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ORIGINAL PAPER

Fingerprints of extreme climate events in *Pinus sylvestris* tree rings from Bulgaria

Momchil Panayotov Panayotov · Nikolay Zafirov · Paolo Cherubini

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Abstract Tree-ring studies may help better understand climate variability and extreme climate event frequency and are especially useful in regions where detailed meteorological records lack. We studied the effect of droughts and unusually cold periods on *Pinus sylvestris* tree-ring width and wood anatomy. Study sites were selected along an altitudinal gradient on Vitosha Mountain, Bulgaria. Drought conditions caused the formation of narrow tree rings or light rings if the drought occurred in July–August at the lower altitude sites. In years with droughts in June and the first half of July, followed by precipitation in the middle of July, intra-annual density fluctuations (IADFs) were formed. Trees in the zone with optimal growth conditions produced fewer light rings and narrow rings in years with either strongest droughts or unusually cold summers. At the timberline zone, low summer temperature triggered narrow tree rings and light rings. Frost rings were formed when there was a drop in temperatures below the freezing point in the second half of May or at the beginning of June. Our findings show that studies of tree-ring anatomy may contribute to obtain further knowledge about extreme climatic events in the Balkan Peninsula and in other regions where meteorological data lack.

Keywords Tree rings · Climatic extremes · Light rings · Intra-annual density fluctuations (IADF) · Frost rings · Balkan Peninsula

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M. P. Panayotov (✉)
Dendrology Department, University of Forestry,
Kliment Ohridski 10 Blvd, 1756 Sofia, Bulgaria
e-mail: mp2@abv.bg

M. P. Panayotov
WSL Institute for Snow and Avalanche Research SLF,
Davos, Switzerland

N. Zafirov
Department of Plant Pathology and Chemistry,
University of Forestry, Kliment Ohridski 10 Blvd,
1756 Sofia, Bulgaria
e-mail: niki_zafirov@yahoo.com

P. Cherubini
Swiss Federal Institute for Forest, Snow and Landscape Research
WSL, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland
e-mail: paolo.cherubini@wsl.ch

Introduction

Extreme climate events can have a large impact on ecosystems and human civilizations. Severe droughts, unusually cold summers or winters, and strong storms, for example, can dramatically change ecological conditions, causing local extinction of plant and animal species, social and economic problems, and human fatalities (Parry et al. 2007). It has been suggested that global warming in recent decades has been changing the frequency and intensity of extreme climate events (Solomon et al. 2007). An accurate assessment of such potential changes requires detailed information about the past. A problem in this context, for many regions in the world, is the lack of long historical records. This requires the use of proxy data, including tree-ring analysis (Schweingruber 1996).

Because tree rings are the result of the combined influence of various ecological factors affecting plant growth, they can be considered as natural archives with high (i.e., annual) resolution (Fritts 1976). Their width and density variations have been widely used as estimates of temperature and precipitation (Hughes 2002), using correlation and response function analysis. Such techniques typically provide information about the average relationship between variations in tree-ring parameters and climate. They are not, however, very useful for understanding the influence of extreme climate events on tree growth (Schweingruber et al. 1990). To solve this problem, some studies have used analysis of the anatomical structure of tree rings or anomalies in tree-ring width, which often contain indications of abrupt changes in temperatures, precipitation regime or natural disturbances. Useful wood anatomical characteristics include: early and latewood frost rings, used as indicators of unusually cold periods during the growth season (Glerum and Farrar 1966; La Marche and Hirschboeck 1984; Brunstein 1996; Hantemirov et al. 2004); light rings as clues for summer and autumn periods with low temperatures (Filion et al. 1986; Yamaguchi et al. 1993; Gindl 1999; Hantemirov et al. 2004); light rings as indicators of very dry summers (Liang and Eckstein 2006); intra-annual density fluctuations (IADF-s) as indicators of summer drought conditions (Rigling et al. 2001; De Micco et al. 2007) or drought-induced dormancy periods in Mediterranean-type climate (Campelo et al. 2007; Bogino and Bravo 2009; Vieira et al. 2009) and radial cracks as indicators of moisture deficiency in summer (Grabner et al. 2006).

