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ORIGINAL PAPER

Climate signal in tree-ring chronologies of *Pinus peuce* and *Pinus heldreichii* from the Pirin Mountains in Bulgaria

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Abstract Numerous proxy climate reconstructions have been developed for Europe, but there are still regions with limited data of this kind. One region is the Balkan Peninsula, which is characterized by complex interactions between mountains and climate. We present and discuss two tree-ring chronologies—a 758-year-long one of *Pinus heldreichii* Christ and 340-year-long one of *Pinus peuce* Griseb. from treeline locations in the Pirin Mountains in Bulgaria. Climate–growth relationships were computed with bootstrap correlation functions and their consistency over time assessed by calculating the correlations over shortened periods. In addition, we reviewed and analyzed climate situations in years with unusually narrow or wide tree rings. Both species were negatively influenced by previous summer drought conditions and cold winters. Early summer temperatures were positively correlated with *P. peuce* radial growth, whereas *P. heldreichii* displayed dependence on summer precipitation. In the second half of the twentieth century, the *P. heldreichii* trees displayed higher sensitivity to summer drought, which was probably a result of increased summer temperatures and decreased winter precipitation. Our findings contribute to more reliable proxy climate records for the region.

Keywords Tree ring · *Pinus peuce* · *Pinus heldreichii* · Temperature sensitivity · Treeline · Balkan Peninsula

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Introduction

Tree-ring data from locations where trees are particularly sensitive to variation in temperature or precipitation are among the most important sources of proxy climate data (Fritts 1976). In the past decades a number of studies on climate variability in the last millennium have been based on high elevation or latitude environments, where radial tree growth responds strongly to summer temperature (e.g. Briffa et al. 2001; Esper et al. 2002; Mann and Jones 2003; Büntgen et al. 2006). These studies have caused much debate over climate change in the twentieth century and especially about unprecedented warmth after the mid 1980s (IPCC2007). One of the discussed issues is whether reconstructions based primarily on data from high-elevation locations in the European Alps, Central Asia, and the tundra treeline in the Northern Hemisphere are representative for other parts of the world and the need to expand existing tree-ring networks (Büntgen et al. 2007; Neuwirth et al. 2007; Popa and Kern 2009). Another topic concerns an observed reduction of temperature sensitivity and non-stationary responses in many tree-ring records during the second half of the twentieth century, known as the "divergence problem" (Briffa et al. 1998; Büntgen et al. 2006; D'Arrigo et al. 2008 and references therein). In this context it is of crucial importance to construct long and reliable tree-ring chronologies, particularly for regions where such records are scarce (Büntgen et al. 2007; Carrer et al. 2007; Popa and Kern 2009).

High-resolution proxy climate data are only limitedly available for the Balkan Peninsula (Xoplaki et al. 2001; Luterbacher and Xoplaki 2003; Popa and Kern 2009) despite their importance with respect to the impact of extreme climate, and drought in particular, for local people and economies (Xoplaki et al. 2001; Knight et al. 2004). Called "The European biodiversity hotspot" (Griffiths et al. 2004), the Balkan Peninsula is a region with complex physical geography, climate interactions, outstanding level of endemism both in the terms of flora and fauna, and a number of relict species preserved in natural ecosystems. Some of the most interesting habitats include the treeline forests. These are often dominated by centuries-old trees with high potential for the development of centennial-length tree-ring chronologies (Griffiths et al. 2004; Panayotov and Yurukov 2007; Popa and Kern 2009). Moreover, some of these species, including *Pinus peuce* Griseb. and *Pinus heldreichii* Christ (also known as *P. leucodermis* Antoine), are locally endemic or sub-endemic (Barbero et al. 1998). The high conservational value of such taxa additionally increases the importance of tree-ring based studies that allow a better understanding of the trees' eco-physiological requirements (Rossi et al. 2006; Todaro et al. 2007; Guerrieri et al. 2008) and therefore improve the protection–management practices. Despite the significance of tree-ring studies in this region, only few results are currently available to the international scientific community (Vakarelov et al. 2001; Panayotov and Yurukov 2007).

Our objective is to present two tree-ring chronologies from treeline locations in the Pirin Mountains (Bulgaria): an improved 340-year *P. peuce* chronology (Panayotov and Yurukov 2007) and a new 758-year chronology from *P. heldreichii.* We evaluate the influence of temperature and precipitation on tree-ring formation of both species, the stability of responses in the past century, and the potential for climate reconstruction.

