Spatiotemporal variations in the climatic response of *Larix decidua* from the Slovakian Tatra Mountains

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Introduction

Understanding past climate variability is crucial for the assessment of recent warming. Only a few millennium-long temperature reconstructions, mainly from Northern Scandinavia and the Alps, have so far been developed in Europe (Büntgen et al. 2011, Esper et al. 2012). For the Eastern part of the continent, dendroclimatological studies extending back into medieval times are, however, restricted to a single tree-ring width (TRW) record from historical timbers and living individuals of *Larix decidua* Mill. from the Slovakian Tatra Mountains (Büntgen et al. 2013). The Tatra comprises two sub-regions: In the High Tatra, trees grow under treeline conditions up to 1500 m asl in a subalpine environment, whereas the Low Tatra lacks alpine and treeline characteristics due to lower maximum elevations of 1100 m asl. A combined TRW dataset integrating samples from both sub-regions displayed a distinct May-June (MJ) summer temperature signal (Büntgen et al. 2013). Most of the historical timbers sampled in this region were, however, used in buildings in lower elevations. The provenance of this historical material could not clearly be identified, though it seems reasonable to assume that the timbers used in lower elevations originate from lower elevation forest sites. Changing climate-growth response patterns as a function of altitude are, however, a well-known feature in alpine settings (Hartl-Meier et al. 2014) and have also been reported for various species across the Tatra Mountains (Büntgen et al. 2007).

Here, we assess the variability of site-specific climate signals of *Larix decidua* Mill. as a function of altitude and time. TRW data from site in the High and Low Tatra were separately analyzed to obtain a better understanding of the underlying climatic controls of tree growth in different altitudes. Temporal robustness of the incorporated climate signals is also tested throughout the 20th century (1901-2009), while focusing on variations in the best-responding seasonal windows within the vegetation period.

Material and methods

Sampling sites and strategy

All TRW sampling sites were selected within the Slovakian Tatra Mountains (Fig. 1), the northwestern part of the Carpathian arc. Continental dry air and local insolation effects (i.e. high summer temperatures subject to exposure angle), in combination with advective humid air masses, predominantly following trajectories from the Atlantic, characterize the local climate. The Siberian High strongly impacts the cold and dry winter season, while summers are influenced by low-pressure cells which provide precipitation maxima in June (Niedzwiedz 1992, Büntgen et al. 2007).

A total of 181 cores were extracted from 69 living *Larix decidua* Mill. trees in November 2012, either around 1550m asl (Mlynicka Dolina: H12; 37 trees; 3 cores per tree) or 850m asl (Vernar: L12; 32 trees; 3 cores per tree) (Fig. 1). Samples were combined with material from nearby locations, previously published (H04, L08, L11) (Büntgen et al. 2007, Büntgen et al. 2009, Büntgen et al. 2013), to increase replication back in time and to extent until present, i.e. 2012. The newly

DOI: 10.2312/GFZ.b103-15069

developed chronologies thus span the 1657-2012 and 1634-2012 periods for the high- and low-elevation site, respectively, at a minimum replication of 5 cores per site.

