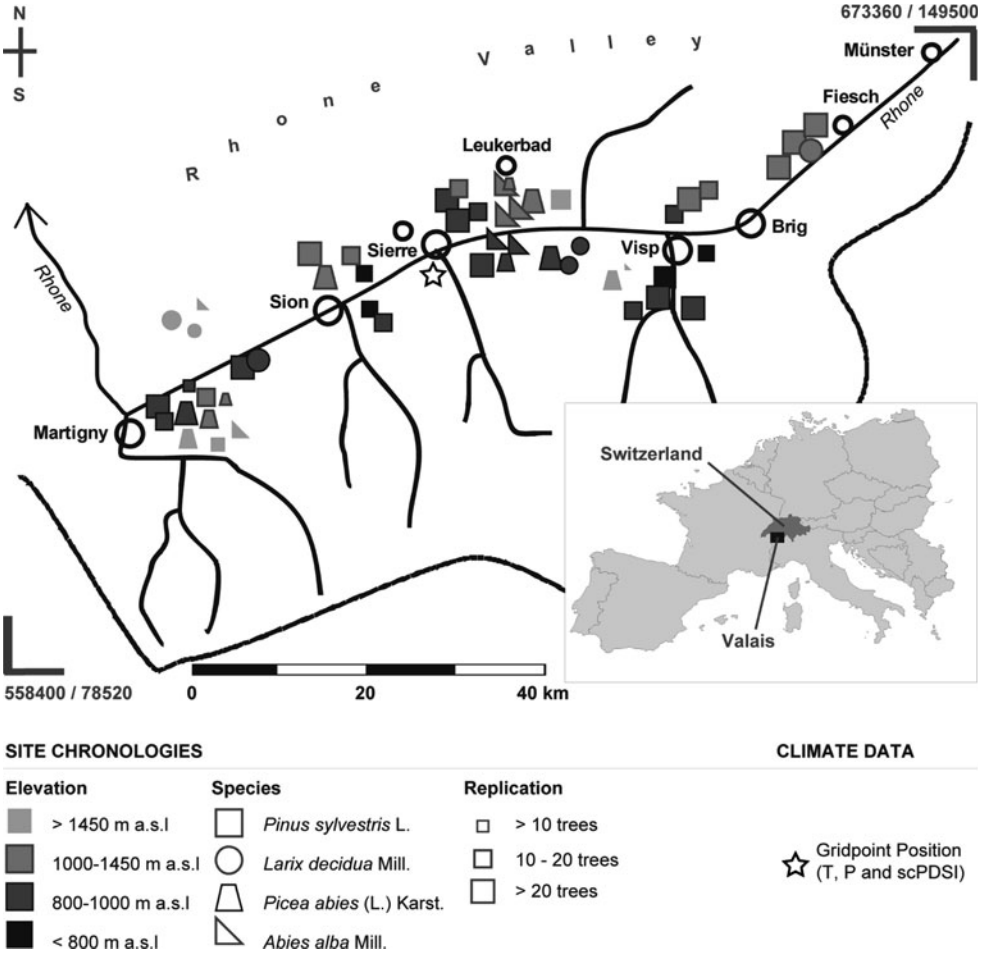

Fig. 1 Location of the TRW sites, classified with respect to elevation, species, and replication

sub-alpine chronology did not correlate significantly with scPDSI.

A comparison of the low-elevation colline chronology—consisting of PISY only—with June scPDSI (Fig. 3a) emphasized common deviations in extreme drought events: 1921, 1944, 1976, 1992, and 1998. The correlation between growth and June scPDSI was further analyzed using a 31-year moving window approach. For the period 1932–1979 (common to all TRW and climate datasets), TRW data corresponded with the scPDSI in high- to low-frequency domains; coefficients up to 0.73 were reached. Shorter time spans at the beginning and the end of the full overlapping period (1902–2001) revealed weaker relationships—sample replication of the colline chronology is low before 1929 and after 1995 (Fig. 3b).