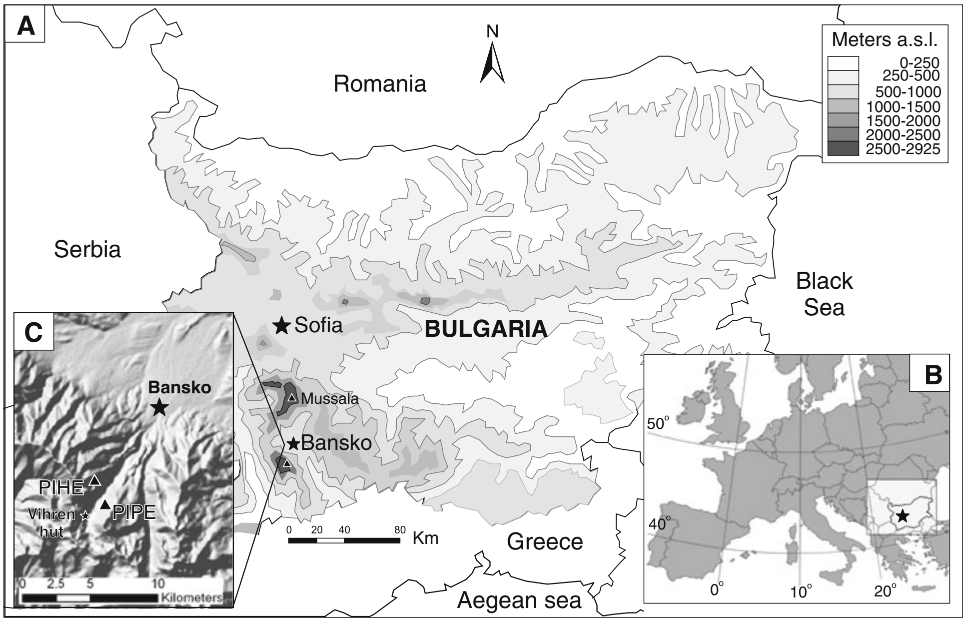
Materials and methods

Study area

Our study area is situated in the Bunderitsa valley in the Pirin Mountains in southwestern Bulgaria (Fig. 1). Most of the highest zone of the Pirin Mountains, including our study area, is currently protected in Pirin National Park and included in UNESCO World Heritage sites list. The *P. peuce* trees are located on the northwestern slope of Todorka peak in the treeline belt (2,000–2,250 m a.s.l.). The *P. heldreichii* trees are on the eastern slope of Vihren peak, from 1,950 to 2,150 m a.s.l. Because there is a rock ridge that limits the spread of trees further up, the selected *P. heldreichii* study site represents the highest trees in that location. The slopes are steep (30–50°) and hardly accessible and were thus not attractive for harvesting trees or pasturing. This limited anthropogenic influence explains why our study sites have retained a natural structure. The *P. peuce* trees that we studied grow on Umbric and Modic Cambisols formed on granite bedrock, whereas the *P. heldreichii* grow on Rendzic Leptosols and Regosols formed on marble bedrock.

The climate in the study region is typical for a mountainous region and is strongly influenced by Mediterranean air masses. The mean annual temperature (Vihren chalet climate station, 1,970 m. a.s.l.) is 3.5°C (Fig. 2). It ranges from a mean monthly temperature of −4.7°C in January to

Fig. 1 Study site locations



12.2°C in August. The annual temperature at the treeline (2,200 m a.s.l.), obtained by extrapolation from the Vihren chalet data, is 1.6°C, with the highest average monthly temperature being 10.2°C. This coincides with the expected values of nearly 10°C in the warmest month at the treeline (Tranquillini 1979; Korner 1998). The annual precipitation amounts to 1,378 mm, with a maximum in autumn and winter. A difference from other high mountains in Bulgaria (e.g., Rila and Stara Planina) is that the Pirin Mountain range serves as a barrier for advancing southwestern Mediterranean air masses, which are more frequent during the autumn–winter period (Brown and Petkova 2007). Deep snow covers, frequently exceeding 2 m, are typical for the region. The absolute maximum snow depth for Bulgaria (472 cm) was recorded at Vihren chalet station. Precipitation reaches a minimum in summer, when sums are often lower than in other parts of Bulgaria (Brown and Petkova 2007). The dry summers, combined with shallow soil profiles on steep rocky sites, might cause local drought conditions on sites with eastern and southern exposures.

Climate data

For the climate/growth correlation analysis, we used data from climate stations in Bansko (936 m a.s.l) and Sofia (550 m a.s.l.), that were provided by the National Hydro-Meteorological Institute (Table 1). The data sets were verified for outliers, but not homogenized. The Bansko station is at the foot of the mountain, 10 km away from the study area, and provides a continuous record since 1933. The Sofia climate station is located further away from the study site (approximately 100 km), but provides one of the longest available climate records in the country (since 1889). Considering the Mediterranean precipitation regime in the Pirin Mountains, which is characterized by higher autumn and winter precipitation and lower summer precipitation than the lowland region of Sofia (Brown and Petkova 2007), the Sofia precipitation time series is probably not representative of our study site. Temperature records between Sofia and the study site (Vihren Hut climate station, see below), on the other hand, are highly correlated, which justifies using the long climate record from Sofia. We chose to use only those series for the climate–growth analysis because other series from Pirin Mountains are too short.

For the pointer year analysis, we completed the climate data set with data from the Vihren hut (1,970 m a.s.l.) and Mussala peak (2,925 m a.s.l.) stations. The Vihren hut station was located in the study valley within less than 1 km from the sites, but operated only for 25 years (1954–1979). Therefore, the record is primarily useful for average data and for precise information about extreme climate situations in certain years. Mussala peak station, which is 43 km away from the study sites, is the highest in the Balkan Peninsula and is situated in the Rila Mountains. We used its data only for obtaining information for extreme years, because of the differences with the Pirin mountains

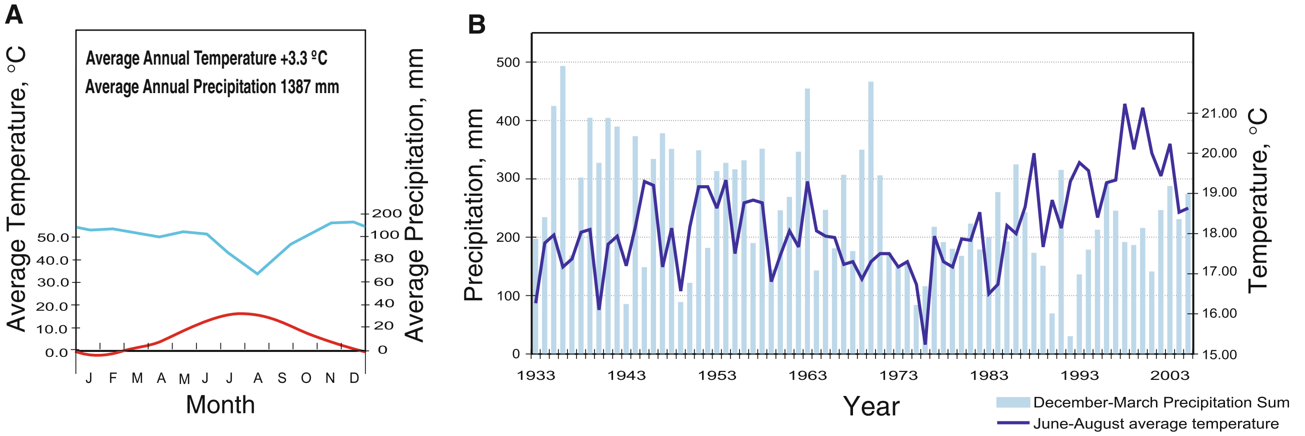


Fig. 2 Climate diagram for Vihren hut **a**; and **b** Winter (December–March) precipitation sums and average summer (June–August) temperatures for Bansko climate station, 1933–2005