Study sites at the boundaries of a species' distribution area or ecological amplitude are particularly valuable for research on the impact of extreme climatic events. At these sites, trees are most sensitive to local limiting factors and react most distinctively to changes in them (Gruber et al. 2010). Typical examples are alpine treeline sites, where low temperatures are the primary limiting factor (Rossi et al. 2008), or dry sites, where low precipitation is the primary limiting factor (Cherubini et al. 2003; Rigling et al. 2001; Büntgen et al. 2010). Yet, studies about the influence of extreme climatic events on tree rings are scarce and limited to only a few locations around the world, thus hindering the broad-scale estimation of possible changes in their frequency. Furthermore, studies that have focused on sites with similar, rather than contrasting, climate conditions, do not allow an estimation of whether a specific anatomical tree-ring feature is indicative of only one type of climate extreme. The importance of such events for society and the lack of reliable proxy climate records for many regions of the world necessitate studies that verify previous findings and broaden the knowledge about the influence of climate extremes on tree rings and thus, facilitate the development of longer and improved proxy records. For this purpose, species with high ecological plasticity, which can grow at various altitude and site conditions, are particularly useful. Scots pine (*Pinus sylvestris* L.) is one of these species and is wide spread world-wide and in specific regions (Richardson 2000). In addition to this, numerous studies are available on *P. sylvestris* tree-ring width, density and anatomy variation and their dependence on climate (Grudd et al. 2002; Briffa et al. 2004; Antonova et al. 1995; Rigling et al. 2001; Eilmann et al. 2006; Büntgen et al. 2010; Oberhuber and Gruber 2010; Gruber et al. 2010; Eilmann et al. 2011). Yet, these studies were generally focused on specific sites or factors and thus, do not provide sufficient evidence of how tree-ring features could be indicative of different extremes dependent on the location.

The Balkan Peninsula is an important region from a climatic point of view and is especially vulnerable to climatic extremes (Xoplaki et al. 2001), but high-resolution proxy climate data inferred from tree rings are scarce and concentrated mostly on the coastal areas (Panayotov et al. 2010). For Bulgaria, studies are limited and with few exceptions (e.g., Panayotov and Yurukov 2007; Trouet et al. 2012) were focused mainly on variations of tree-ring width. Old trees growing in various climatic conditions, however, are available in this region and provide a chance for the construction of sensitive proxy records.

The aim of this study was to assess the effect of extreme climate events on the radial growth and wood anatomy of *Pinus sylvestris,* particularly at its distribution boundaries in Bulgaria. We selected this species primarily based on two criteria: (a) it's wide distribution in Bulgaria and the chance to find sites with contrasting climate conditions which provide the opportunity to obtain tree-ring based proxy data and (b) the lack of sufficient studies on the reflection of climate and extreme events in *P. sylvestris* tree rings for Bulgaria, which itself hinders more detailed studies of climate variability for longer periods. We aim at analyzing the following specific research questions: (1) How does climatic variability and extremes affect tree-ring width and anatomy at sites along a gradient on a mountain slope? (2) Are similar tree-ring features formed under different climate conditions? and (3) What tree-ring parameters are most suitable to reconstruct past climate variability and extremes at different altitudes?

Materials and methods

Study area

The four study sites were situated along an altitudinal gradient on the northern slope of Vitosha Mountain in western Bulgaria (Fig. 1). All studied forest stands are plantations of *P. sylvestris* with an age ranging between 60 and 100 years (Table 1). The lowest natural *P. sylvestris* forests in Bulgaria are situated at 800 m a.s.l. and the highest reach the local treeline as isolated stands at 1,800–2,100 m a.s.l. In order to cover the range of ecological conditions under which the species grows, we selected sites from a zone at the lowest growth boundary (site LOW), from the zone characterized by optimum growth conditions, one at a lower (site MID-L) and one at a higher (site MID-H) elevation, and from the local treeline (site HIGH). The location of site HIGH was chosen so as to be protected from the strong winds that are frequent during winter in the area while being subjected to the typical high mountain temperature and precipitation regime. According to forest management plans and records, these plantations have not been subjected to management practices and only occasional removal of dead and dying trees was performed in the past. Tree growth was therefore mainly affected by natural factors including climate and competition among trees.

Meteorological data

We used meteorological data recorded at the Sofia and Cherni Vrah climate stations (Fig. 1). The Sofia station is situated at 550 m a.s.l. (42°42′N; 23°20′E), 9 km from study site LOW and 9.5 km from site MID-L, and has one of the longest meteorological data series in Bulgaria (1881-present). The Cherni Vrah station is situated on the top of Vitosha Mountain (2,286 m a.s.l., 42°34′N; 23°17′E), 3.6 km from study site HIGH and 4.4 km from study site MID-H, with continuous measurements available from 1935 onwards. For data on climatic conditions in several specific years, we used records from Aleko hut (1,800 m a.s.l.) and Boerica hut (1,700 m a.s.l.) stations that operated for at least 30-year periods in the first half of the twentieth century.