With respect to species composition, PISY data indicated strongest coherency with the scPDSI (Fig. 4a). Correlations were positive over all seasons, with overall less similarity found with prior May–June and current October. PCAB showed also good agreement with May–December scPDSI in the year prior to tree growth and in current year January–July. The LADE chronology revealed an overall reduced positive relation to drought. Coefficients were only significant with previous year November–December, as

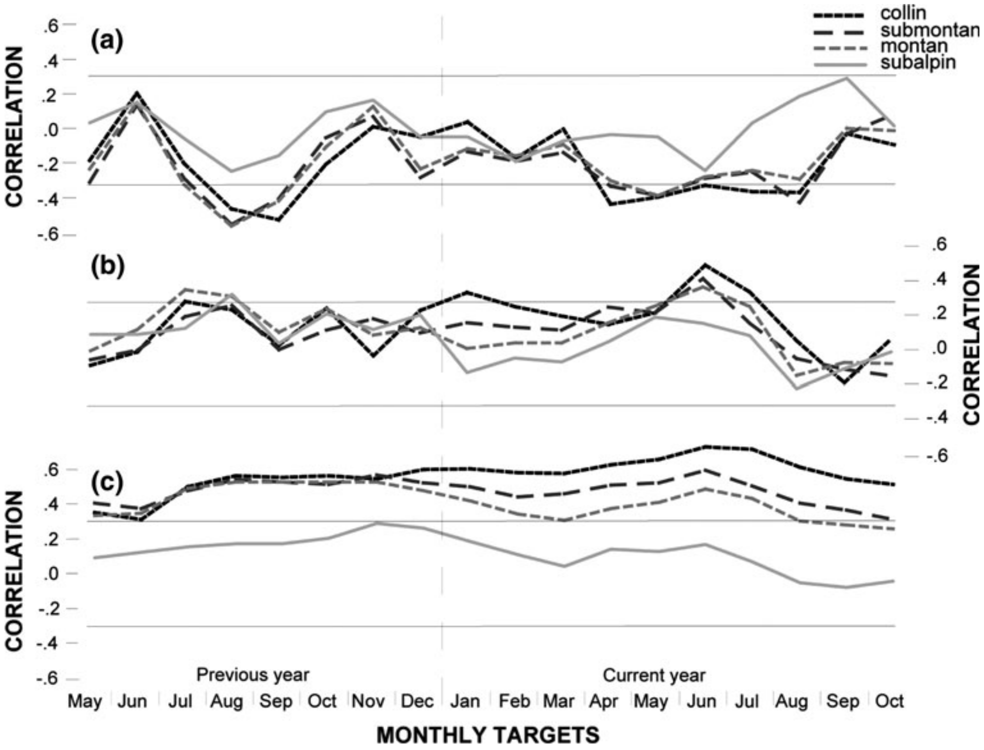

Fig. 2 Correlation (1932–1979) between altitudinal chronologies and gridded monthly **a** temperature, **b** precipitation, and **c** scPDSI data from previous year May to current year October. Horizontal lines are 95% significance levels corrected for *lag-1* autocorrelation