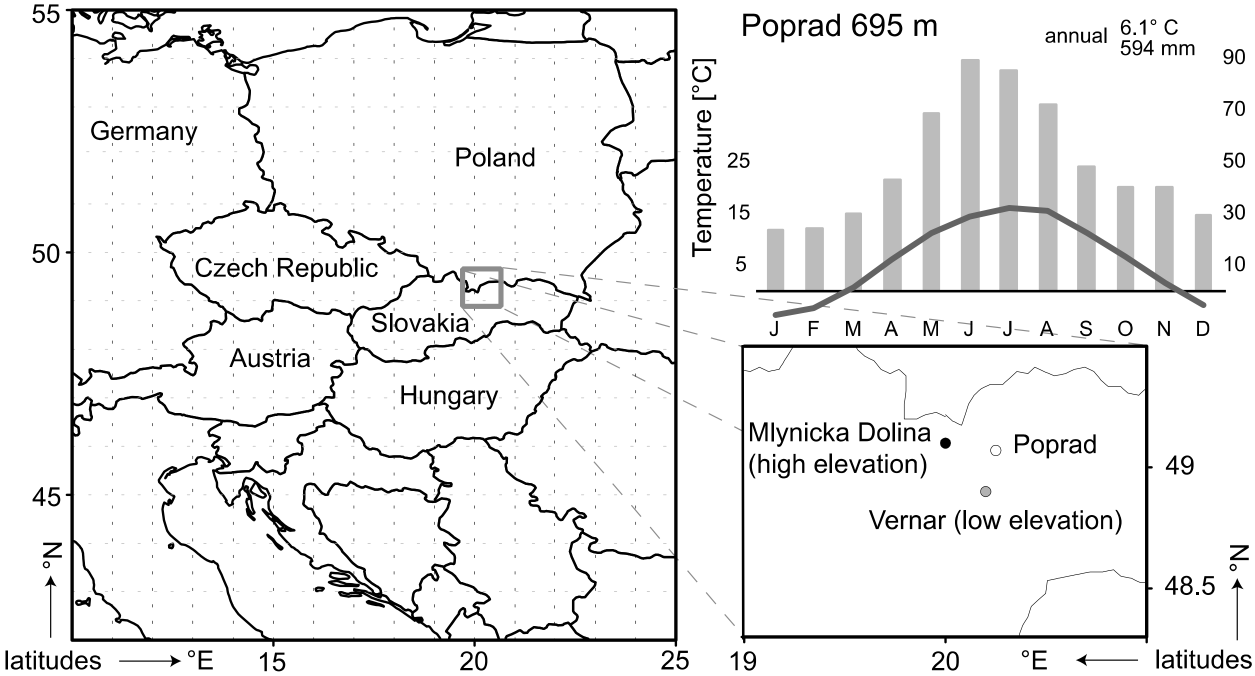

Figure 1: Map of the study region and climate diagram of the Poprad meteorological station (1951-2012). Grey curve is temperature, bars are precipitation.

Data treatment

TRW was measured and crossdated using commonly applied software, such as COFECHA (Holmes 1983) and ARSTAN (Cook 1985). The age trend was removed by detrending with two different methods to address varying frequency domains: 30-year cubic smoothing spline standardization (Cook & Peters 1981), and negative exponential standardization (Fritts 1976). Prior to detrending all TRW data were power-transformed (Cook & Peters 1997), and the resulting chronologies were variance stabilized (Osborne et al. 1997, Frank et al. 2007). All data were high-pass filtered by calculating residuals between the original data and its corresponding 10-year cubic smoothing splines to retain only high-frequency variations. Running correlations, rbar and EPS statistics are denoted with a 31-year moving window and 30-year overlap (Wigley et al. 1984).

Table 1: Site and chronology statistics (negative exponential standardization)

Code (altitude in m)	*Period*	*oldest/ youngest tree*	*MSL (years)*	*AGR (mm)*	*Number of cores*	*Series Inter-correlation*	*rbar*	*EPS*
L12 (850)	*1698-2012*	*374/ 29*	*202*	*0.54*	*81*	*0.712*	*0.50*	*0.95*
L11 (950)	*1883-2011*	*152/110*	*121*	*1.63*	*31*	*0.676*	*0.51*	*0.97*
L08 (800)	*1634-2008*	*402/45*	*173*	*0.47*	*36*	*0.658*	*0.51*	*0.93*
H12 (1550)	*1669-2012*	*383/177*	*231*	*0.61*	*100*	*0.764*	*0.59*	*0.97*
H04 (1450)	*1676-2004*	*342/19*	*165*	*0.56*	*64*	*0.719*	*0.58*	*0.96*
L (<1000)	*1634-2012*	*402/45*	*178*	*0.59*	*164*	*0.644*	*0.47*	*0.96*
H (>1400)	*1657-2012*	*383/19*	*205*	*0.56*	*148*	*0.746*	*0.57*	*0.98*