The typical climate in the region is transitional–continental, influenced by both Atlantic and Mediterranean air masses. The precipitation maximum occurs at the end of spring and the beginning of summer (Fig. 2; Table 2). The lowest precipitation is in August and September. No typical dry period is observed in the average record of Sofia meteorological station (Fig. 2), but extensive droughts with strong environmental impact occur in the valleys in some years (Zahariev 1930; Raev et al. 2003; Koleva et al. 2004).

To determinate drought conditions, we calculated the Palmer Drought Severity Index (PDSI) (Palmer 1965). This index has the advantage of providing a standardized value, based on the precipitation and temperature for the current and the previous months. Therefore, it can indicate drought conditions with duration of more than 1 month, which are the most likely to cause water deficit in trees. To determine droughts on the basis of PDSI values, we used Palmer's original classification, which lists values below −2 as indicative of moderate drought conditions, while those below −3 indicate severe droughts (Palmer 1965). We

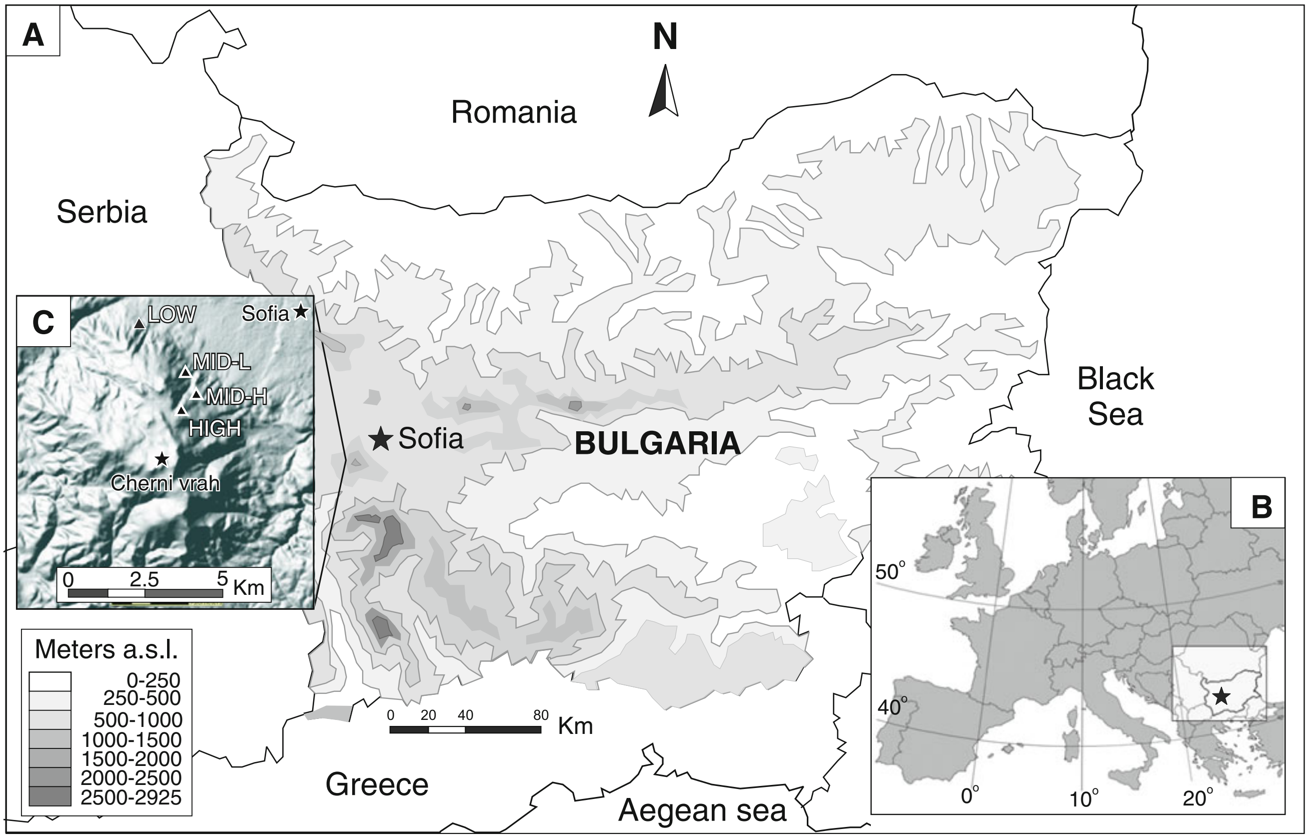

Fig. 1 Location of the research area. Position of the study sites is marked with *triangles*. Position of climate stations is marked with *asterisks*