Table 1 Descriptive parameters of used climate stations and data

Climate station	Distance from study site (km)	Altitude (m a.s.l.)	Location, (lat/long)	Period covered	Percent of missing data
Bansko	10	936	41°50′N/23°29′E	1933–2005	0.46
Sofia	100	550	42°41′N/23°20′E	1889–2005	1.27

climate, particularly in terms of precipitation (Brown and Petkova 2007). Additionally, the precipitation series from climate station situated on a mountain peak is not truly representative because of the frequent strong winds during rains and snowfalls.

Data collection, chronology development, and statistics

Tree ring cores were collected at breast height (1.3 m) from dominant trees using an increment borer, mounted on wooden boards, and sanded. Ring widths were measured using an incremental measuring table with accuracy of 0.01 mm. Measured tree-ring width series were visually cross-dated (Stokes and Smiley 1968), and the cross-dating was checked using COFECHA software (Holmes 1983). The data were then standardized based on negative exponential function, using ARSTAN software (Cook 1985), in order to remove the age-related growth trends and preserve the climate signal. The final chronologies were computed by calculating bi-weighted robust means of annual tree-ring indices. We computed several statistical parameters commonly used in dendrochronology from the non-standardized tree-ring width series. The mean sensitivity (MS) measures year-to-year variation in tree-ring width and is thus considered an estimate of the extent to which the chronology reflects local climate variation (Cook and Kairiukstis 1990). The first-order autocorrelation (first AC) reflects the influence of previous year's growth on current growth. The expressed population signal (EPS) quantifies the degree to which the constructed chronology portrays the hypothetically perfect one (Wigley et al. 1984). We used an EPS value of 0.85 as a threshold for the reliability of our chronologies (Wigley et al. 1984).

We compared our chronologies with other chronologies from these species that were available in the International Tree-Ring Data Bank (ITRDB). We used *P. heldreichii* chronologies from Oros (Olympus Mts., Greece, 2,250 m a.s.l., 1583–1981), Sierra da Crispo (South Italy, 2,000 m a.s.l., 1441–1980) and *P. peuce* chronology from the Pelister region in the Baba Mts. in Macedonia (1,900 m a.s.l., 1837–1981) (Schweingruber 1981a, b). We compared the series by calculating the Gleichlaufigkeit values (GLK) and t values with the use of the RINNTECH TSAP-Win Software and with Pearson's correlation analysis. All other calculations, except when noted, were performed with the StatSoft package STATISTICA 6.0.

Climate–growth relationship analysis

The climate–growth relationship analysis was performed with DENDROCLIM2002 software (Biondi and Waikul 2004). This package allows the computation of bootstrapped correlation functions for single and multiple periods. Correlation coefficients were considered significant if they exceeded, in absolute value, half of the difference between the 97.5th quantile and the 2.5th quantile of 1,000 estimates calculated in the bootstrapping procedure (Biondi and Waikul 2004). We used average monthly temperatures and precipitation sums for the months from May of the year prior to growth to October of the growth year.

We conducted a composite analysis to study the similarities and differences between the *P. peuce* and *P. heldreichii* chronologies in more detail, and to emphasize the non-linear character of the climate–growth relationships. Gridded monthly and seasonal temperature and precipitation fields for the period 1901–2006 (CRU TS3.0; Brohan et al. 2006) were averaged over years of high and low indices in the *P. peuce* and *P. heldreichii* chronologies. Low and high values were defined by the 10th and 90th percentile. Composite maps were generated using the KNMI Climate Explorer (Oldenborgh and Burgers 2005; http://climexp.knmi.nl). Additionally, we compared pointer years in *P. peuce* and *P. heldreichii* chronologies with the available climate data (1888–2005) to make an independent verification of statistical analysis. Higher or lower than normal values in temperature and precipitation records were selected as exceeding the threshold of the series mean plus or minus one standard deviation.

Results

Chronology development

The *P. heldreichii* chronology (Fig. 3b) was composed of 50 cores from 40 trees (Table 2) and was truncated at 1,250 to ensure a minimum of five contributing samples. The oldest studied tree had 802 tree rings. The EPS reached a value of 0.85 after 1330, but stayed steadily above 0.85 after 1440. In the twentieth century it was above 0.92 (Fig. 3c).

The *P. peuce* chronology (Fig. 3a) was composed of unique cores from 27 trees (Table 2). We improved a previously existing chronology (Panayotov and Yurukov 2007) by adding several previously excluded series segments, which were not cross-dated until now. The oldest studied *P. peuce* tree contained 614 tree rings, but the chronology was truncated in 1664 to have a replication of at least four contributing trees. An EPS value of 0.85 was reached in 1795 (Fig. 3c). During the twentieth century it was above 0.88.