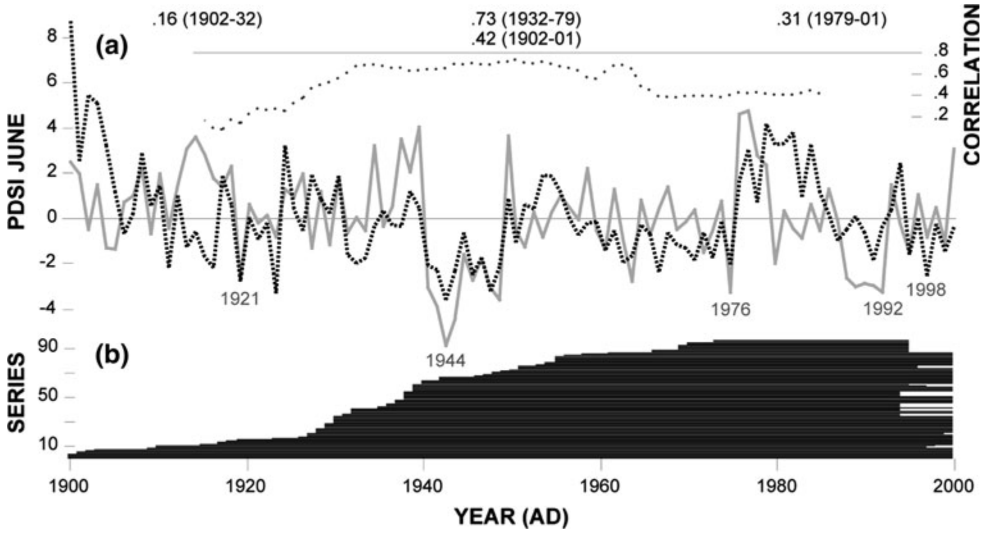

Fig. 3 **a** Comparison of the colline chronology (*black dashed*) and June scPDSI (*gray*). The TRW proxy was scaled (i.e., their variance and mean adjusted) to the climatic target (1901–2002), *black dots* indicate their 31-year moving correlations and **b** TRW sample replication is indicated

well as with April and June of the vegetation period. ABAL even did not show any significant correlation except with previous year September–November. For a better understanding of the obtained species-specific responses, chronologies were additionally distinguished in high (montane and sub-alpine) and low (colline and sub-montane) altitudes (Fig. 4b). In comparison with the June scPDSI, chronologies from lower elevation showed consistently higher correlations than those from higher elevations, independent of the species used.

To further explore frequency-dependent relationships between the altitudinal proxies and scPDSI targets, tree-ring and instrumental data were high-, and low-pass filtered. Low-frequency variations correlated higher for the low- to mid-elevation chronologies. In both the low- and high-frequency domain, the strongest relation was found between the colline chronology and the scPDSI (0.8 in August and 0.68 in June, respectively), whereas the sub-alpine chronology did not correlate significantly at all.

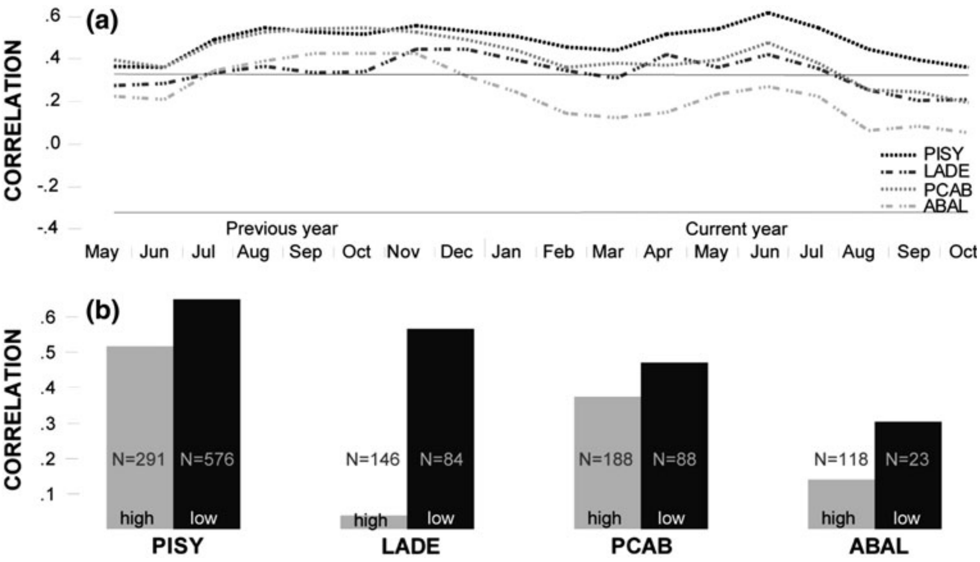

Fig. 4 **a** Correlations between the species-specific TRW chronologies and scPDSI data from previous year May to current year October. **b** Species- and altitudinal-specific growth response patterns to June scPDSI