Meteorological data and calibration trials

Since instrumental temperature and precipitation station readings in the immediate surrounding of the sampling sites are scarce and do not extend prior to 1951, monthly temperature means, precipitation totals (CRU TS3.1; Harris et al. 2014), and drought indices (van der Schrier et al. 2006) were derived from gridded data (accessible via KNMI Climate Explorer: http://climexp.knmi.nl) of the two best-fit grid points (high elevation: 49°25N, 19°75E; low elevation: 48°N, 20°75E), covering the longer 1901-2009 period. The assessment of climate signals focused on calibrating the TRW chronologies against climate data over the 1901-2009, and two split periods (1901-1954 and 1955-2009). Degrees of freedom were adjusted considering the timeseries' autocorrelation in order to calculate reliable confidence limits (Konter et al. 2014).

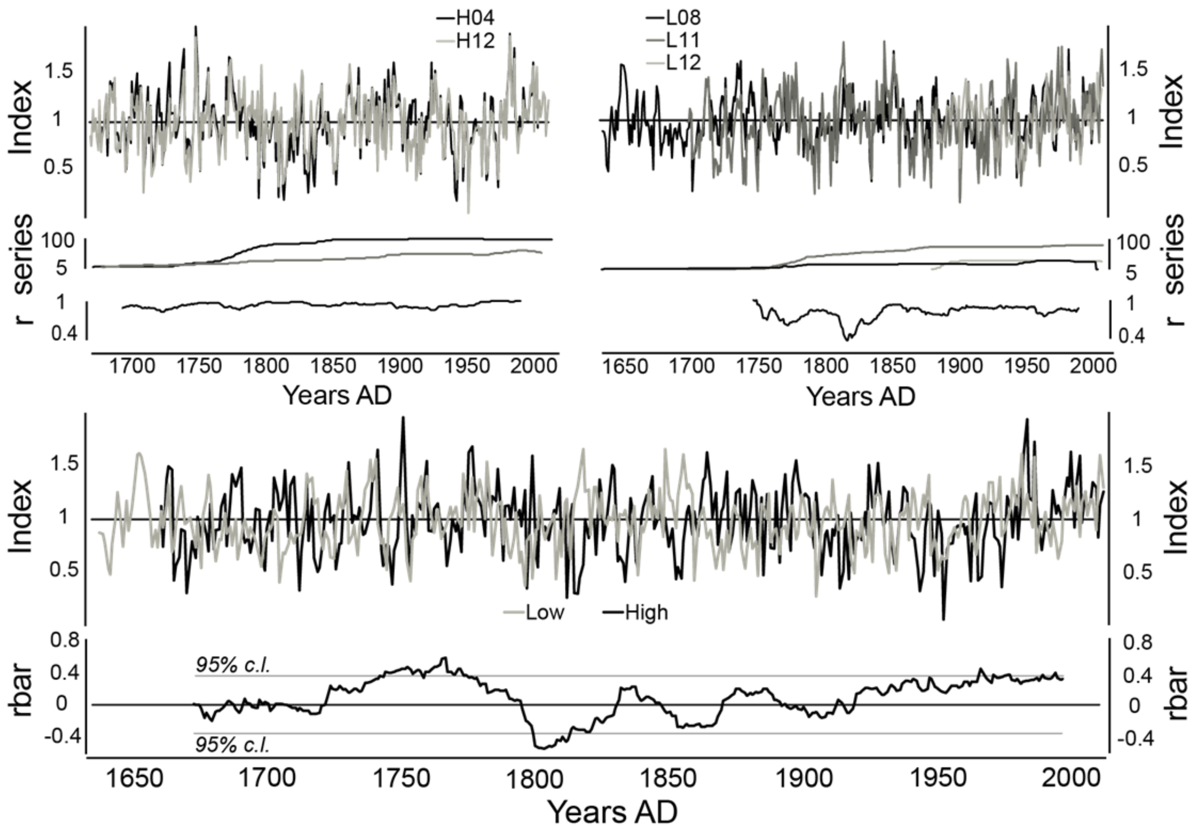

Figure 2:Tatra Mountain tree-ring chronologies (negative exponential detrending). Upper left: H04 and H12 high-elevation chronologies (top panel), number of TRW series (middle), and running correlations (bottom). L08, L11, and L12 low-elevation chronologies, number of TRW series, and running correlations. Bottom panels show the combined site-chronologies (low-elevation in grey and high-elevation in black) and running correlations (black) together with 95% confidence limits (grey). All running correlations calculated in a 31-year window with a 30-year overlap.

Results and Discussion

Intra- and inter-site coherence

Between-tree correlations and site chronology statistics exceed commonly accepted thresholds (Tab. 1; Fig. 2, upper panel). Correlation values between the two high-elevation chronologies ($r_{1698-2004}$=0.92, $p<0.001$) are clearly higher in comparison to the low-elevation sites ($r_{1698-2004}$=0.70, $p<0.001$), supporting the general assumption of more distinct climate-growth associations at higher elevations (Büntgen et al. 2007). Inter-site correlations display more ambiguous results ($r_{1657-2012}$=0.097): Running correlations between the two site chronologies oscillate from significantly positive (~1750 AD) to significantly negative (~1800 AD). 20th century running correlations are positive ($r_{1901-2012}$=0.25, $p<0.05$) due to synchronizing low-frequency trends in both chronologies

DOI: 10.2312/GFZ.b103-15069

(Fig. 2, lower panel). A significant correlation is displayed after high-pass filtering the data ($r_{HP1657-2012}$=0.13, p<0.05). TRW data of both sites share variance in the high-frequency domain, but appear less synchronized in the lower frequency domain ($r_{LP1657-2012}$=0.04).