Our *P. heldreichii* chronology correlated well with the Oros chronology ($R = 0.66$, $p < 0.001$, common period 1600–1981; GLK = 70%; $t = 16$) and to a lesser extent with the Sierra da Crispo chronology ($R = 0.41$, $p < 0.001$, common comparison period 1556–1981; GLK = 63%; $t = 9.3$). The correlation of our *P. peuce*

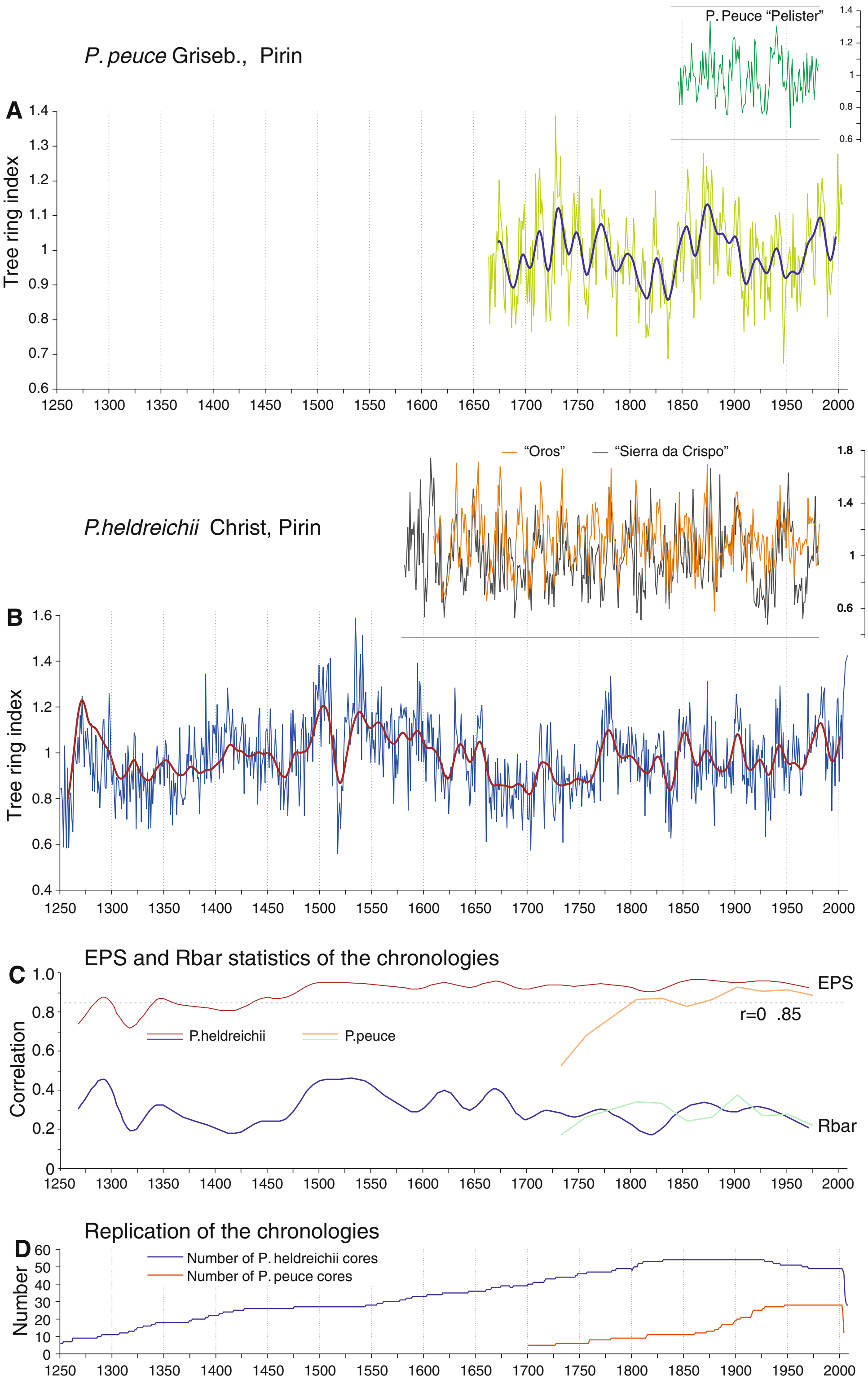


Fig. 3 Tree ring chronologies of *Pinus peuce* (**a**) and *Pinus heldreichii* (**b**), Pirin Mts., Bulgaria, EPS and Rbar statistics (**c**) and replication of the chronologies (**d**). Smooth lines are 20 year low-passed indexed series. Series from the International Tree Ring Data Bank are displayed as truncated at the year with a minimum of four samples

chronology with the Pelister chronology from Macedonia was statistically significant, but not very high ($R = 0.41$, $p < 0.05$, common period 1837–1981; GLK = 62%, $t = 3.8$). Pointer years generally coincided in-between all *P. heldreichii* and *P. peuce* chronologies (Fig. 3).

Climate–growth relationships

Our *P. peuce* chronology was positively correlated with temperatures at the beginning and end of the previous vegetation season (May, June and October; Bansko) and

Table 2 Main tree-ring width chronologies statistical and descriptive parameters

Chronology	Year span	First year	Last year	No. of cores	Mean ring width (mm)	Standard deviation	First order auto-correlation	Mean sensitivity	Inter-series correlation
Pinus peuce Griseb.	340	1664	2004	27	0.099	0.034	0.775	0.162	0.456
Pinus heldreichii Christ	758	1250	2008	50	0.073	0.032	0.778	0.210	0.564

negatively with previous July and August temperatures (Sofia; Fig. 4a). Correlation coefficients for previous December and current January were positive for both climate stations, but not significant. *P. peuce* tree growth was negatively correlated with previous November (Bansko) and current September (Sofia) precipitation. Positive but non-significant correlations were found for previous August and current March.

Negative correlations with previous July and August temperatures were also found for our *P. heldreichii* chronology, as well as positive correlations with December and January temperatures (Fig. 4b). Additionally, we found negative correlations with current June temperature (Sofia). The *P. heldreichii* chronology was positively correlated with previous August precipitation (Bansko) and current summer precipitation (Sofia) and negatively correlated with April precipitation in Sofia.