Discussion

The altitudinal- and species-specific master chronologies integrate varying quantities of site chronologies with unequal replication, time cover, and segment length (Table 1). Such heterogeneity most likely affects the identification and quantification of climatic signals. The master chronologies, however, contain a high degree of common variability caused by a universal forcing (Figs. 2a–c), in line with former studies using smaller data sub-sets from the same region (e.g., Kienast et al. 1987; Rigling et al. 2002; Weber et al. 2007). Some of the chronologies from lower elevations cover rather short periods during the 20th century. Finding long-lived trees at lower elevations remains difficult due to extensive past anthropogenic impacts within the Rhone valley, including clear-cutting and pasturing (Gimmi et al. 2008). Furthermore, the lower elevation forests were frequently replaced by vineyards or affected by natural hazards, such as rock fall, debris flow, and avalanches (e.g., Gärtner et al. 2004).

The altitudinal master chronologies indicated characteristic climate–growth relationships, namely drought sensitivity at lower elevations and a tendency toward temperature-limited growth at higher elevations. Reduced water availability during the growing season at lower altitudes (Rigling et al. 2002; Eilmann et al. 2006; Weber et al. 2007) and growth-limiting temperatures at high elevations (Büntgen et al. 2005, 2006, 2008, 2009b) are likely also the key reasons for substantial productivity changes with elevation (Neuwirth et al. 2004), including enhanced growth rates at ~1,300 m asl, and clearly lower growth rates below 1,000 m asl and toward the upper treeline (Fig. 5). These results are in agreement with patterns initially described by Kienast et al. (1987), who assessed altitudinal gradients at a few sites in the Rhone valley and with Frank and Esper (2005a), who showed a decrease in

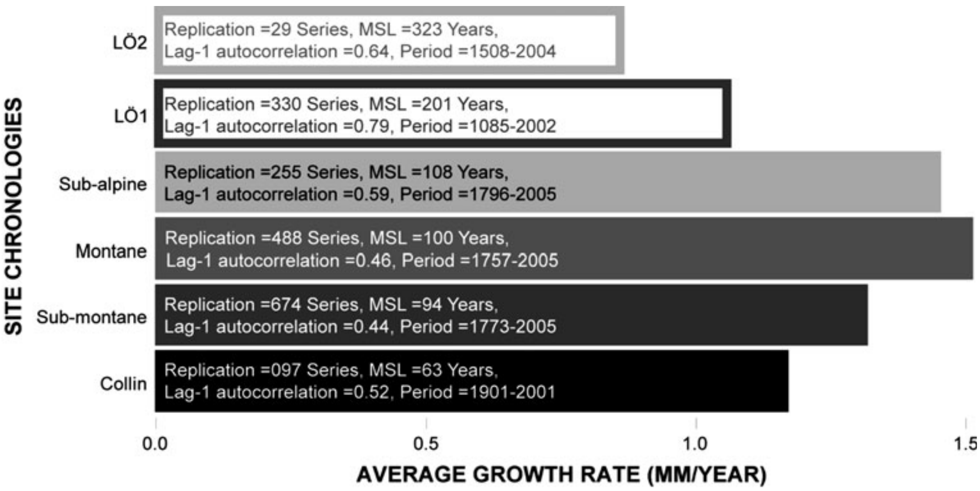

Fig. 5 Absolute growth rates of the low- to mid-altitudinal master chronologies and TRW data from higher elevations (Büntgen et al. 2005, 2006; LÖ1 in 1,600–2,100 m asl and LÖ2 in 2,100–2,300 m asl). Chronologies <1,000 m asl are limited by soil moisture water availability and chronologies >1,450 m asl by temperature of the growing season, with the overall growth optimum being reached ~1,250 m asl. Growth rates (mm/year) are expressed as the average values computed over the 50 innermost rings (cambial age 0–50) per subset

(positive) temperature response toward lower elevations in a multi-species network across the Alps.