Table 1 Study site information

Site abbreviation	LOW	MID-L	MID-H	HIGH
Site name	Low altitude	Medium altitude: lower	Medium altitude: higher	High altitude
Coordinates, lat/long	42°39′15″N 23°14′25″E	42°36′53″N 23°17′44″E	42°36′13″N 23°18′40″E	42°35′48″N 23°17′23″E
Altitude, m a.s.l.	750	1100	1350	1750
Exposition	N	NE	N	W
Slope, °	10	18	27	26
Tree species	PISY (60 %), PINI (40 %)	PISY (100 %)	PISY (90 %), PIPE (10 %)	PISY (100 %)
Age	105	65	65	60
Mean DBH, cm	38	24	32	22
Mean tree height, m	26	21	24	13
Trees per 1 ha	600	850	950	1205
Soil type (FAO)	Humic cambisols	Dystric cambisols	Dystric cambisols	Dystric cambisols
Soil thickness	Shallow	Deep	Deep	Shallow
Base rock	Diluvial clay accumulation	Andesite	Andesite	Andesite

Species abbreviations: PISY, *Pinus sylvestris* (L.); PINI, *Pinus nigra* Arnold; PIPE, *Pinus peuce* Griseb

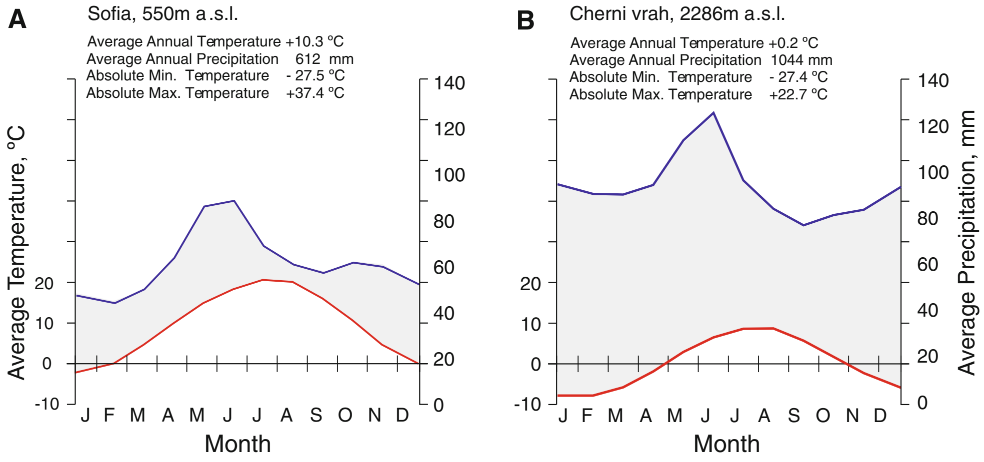

Fig. 2 Climate diagrams for Sofia (**a**) and Cherni vrah (**b**) climate stations. Average values are calculated for the period 1881–2005 for Sofia climate station and 1935–2005 for Cherni vrah climate station

Table 2 Climate data for the study region

Station (m a.s.l.)	Average annual precipitation (mm)	Average temperature (°C)	Average temperature of coldest month (°C)	Absolute min. temperature (°C)	Average temperature of warmest month (°C)	Absolute max. temperature (°C)
Sofia, 550 m	612	10.3	−1.7	−27.5	21.2	37.4
Boerica hut, 1,700 m	1,060	4.0	−5.2	−26.0	12.9	32.0
Cherni Vrah, 2,229 m	1,178	0.2	−7.8	−27.4	9.0	22.7

calculated August PDSI values for Sofia station using PDSI software (Wells 2003) of the National Agricultural Decision Support System (http://greenleaf.unl.edu, accessed on April 18, 2012).

Sampling and chronology preparation

At each site, 19–27 dominant and co-dominant trees were selected. From each tree, two cores were extracted at breast height from opposite directions. All cores were cross-dated, thus confirming correct identification of the calendar year of formation of each tree-ring, and of missing and false tree rings. Crossdating was conducted by visual analysis (Stokes and Smiley 1968) and verified with the software program COFECHA (Holmes 1983). Tree-ring widths were measured with a resolution of 0.01 mm at the dendrochronological laboratory in the University of Forestry in Sofia. The data were then standardized by applying several detrending techniques—a general negative exponential function, spline functions with 50 % frequency response of 60 years and with fixed cutoff of 30 years and Hugershoff function (Cook and Kairiukstis 1990), using ARSTAN software (Cook 1985). 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 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 (1st 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 computed the EPS over 30-year windows lagged by 15 years and used an EPS value of 0.85 as a threshold for the reliability of our chronologies (Wigley et al. 1984).