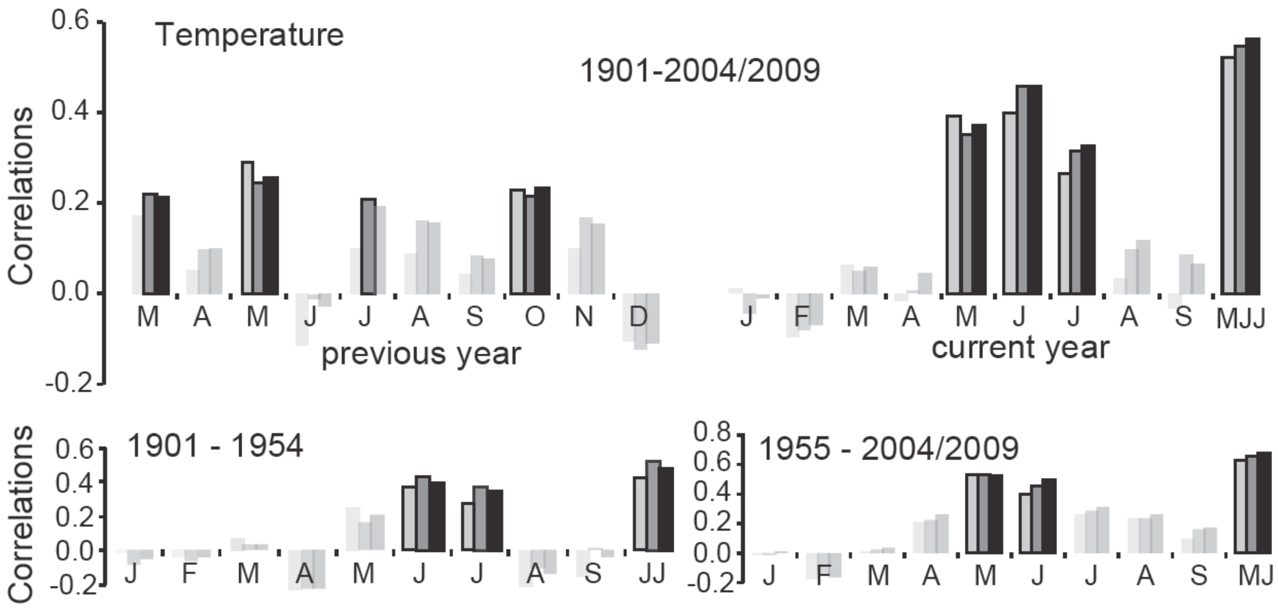

Figure 3: Climate-growth relationships of the high-elevation TRW data (negative exponential standardization). Monthly and seasonal correlations between TRW chronologies (single chronologies in grey scales, combined site-chronology in black) and temperatures. Significant correlations (p<0.05) framed in black.

Climate Signals

Tree growth at higher elevations is mainly controlled by variations in May-July (MJJ) summer temperatures (Fig 3), and non-significant relationships are found when calibrating TRW against precipitation data (not shown). The best seasonal response ($r_{1901-2009}$=0.56, p<0.001), however, varies over time, shifting from a June-July signal ($r_{1901-1954}$=0.48) to an early summer (May-June, $r_{1955-2009}$=0.68) signal.

Climate signals incorporated in TRW from low-elevations appear to be less distinct (Fig. 4). Correlations between temperatures and TRW reveal minor impact on tree growth. Only one of the low elevation chronologies displays significant values (p<0.05) for May (r_{H04}=0.20) and August temperatures (r_{H04}=-0.25). Calibration against precipitation totals reveals indistinct results. July precipitation shows significant positive results (r_L=0.23, p<0.05), while September is associated with significant negative values (r_L=-0.24, p<0.05). The analysis of the scPDSI, integrating temperature, precipitation, and soil information, provides a clearer pattern, though correlations remain overall quite low. The most distinct seasonal response is detectable for the March-July season (r_L=0.23, p<0.05). Additionally, previous year's drought conditions impact current year's growth to a greater extent than conditions of the actual year, exacerbating a clearer interpretation of this climate parameters control mechanism on tree growth.

Generally, correlation values reported from calibration trials using TRW from low-elevations are much lower with the highest values with July precipitation (r=0.23, p<0.05) and April scPDSI (r=0.23, p<0.05), complicating a clear interpretation of the results.