For different reasons, the colline PISY chronology showed slightly lower correlations with June scPDSI at the beginning and the end of the 20th century (Fig. 3). Low replication likely contributed to the reduced correlation coefficients during the early period, whereas the number of samples significantly increased from the 1930s to present. A higher proportion of juvenile wood (Esper et al. 2008) and ceasing growth in dying PISY trees (Bigler et al. 2006; Weber et al. 2008), may additionally have led to decreasing significance at the end of the analysis period. Nevertheless, the strong correlation over 50 years between the low-elevation colline chronology and the June scPDSI indicated that radial growth is mainly controlled by moisture availability at sites <1,000 m asl. This is well in line with findings of Dobbertin et al. (2005) who showed drought-induced PISY mortality at lower elevations whereas in higher altitudes (>1,000 m asl) mortality occurred less frequent. In contrast, the sub-alpine chronology did not reveal significant correlations with the drought index nor with temperature of the vegetation period, suggesting that the sub-alpine zone acts as transition zone where climate is not exceptionally dry or cold and growth conditions for conifers are not yet constraining (Kienast et al. 1987). The moderate levels of both temperature and moisture constraints at these mid-elevations are likely responsible for the overall high biomass productivity (Fig. 5).

Moreover, the uneven distribution of species within the network made it difficult to determine the influence of species relative to altitude on the obtained tree growth/climate interactions. Schweingruber and Nogler (2003) attribute a strong relationship between climate and maximum ring width to species-specific differences in the onset and duration of radial growth in trees across the Central European temperate zone. While multiple factors are known to influence tree growth under temperate climate conditions, more distinct factors are hypothesized to control climatically extreme sites in regions such as in the inner Alpine Rhone valley (Rigling et al. 2002). Since our dataset was restricted to dry sites only, a common drought response of all four species at altitudes <1,000 m asl was to be expected. Similar correlation patterns of the species-specific time-series, although variable in strength, clearly confirmed the main growth-controlling factor across the network to be soil moisture availability. While PISY responded very strongly to drought, ABAL revealed a reduced hydro-climatic signal. These differences might be explained by species-specific response strategies to varying climatic conditions. In fact, PISY that mainly grows on shallow soils reacts different to drought variability than ABAL, commonly growing on deeper soils. The species-specific growth response to different drought levels thus transforms into different radial growth patterns (Frank and Esper 2005a; Rigling et al. 2001). The classification of species-specific chronologies into high- and low-elevation subsets finally implied a strong influence of altitude on drought response. The lack of drought response in LADE at higher elevations might be explained by the fact, that in these altitudes potential evapotranspiration is lowest (see Friedrichs et al. 2009 for a detailed description of drought-, cloud-cover-, and vapor pressure-effects on forest productivity). In addition, it remains unclear how well the scPDSI metric can represent soil moisture availability of the high-elevation sites, because climatic input variables mainly derived from low-elevation climate stations. This might be relevant for precipitation but less for spatially robust temperature records, both of which feed into the improved scPDSI drought index used.

Due to the nature of the initially developed PDSI metric (e.g., van der Schrier et al. 2006), one should consider its limitation in robustly reflecting drought fluctuations over mountainous regions, such as the Alpine arc. This constrain is mainly related to the algorithm, which assumed all precipitation—independent of the seasonal cycle—to be in the liquid phase. The herein used scPDSI introduced by van der Schrier et al. (2007), however, included a snow accumulation and melt model in the water balance calculations to overcome this limitation. High correlation coefficients between the colline TRW chronology and the summer scPDSI confirmed its correctness as a drought metric for this region.

Conclusions

Data from colline and sub-montane sites in the Rhone valley, Valais, Switzerland contained a clear summer drought signal with expression of the drought events in 1921, 1944, 1976, 1992, and 1998. The signal was strongest in PISY chronologies and less pronounced in higher elevations, pointing at the potential of both, living and historic material from lower elevation sites for drought reconstruction purposes. The statistical data characteristics herein provided a useful impetus to provenance ancient construction timbers to subsequently extend the database for drought reconstructions back in time. Improved understanding of past drought variability in the Alps will contribute to the analysis of shifts in the hydrological cycle, which is highly relevant for any prediction of future climate trends. In addition, this study demonstrated how drought limitations impact radial growth, which is of relevance for understanding forest productivity and carbon sequestration in a changing environment.

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