We recorded tree rings characterized by unusual wood anatomical features, e.g., low lignin content in latewood,

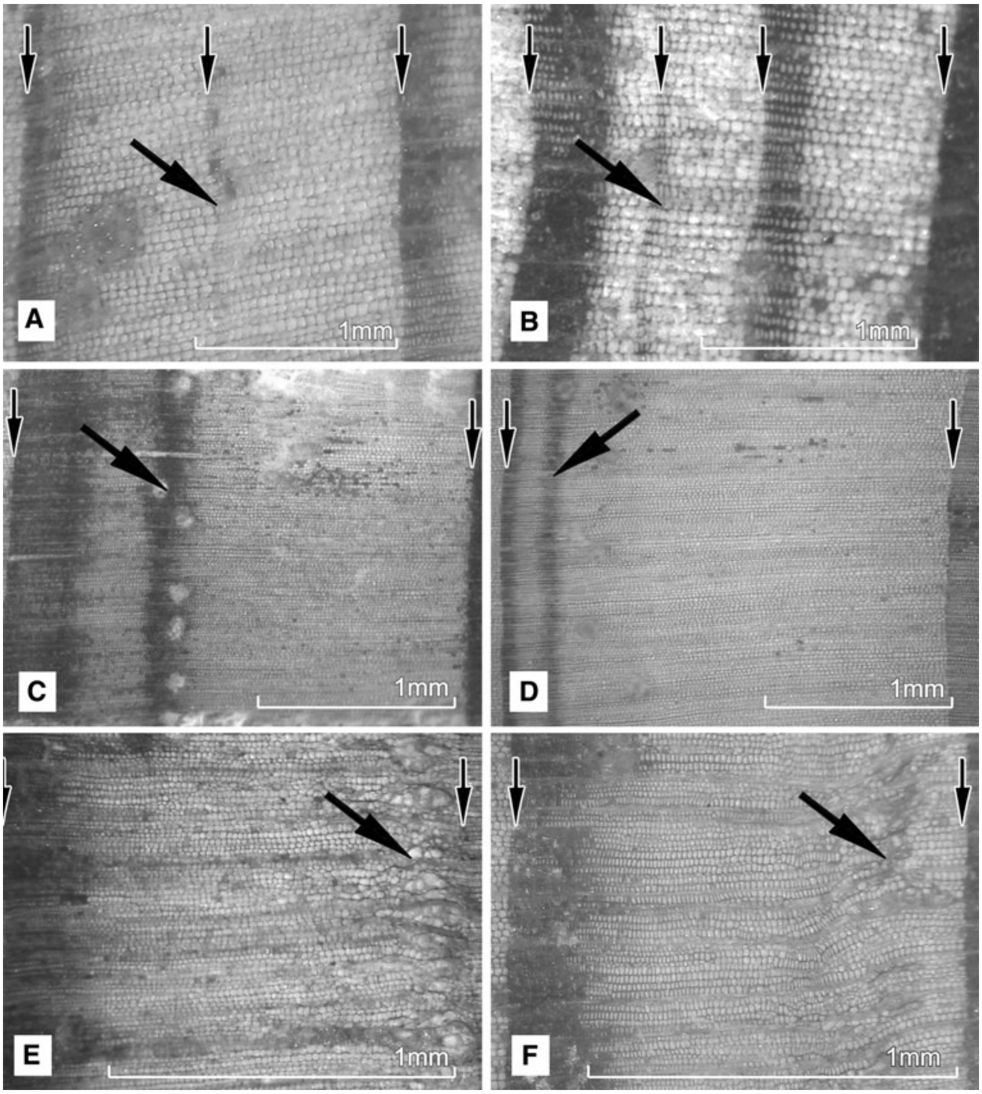

Fig. 3 Tree rings features: **a** light ring (LR); **b** narrow-latewood light ring (NLR); **c**, **d** tree rings with intra-annual density fluctuation (IADF); **e** earlywood frost ring (EwFR) formed at the end of May (i.e., 1952); and **f** earlywood frost ring (EwFR) formed at the beginning of June (i.e., 1962). *Vertical arrows* indicate tree ring boundaries. *Diagonal arrows* indicate intra-annual anatomical features of interest

i.e., light rings (Filion et al. 1986), rows of cells collapsed because of exceptionally low temperatures, i.e., frost rings (Glerum and Farrar 1966), intra-annual density fluctuations (IADFs) (Cherubini et al. 2003), and very narrow rings, i.e., negative pointer years (sensu Schweingruber et al. 1990). Tree rings with unusual wood anatomical features were analyzed with a Carl Zeiss Stemi 2000-C stereomicroscope, photographed and encoded with number codes. Thus, we obtained frequency series of the specific tree-ring features.