To verify the temporal stability of the correlations, we compared the tree ring chronologies with Bansko climate data over two 40-year-long periods (1934–1974 and 1964–2004), covering the beginning and end of our data range. The correlation patterns of the *P. peuce* chronology with previous June and January temperature and previous August and current March precipitation that we found for the full period (Fig. 4a), are present in both periods (Fig. 4c). Negative correlations with preceding July, August, positive with October temperatures and negative with previous November precipitation, however, only occur over the early period.

A more stable temporal pattern was revealed for the *P. heldreichii* chronology (Fig. 4d). Correlations with preceding August, current January and June temperatures, previous August and current July precipitation were strong over both periods. Overall stronger correlations were found for the early period compared with the late, particularly for previous December and May temperatures, and for previous October and March precipitation. Exception is previous August precipitation, for which correlations were higher for the period covering the last decades of the twentieth century.

The pointer year comparison between *P. peuce* and *P. heldreichii* chronologies revealed four possible combinations: (1) years with low indices in both chronologies; (2) years with high indices in both chronologies; (3) years with low indices in *P. heldreichii* chronology, but high or normal in *P. peuce* series; and (4) years with low indices in *P. peuce* chronology, but high or normal in *P. heldreichii.*

The climatic drivers of low indices for both *P. peuce* and *P. heldreichii* differed strongly between years (Table 3): extremely low summer precipitation in the current or previous summer (e.g., August 2000; 1945–1946; Fig. 5b), high winter or spring precipitation combined with low summer temperatures or precipitation (e.g., 1909, 1916, 1919, 1938, and 1963), or low summer temperatures (e.g., 1933 and 1934; 1913; 1989). The years in which both species produced wide tree rings, on the other hand, were characterized by normal or slightly warmer temperatures and normal precipitation in the vegetation period. In three out of four cases winter precipitation was abnormally high. Our composite analysis revealed anomalously high April temperatures for these years (Fig. 5d).

When *P. heldreichii* growth was low, but *P. peuce* growth was either normal or high, June or June–July precipitation was lower than normal in five out of six cases (Fig. 5a; Table 3). In the other case (1973), temperatures at the end of the preceding summer and autumn were unusually low. The inverse situation, when *P. peuce* indices, but not *P. heldreichii* were low, was primarily characterized by cold summers in the year of growth or the preceding year (Fig. 5c; Table 3).

Discussion

Tree-ring chronology development

P. peuce and *P. heldreichii* are two species with great importance for the subalpine forests of the Balkan Peninsula and that are found either only in this part of Europe (*P. peuce*) or in only few isolated locations elsewhere (e.g., *P. heldreichii* in South Italy, Barbero et al. 1998). Yet tree-ring studies of these species are scarce. Considering the high conservational importance of the species, a better understanding of their physiological response to climate conditions is needed, especially with respect to ongoing climate change (IPCC 2007).

We developed a well-replicated *P. heldreichii* chronology based on more than ten cores after AD 1307 (Fig. 3).