DOI: 10.2312/GFZ.b103-15069

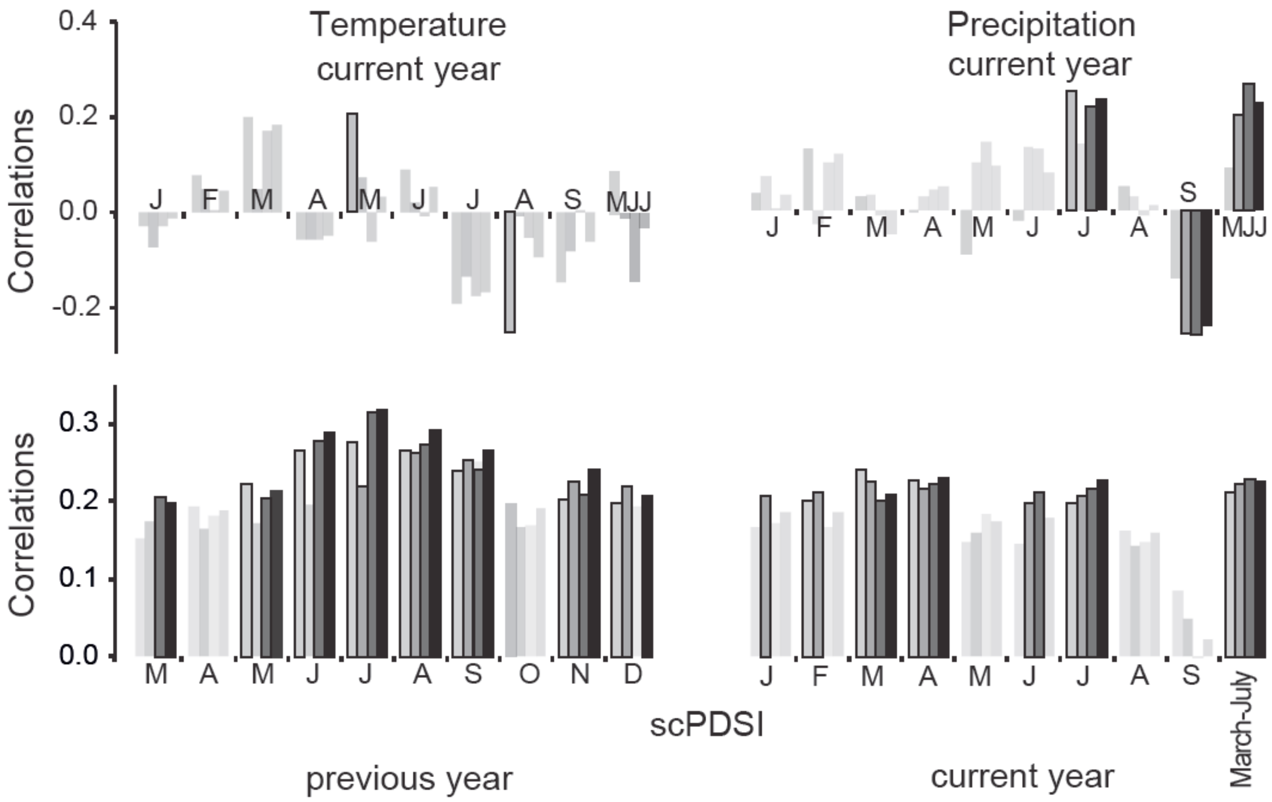

Figure 4: Climate-growth relationships of the low-elevation TRW data. Monthly and seasonal correlations between TRW chronologies (single chronologies in grey scales, combined site-chronology in black) and temperatures (upper left panel; TRW data: negative exponential standardization), precipitation (upper right; TRW data: 30-year cubic smoothing spline standardization), and scPDSI (lower; TRW data: negative exponential standardization). All significant correlations (p<0.05) in bright grey and black framed in black.