We distinguished two types of light rings. The typical light rings (abbreviated "LR") were very pale in color and their latewood was hardly visible (Fig. 3a). The other type (here named "narrow-latewood light rings" and abbreviated "NLR") was tree rings with very narrow latewood or only a few layers of dark-colored cells in the latewood, but clearly visible as a thin slightly darker band at the end of the tree-ring (Fig. 3b). The NLR subtype of light rings are tree rings with extremely narrow latewood already demonstrated to be representative of drought situations in other regions of the world (Liang and Eckstein 2006). Therefore, it would be valuable to verify if the same conclusions are applicable for tree rings from a European location.

Frost rings at our sites were mostly found in the earlywood (EwFR). We recorded the position of the band with buckled cells typical of frost rings—either at the very beginning of the tree-ring (Fig. 3e), or as a separate layer in the middle of the earlywood (Fig. 3f).

Tree rings with intra-annual density fluctuations (IADF, Fig. 3c, d) and visually distinguishable narrow rings (NR) were recorded without additional subdivision of types.

To enable a frequency comparison of different tree-ring types over time, we calculated the stabilized frequency (F_s), which accounts for the changing sample depth. The calculation was performed as suggested by Rigling et al. (2001), based on the scaling of Osborn et al. (1997):

$$F_s = (n_x/N)N^{0.5}$$

where n_x is the number of the specific anomalous tree-ring type and N is the number of all tree rings in that year. We performed the F_s calculation only for years in which more than two trees per site produced the specific tree-ring feature.

Correlation analysis

We calculated climate-growth correlations using average monthly temperatures and precipitation sums for the months from June of the year prior to growth to September of the present year and added several seasonal windows—previous summer (June–August), previous autumn (September–November), winter (December–March), spring (April–May), present summer (June–August) and present summer-early autumn (June–September). Correlations with July, August and September PDSI values were also calculated. We conducted a composite analysis to explore the possible relationship between climate anomalies and frequencies of tree-ring features. Improved gridded (0.5° × 0.5°) monthly and seasonal temperature and precipitation fields for the period 1901–2006 (CRU TS2.1; Mitchell and Jones 2005) and scPDSI (van Der Schrier et al. 2006) were averaged over years of high frequencies of LRs and NRs. We did not perform composite analysis for IADFs due to the low number of years with this parameter, or for EwFRs due to the short duration of the climate anomaly usually associated with this anatomical feature and hence the fact that it is not represented in the average monthly series. Composite maps were generated using the KNMI Climate Explorer (van Oldenborgh and Burgers 2005; http://climexp.knmi.nl). Correlations between the F_s series were calculated with the non-parametric Spearman's rank order correlation. Correlations between the indexed tree-ring chronologies were calculated with Pearson's linear correlation.

Results

Tree-ring width chronologies

Mean tree-ring width was higher in trees growing at the growth-optimum altitudes and lower at the highest and lowest altitudes (Table 3). The sensitivity of the series, and thus their dependence on the variation of local climate conditions, was higher in the lower-altitude sites and lowest in the highest altitude site (HIGH).

The averaged tree-ring width chronologies (e.g., raw chronologies, Fig. 4a) and the mean standardized chronologies (Fig. 4b) showed different growth patterns. Regardless of the applied detrending procedure, similar

Table 3 Descriptive statistics of composed chronologies

Chronology	LOW[a]	MID-L	MID-H	HIGH
Start, year	1900	1936	1938	1947
End, year	2005	2004	2005	2004
Length, years	105	69	68	58
Number of trees	21	23	27	19
Mean tree ring width (TRW), cm	0.170	0.250	0.215	0.173
Standard Deviation of TRW	0.090	0.169	0.105	0.069
Median tree ring width, cm	0.170	0.238	0.207	0.182
First-order autocorrelation	0.690	0.777	0.704	0.736
Sensitivity	0.329	0.293	0.226	0.205

The descriptive statistics were calculated from non-standardized tree ring chronologies

[a] The descriptive statistics for chronology LOW were calculated over the period 1900–1970 to match the cambial age of the other chronologies