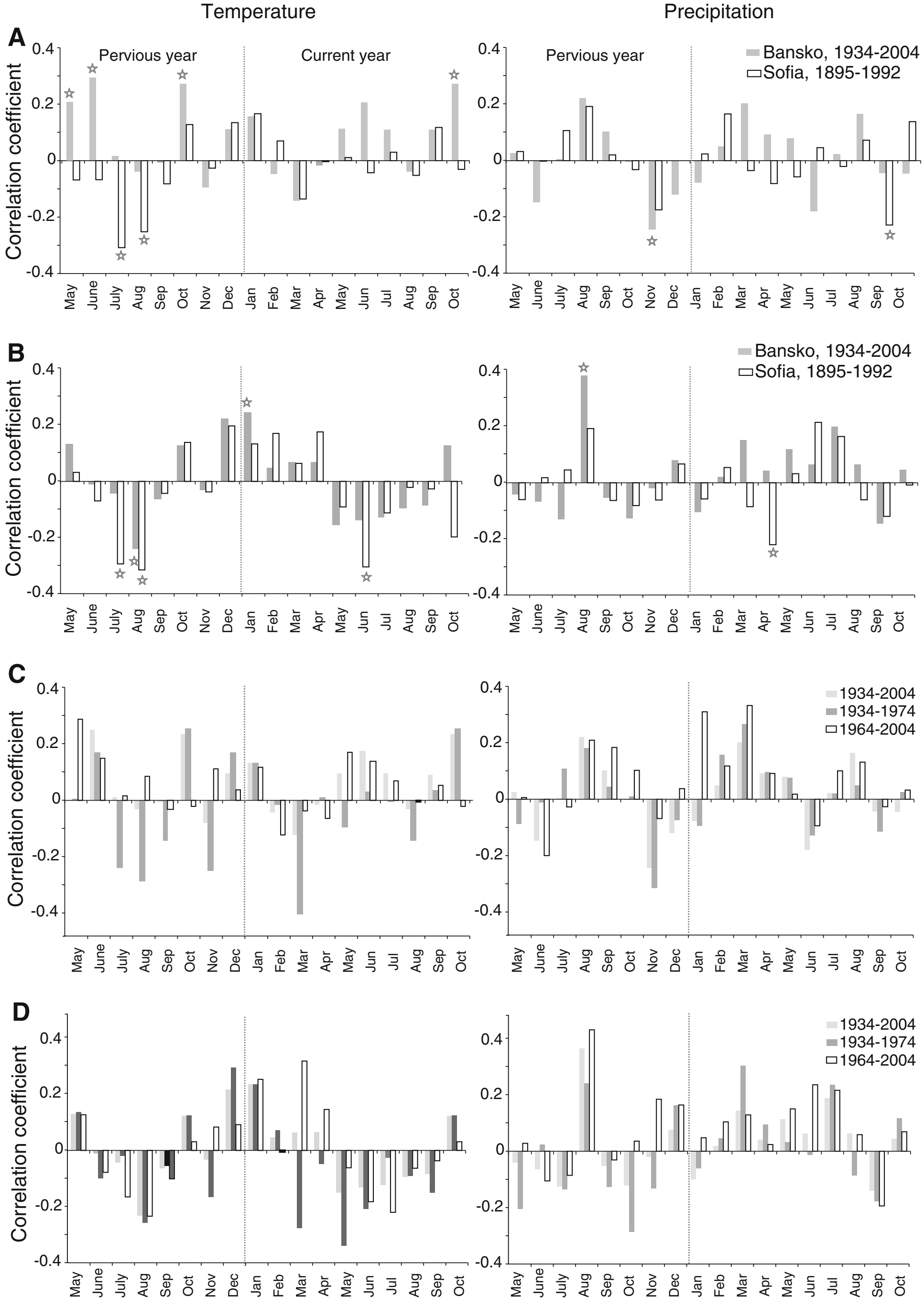


Fig. 4 Correlation coefficients for the climate–growth relationships of *P. peuce* (**a**, **c**) and *P. heldreichii* (**b**, **d**) chronologies. Correlation coefficients in **c** and **d** were calculated for Bansko climate data over two periods (1934–1974 and 1964–2004). Statistically significant values are marked with *asterisks*

This chronology is suitable for climate–growth studies and could potentially be used as proxy climate record from 1435 onwards, when EPS values stay above 0.85. The quality of the presented chronology could be further increased in earlier periods by adding more cross-dated series. We note that an increase of tree-ring widths and consequently indices was observed during the de-trending procedure for the past decades in some older trees. This has also been found in other long tree-ring chronologies and was often attributed to a changing temperature regime in the second half of the twentieth century (D'Arrigo et al. 2008; Esper et al. 2008; Oberhuber et al. 2008).

Our *P. heldreichii* chronology corresponds well to a *P. heldreichii* chronology from the Olympus Mountains in Greece, an area influenced by similar air masses and weather patterns due to its proximity. Correlation with a chronology from the south of Italy is lower due to larger distances and resulting differences in climate conditions. Precipitation and temperature regimes are strongly varying over Europe, particularly in the southern part of the

Table 3 Corresponding and disagreeing pointer years in *P. peuce* and *P. heldreichii* chronologies and probable climate driving factors

Year	Indices in chronology		Climate situation
	P. heldreichii	*P. peuce*	
1908	Low	Low	No unusual values in monthly climate data;*
1909	Low	Low	Wet March; dry June;*
1913	Low	Low	Very low temperatures in July and August;*
1916	Low	Low	Wet April and May; dry June;*
1919	Low	Low	Very wet March and April; wet May and lowest May temperature;*
1929	Low	Low	Dry July;*
1934	Low	Low	Low April to September temperatures in Bansko in 1933. Lowest June temperature in 1933 in Mussala peak station
1938	Low	Low	Dry April and June
1946–1947	Low	Low	Very dry period in the country (1945–1946). Very dry August (1946)
1963	Low	Low	Wet January and February, dry August, low temperatures in April and May;
1989	Low	Low	Low June temperature; lowest previous November temperature
2000	Low	Low	Very dry August; high April–July and September temperatures
1956	High	High	Wet February and March,
1970	High	High	Wet March, high temperatures in April
1983	High	High	Wet June, high April temperature
1986	High	High	Wet January and February. High April temperature
1999	High	High	Warm summer
1952	Low	Normal	Long precipitation-free periods in June (28 May–21 June) and July; dry August
1958	Low	High	Dry May and July
1973	Low	High	Low temperatures in August and September and record-cold October of previous year
1978	Low	High	Very dry June; low temperatures in August until November
1987–1989	Low	Normal	Very dry June, higher than normal July temperature; dry November and December of previous year
1993	Low	Normal	Dry June and driest July in Bansko record. High June and July temperatures
1971	Normal	Low	Wet July; low July, September, and October temperatures
1976	Normal	Low	Coldest summer in the mountain records. Very wet July and August
1977	High	Low	Coldest mountain summer in the previous year
1992	Normal	Low	Lowest previous May temperature, very dry winter and dry August

Sorting is in order of pointer year combination types

* Data only from Sofia climate station

continent, where high mountains cause strong local effects (Büntgen et al. 2006; Carrer et al. 2007). Moreover, a recent study of the ecophysiological responses of *P. heldreichii* trees in the Monte Pollino region in Italy showed high importance of local humid currents from the Tyrrhenian Sea, which help trees avoid the negative effects of summer droughts (Todaro et al. 2007).

Our *P. peuce* chronology is less well replicated and also consists of only one core per tree. It is therefore not surprising that the EPS is below the desired threshold of 0.85 until the start of the nineteenth century. Yet, the period covered by our climate–growth analysis does not extend beyond the twentieth century, for which there is high replication (above 20 cores) and EPS above 0.88. We consider that for future climate reconstructions more treeline series should be added to improve the EPS in earlier periods and to increase the chronology length.

The comparison with a *P. peuce* chronology from the Pelister Mountains (Macedonia) revealed statistically significant, but fairly low correlations. This can be explained by local site and climate-related differences. The trees in Pelister were sampled at about 1,900 m a.s.l., which is approximately 300 m below the local treeline. We hypothesize that the non-tree line character of the samples is a probable reason for differing sensitivity and differing responses to climate extremes and the resulting divergence between the chronologies. Also, the majority of our trees are probably older than the Pelister ones, although some of the series were not so long due to rotten inner parts of the trunks. While possible differences in cambial activity of young and old trees have been debated (Carrer and Urbinati 2004; Esper et al. 2008), a recent study by Rossi et al. (2008) demonstrated delayed start of cell production and overall shortened xylem differentiation of old *P. cembra*