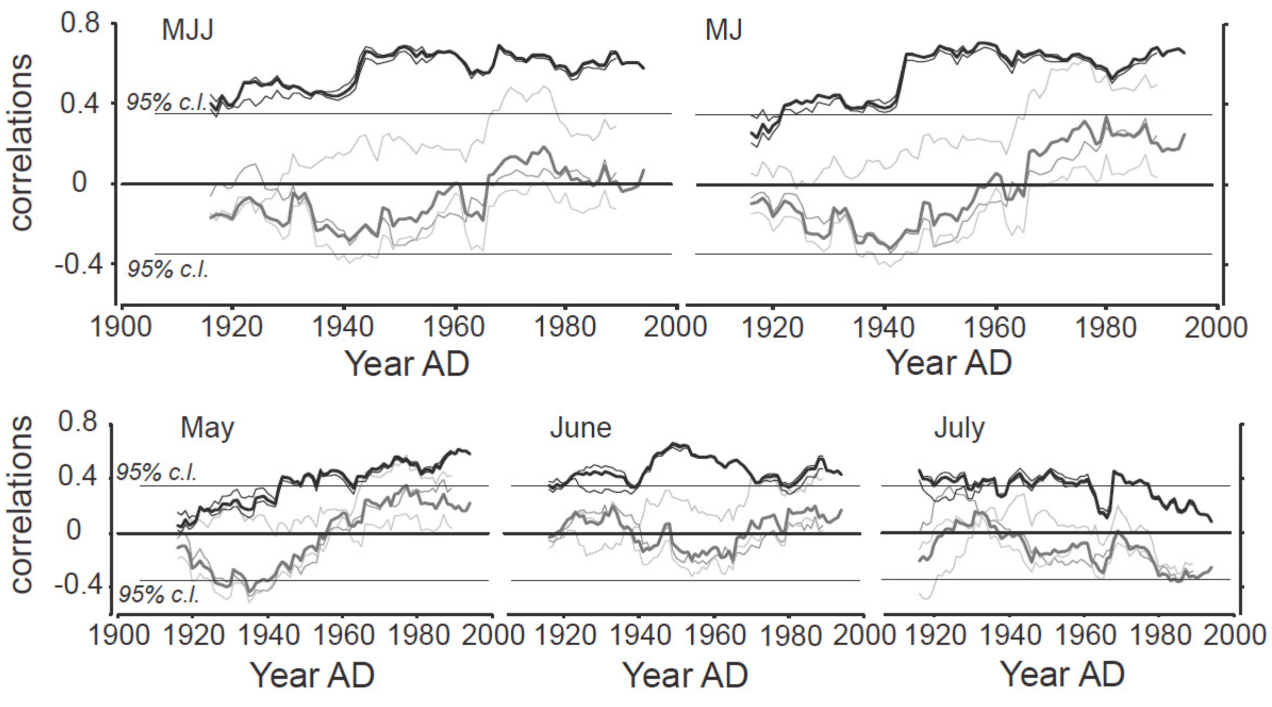

Figure 5: Temporal instability in the monthly temperature sensitivity of TRW chronologies from the Tatra. Black curves refer to the high elevation sites (bold in the combined data), grey curves denote the low elevation sites.

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Focusing on the temporal robustness of the MJJ temperature signal of the high-elevation TRW data, a shift towards earlier summer months excluding July can be observed in the most recent times (Fig. 5). In particular, temperatures in May tend to show increasing relevance for tree growth, since summer months, such as June and especially July, became hotter and simultaneously drier (Büntgen et al. 2010). The trees consequently shift their main growing season to earlier periods of the year, when water availability is guaranteed due to moderate temperatures with simultaneously occurring precipitation events and succeeding snow melt (Fig. 1; upper right panel).

Interestingly, this shift can also be seen in the running correlations of the low-elevation data, in particular for the MJ season and May: although no significant temperature response is traceable due to the overall mixed climate-growth relationship in this altitude, correlations change from negative to positive values in the 20th century (Fig. 5). The increasing importance of early summer temperatures for tree growth in lower elevations could explain the synchronization of long-term trends in the chronologies from both sites within the 20th century ($r_{LP1901-2012}$=0.45; Fig. 2).

Conclusions

Chronologies comprising historical timber and relict wood with samples from living trees to extend their length back to medieval or Roman times are ideally used in dendroclimatological studies (Büntgen et al. 2008, Büntgen et al. 2011, Esper et al. 2012, Büntgen et al. 2013). Key to this technique is the transfer