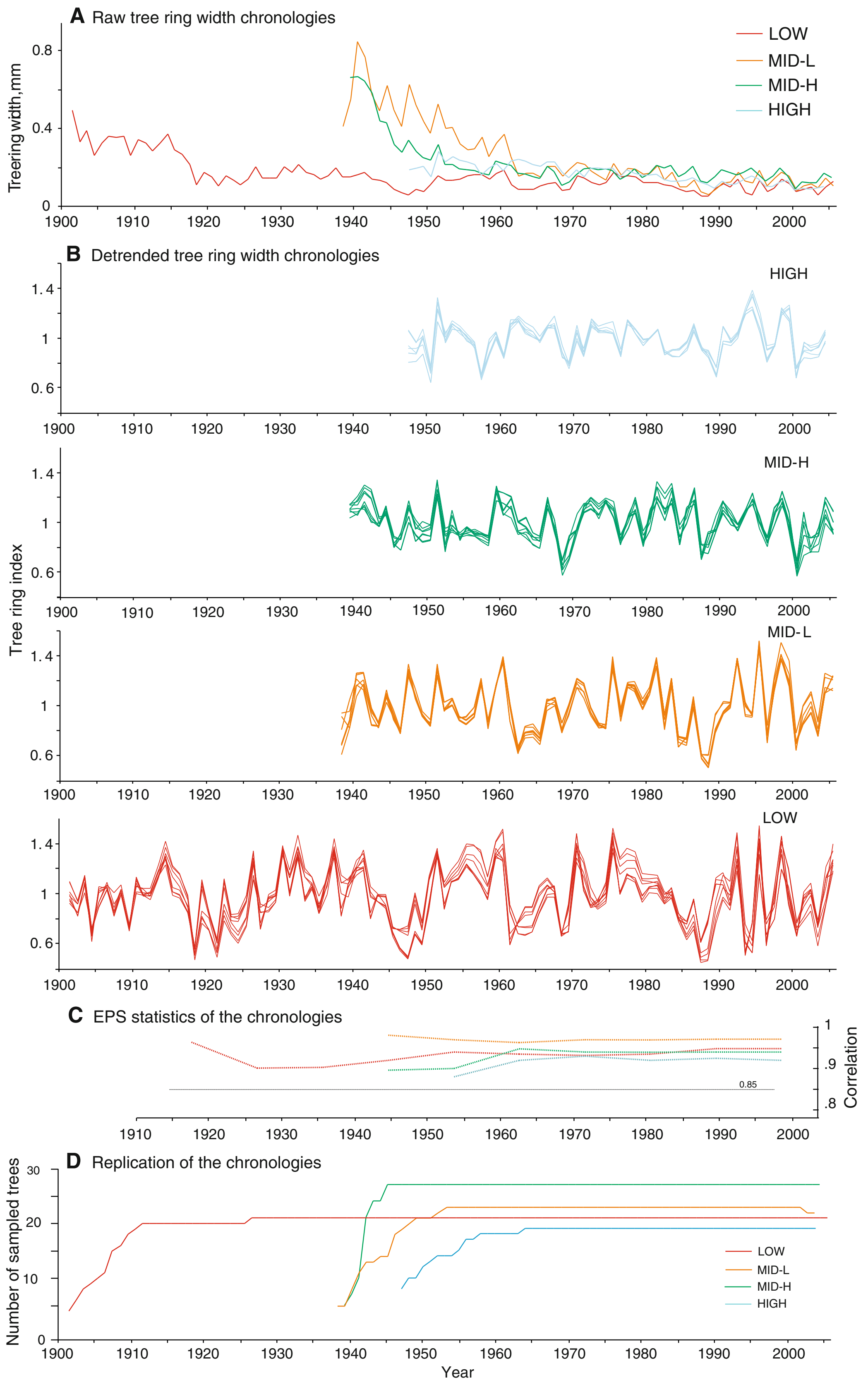

Fig. 4 Raw tree-ring width chronologies (**a**), standardized site tree-ring chronologies after different detrending techniques (**b**), internal signal strength expressed as EPS statistics (computed over 30 years lagged by 15 years) and series replication (**d**)

synchronous occurrence of low and high indices was found in the chronologies from sites LOW and MID-L, which correlated strongly ($r = 0.51$ to $r = 0.75$, $P < 0.001$). The narrowest tree rings and the lowest indices (e.g., 1945–1947, 1949–1950, 1962–1964, 1968, 1972–1974, 1984–1985, 1987–1988, 1993–1994, 1996, 2000, and 2003) occurred synchronously and most of the occurrence years are known to have been dry as reported in Koleva et al. (2004) and this was also indicated by our composed August PDSI dataset (Fig. 9).

The overall correlations of the MID-H chronologies with other chronologies were higher for its adjacent site (MID-L, $r > 0.41$, $P < 0.001$) than for the site above (HIGH, $r > 0.35$, $P < 0.05$). Most of the lowest tree-ring indices from site MID-H matched those of LOW and MID-L, but some (e.g., 1976 and 1979) corresponded to low indices in chronologies from site HIGH.

In site HIGH, the majority of the lowest indices (e.g., 1950, 1957, 1960, 1969, 1976, 1982–1984, 1989) were not matched by the chronologies at lower sites. Low indices occurred in years with low PDSI values (e.g., 1950, 2000), but the majority occurred in years with a short growth season or unusually low temperatures as reported by Panayotov and Yurukov (2007).