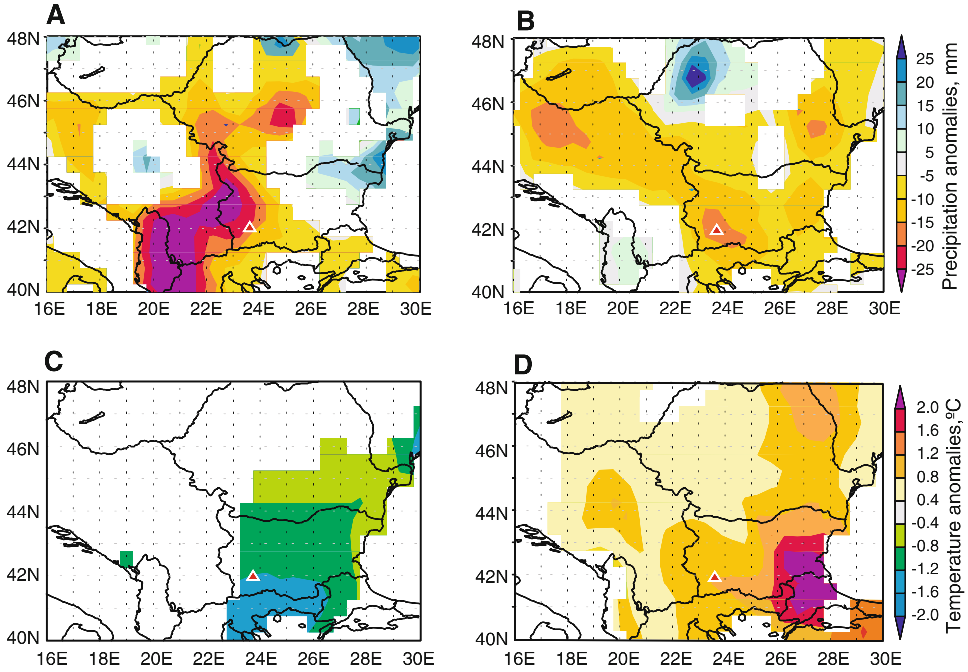


Fig. 5 Composite maps for gridded precipitation anomalies in: (**a**) June in years with low indices only in *P. heldreichii*, (**b**) July in years with low indices in both *P. heldreichii* and *P. peuce*; and gridded temperature anomalies in (**c**) July in years with low indices only in *P. peuce*, and (**d**) April in years with high indices in both *P. peuce* and *P. heldreichii* chronologies. Study site is marked with *triangle*

trees at treeline. Thus, we can expect minor differences between our chronology and the one from Pelister due to differing tree ages between the sites.

Climate–growth relationships

We found strong relationships between both tree ring chronologies and climate conditions of the year previous to the growth. At treeline locations, the growth period is relatively short and most active tracheid formation occurs at the beginning of the summer (Rossi et al. 2006). Therefore, for production of wide tree rings the combination of early cambial activity start with enough available resources, i.e., stored carbohydrates and other substances produced in the previous growth period and favorable climate conditions during the late spring and early summer months of the growth year is needed. The effect of climate in the previous year is expressed by strong first-order autocorrelation often found in treeline trees (Fritts 1976) and also in our series.

Both species are sensitive to summer drought stress, as reflected by the negative correlations with June and July temperatures and positive correlations with August precipitation. This suggests that tree growth is limited in years with dry and hot summers. Such findings are remarkable for tree-line sites, where tree growth mostly reacts positively to high summer temperatures (Korner 1998; Büntgen et al. 2006; Carrer et al. 2007). However, prolonged summer droughts are not unusual for the Bulgarian climate and even trees in high mountain environments can experience moisture shortage during such events. This could be especially important for trees growing on steep sun-exposed sites with shallow rooting as our *P. heldreichii* ones. Similar findings about positive influence of summer precipitation on *P. heldreichii* tree growth were reported for southern Italy (Todaro et al. 2007). Yet, there local moisture currents in summer reduced chances for drought conditions and therefore higher temperatures did not have as negative effect as they seem to have at our study site.

A long drought was observed in Bulgaria in the 1940s (Knight et al. 2004), which might explain stronger reactions for *P. peuce* during the first half of the twentieth century (Fig. 4c). *P. heldreichii* trees, on the other hand, showed an increased sensitivity to August precipitation during the second half of the twentieth century (Fig. 4d). The climate record for Bansko station reveals a continuous increase of summer temperatures (June–August) since the 1980s and several consecutive record high values (e.g., 1988, 1993–1994, 1998–2001, 2003) (Fig. 2). In addition to this, there was a marked decrease of winter precipitation (December–March) starting in the 1970s. *P. heldreichii* trees have therefore experienced both decreased availability of winter soil moisture reserves and increased temperatures in summer since the 1980s. Combined with specific micro-site conditions including very thin soils on sun-exposed steep slopes with marble bedrock, this can explain the recent increased drought-response of *P. heldreichii* trees. The drought effect on *P. peuce* trees on the shady western slopes was probably less pronounced.

Todaro et al. (2007) also report changed tree responses for *P. heldreichii* in the second half of the twentieth century and similar results were also found for *P. cembra* in

Austria, where Oberhuber et al. (2008) report divergent response of treeline trees to July temperatures after the 1980s and related it to local drought. In Switzerland, Esper et al. (2008) studied reactions of *P. cembra* growing on shady and sun-exposed slopes and reported change in response of trees on sunny sites after the 1980s, which they attributed to local drought conditions.

Both species are also positively influenced by milder winters (e.g. December and January temperatures). Such results have also been described for *P. heldreichii* by Todaro et al. (2007), who found correlation between minimum and average January temperatures and earlywood width. From a physiological point of view winter temperatures cannot directly influence cambial activity since the trees are dormant. However, during warmer winters, more precipitation falls as rainfall, rather than as snow (IPCC 2007). In our case, it is more probable that precipitation in cases with warmer winter temperatures is in the form of wet snow, which on its side is less prone to wind transport and immediate sliding along steep slopes and therefore could contribute to a deeper snow cover. This can provide more soil moisture after snowmelt and be a prerequisite for increased cambial activity given other conditions are favorable.