of calibration results of the most recent period to the period covered by historical wood (Tegel et al. 2010). Separately analyzed, TRW data from high- and low-elevation sites, however, display diverging results in terms of climate-growth relationships. While high elevation tree growth is mainly controlled by summer temperature, tree growth at lower elevations is also affected by water availability, which is somewhat dependent on both, temperature and precipitation.

The transfer of the calibration results from living trees to historical timber remains challenging, since most of the ancient construction wood originate from buildings at lower elevations, thus, indicating a potential provenance from lower elevations. In addition to these spatial climate signal variations, the temporal robustness is subject to slight seasonal shifts from summer to early summer temperature signals in TRW data at both sites in the 20th century. Summer conditions, especially in July, evolved to be characterized by more droughty conditions in the most recent years, particularly at the lower elevation sites.

These spatial and temporal climate signal variations in the Tatra Mountains aggravate the transfer of calibration results within the 20th century to the pre-industrial period. Büntgen et al. (2013) used trees from high- and low-elevations to envelope the boundaries of natural occurrence of *Larix decidua* Mill. in the Slovakian Tatra Mountains for calibration purposes. This technique, however, possibly weaken the accuracy of the millennium-long reconstruction, because the provenance of the historical timber is not fully traceable. The sparseness of historical climatic data in this region though emphasizes the importance of such long-term reconstructions and demands further research to address the questions arising from this analysis.

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