Negative effects of unusually cold winter periods on tree growth, however, cannot be ruled out, including damages to the fine roots, frost, desiccation damages to needles, and frost damages to buds (Tranquillini 1979). Fine-root damage in periods with extensive cold temperatures appears the most likely at the *P. heldreichii* site, where a big part of the rooting system is placed close to the surface or in rock cracks due to the very shallow soils. In both cases this means that the roots do not benefit the effective insulation of a deeper soil profile. Since the site is very steep and exposed to winds, in cold periods when the snow is powdery it can also not hold thick snow covers which could further insulate the roots and therefore in cases of extremely low temperatures, damages to fine roots would be possible. Frost damages, on the other hand, have been widely described for broadleaf species (Pederson et al. 2004), but we have not observed evidence for winter damages to *P. peuce* or *P. heldreichii* needles.

An important difference between *P. peuce* and *P. heldreichii* trees is the positive growth response of *P. peuce* to high previous early summer and autumn temperatures, which is consistent with previous findings (Vakarelov et al. 2001) and as expected for treeline species. This suggests that years with an earlier start and later end of the growing season stimulate formation of wider tree rings. In the Pirin Mountains, lower summer temperatures are usually related to higher precipitation and vice versa (R for August $= -0.53$, $p < 0.05$, Vihren hut data). Thus, negative response of *P. peuce* trees to June and November precipitation most probably reflects an unfavorable start and end of the growing season. A previous study by Panayotov and Yurukov (2007) demonstrated that unusually cold periods at the end of May or beginning of June caused formation of frost rings with bands of damaged cells at the start of the earlywood, which is an indication that cambial activity started shortly earlier (e.g., in early to mid May). Low temperatures in May and June could therefore slow down the initiation and first stages of cell division and development. In addition to this, unusually low temperatures in July and August can also slow down the development of cells, normal formation of secondary cell walls, and deposition of lignin, and can therefore be responsible for production of light rings or narrow tree rings in extreme years (Gindl 1999; Rossi et al. 2006). Light rings have been previously described for the *P. peuce* trees for years with unusually cold summers (e.g. 1933, 1959 and 1976, Panayotov and Yurukov 2007). A positive response to spring and summer temperatures has also been found in a number of studies of *P. cembra* in the European Alps (Carrer and Urbinati 2004; Carrer et al. 2007; Esper et al. 2008) and the Carpathian Mountains (Popa and Kern 2009). *P. cembra* also belongs to the *Strobus* sub-genus of *Pinus*, grows at treeline locations in Europe, and is therefore genetically and ecologically the closest European species to *P. peuce* and could have similar response.

Our pointer year analysis confirms the summer drought effect on *P. heldreichii* tree-ring formation, and showed that the effect was strongest for June precipitation. The negative response of *P. peuce* trees to cold summers was also consistent with conclusions from the previous analysis. The composite analysis also showed that extremely dry summers could affect *P. peuce* whereas abnormally cold summers could affect *P. heldreichii* trees. While such responses to unusual climate are logical from a physiological point of view, they were not clearly revealed by the correlation analysis. Correlation analysis also failed to show a possible negative reaction to increased late-winter and early-spring precipitation. While normal snow pack is needed for soil moisture reserves, a higher-than-usual snow pack can postpone the beginning of the growing season, especially if late spring and early summer temperatures do not favor increased snowmelt. Similar situations may affect tree growth, especially when combined with other negative factors in summer or early autumn. Kirdyanov et al. (2003) gave similar explanations for growth limitation in Siberia. The positive response of both species to higher April temperatures in the southeastern part of the country reflects the influence of warm spring winds that come from a SE direction, which are typical for Bulgaria for this period and in some years may cause very fast snow melt and thus an earlier start of the growth period in mountains.

Anomalous years were not so frequent and this might be a reason why the correlation analysis failed to reveal the possible effects. The composite analysis, however, demonstrated the non-linear reaction of tree growth to climate. Comparison of the climatic reactions of both species and of other species with a more defined response to a specific type of climate extreme (e.g., drought and valley bottom species), could provide better insight into what was the real nature of particular climate situations. This could be especially valuable in studies of past climate, when often the only available data are low-quality historical records from specific locations. In such cases, if information for extremes in the historical records and conclusions from the tree-ring study differed, the divergence could be considered a mistake in the proxy reconstruction. At the same time, it might be a specific climate situation, resulting in opposite responses in tree-ring chronologies from different species. A recent example of this is the summer of 1976. While it was unusually dry in Europe (Schweingruber 1996), it was the coldest summer in the Bulgarian mountains (Panayotov and Yurukov 2007). Also, the reactions of *P. heldreichii* and *P. peuce* in that year differed. Our analysis also showed that conclusions for the climate–growth relationships are highly dependent on the choice of climate data. This is due to existing differences, especially in the precipitation regime of Sofia and Bansko stations and implies that for future proxy climate reconstructions based on tree rings from the Pirin Mountains region one of the major challenges will be the appropriate choice of climate data.

Conclusion

Two tree-ring chronologies of *P. heldreichii* and *P. peuce* from closely situated treeline locations revealed complementary summer temperature and precipitation signals. *P. peuce* trees were most sensitive to previous summer temperatures, whereas *P. heldreichii* showed strong drought reactions with negative response to low early-summer precipitation and high temperatures. A simultaneous analysis of the two chronologies revealed the importance of extreme climate situations, which caused specific reactions in both species and thus can be used for detailed reconstruction of such events. The general lack of reliable data about climate variability in the Balkan region during the past millennium and the potential to construct long tree-ring chronologies from both species promote future dendrochronological work with them. This can be of great importance with respect to the impact of extreme climate and particularly droughts for local people and economies, the lack of reliable historical chronologies for that region, and the need to evaluate climate variation and extremes with respect to observed climate changes.

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