Climate-growth relationships

Summer precipitation has a strong positive influence on tree-ring growth at the LOW and MID-L sites (Fig. 5). At site LOW the precipitation in spring (i.e., April–May) is more important than at the other sites and the correlations of the chronologies from site MID-L were highest with summer precipitation (June–July). Summer PDSI values were strongly positively correlated with chronologies form sites LOW and MID-L. The temperature influence was positive at the end of the winter season (March) for trees at sites MID-L and MID-H, and negative in late spring and early summer for trees at sites LOW, MID-L and MID-H.

Summer precipitation appeared to have no statistically significant influence on the MID-H chronology. There was no statistically significant influence of the temperature regime on the chronologies at site HIGH, but negative correlations with previous summer precipitation were found at this site.

Tree rings with anomalies in the wood morphological structure

Approximately 8 % of all tree rings from the LOW and MID-L sites were classified as light rings (Table 4). The dominant subtype was light rings with very narrow latewood (NLR). With few exceptions, the highest frequencies of light rings in chronologies LOW and MID-L were found in the same years (Fig. 6). Our composite analysis revealed that in years with high frequencies of LRs in chronologies LOW and MID-L, scPDSI was lower than average over the central parts of the Balkan Peninsula (Fig. 7). In the majority of these years August PDSI values in Sofia was either below −2, which indicated persistent drought conditions, or there was a long precipitation-free period in July–August (Table 5).

With increasing altitude, the percentage of light rings decreased to about 5 % in site MID-H and 3 % in site HIGH. The NLR subtype was predominant in MID-H, but

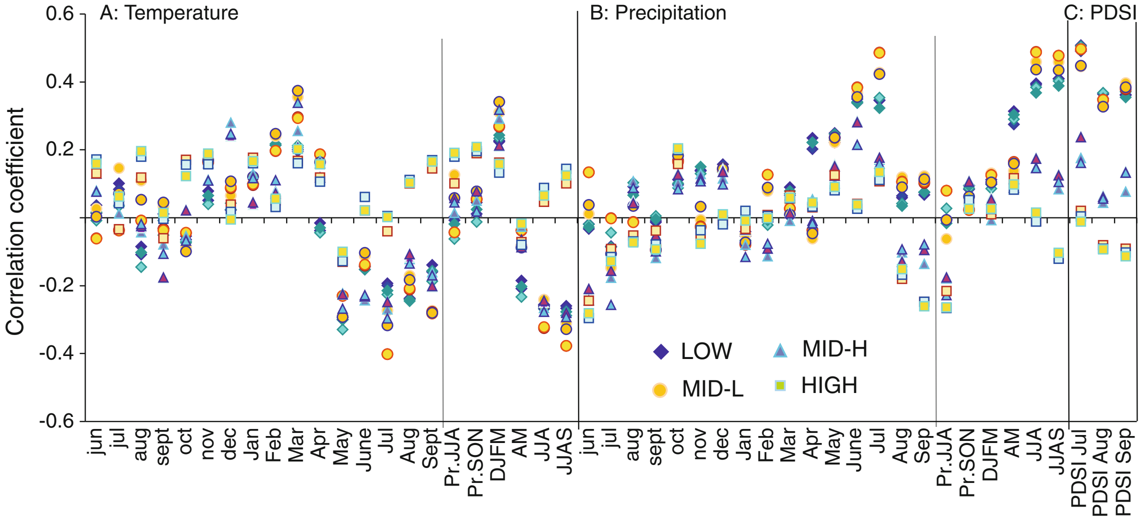

Fig. 5 Correlations between the four site chronologies marked with *diamonds* (LOW), *circles* (MID-L), *triangles* (MID-H) and *squares* (HIGH) and monthly and seasonal precipitation (**a**) and temperatures (**b**) from June of the year prior to growth to September of the current year and PDSI (**c**) of July to August of the current year

Table 4 Descriptive statistics of tree-ring features

Site	LOW	MID-L	MID-H	HIGH
Total number of tree rings	1,927	1,403	1,806	1,123
Total number of light rings (LR + NLR)	169	105	47	28
Percent of light rings	8.77	7.48	2.60	2.49
Number of LR	47	15	17	23
Number of NLR	122	90	30	5
Number of NR	145	65	70	67
Percent of NR	7.52	4.63	3.88	5.97
Number of tree rings with IADFs	44	64	20	0
Percent of IADFs	2.28	4.56	1.11	0
Number of EwFR	21	10	16	32
Percent of EwFR	1.09	0.71	0.89	2.85

80 % of the light rings in site HIGH were of the LR subtype. There was one specific year (i.e., 1976, Fig. 6), in which every third tree in site MID-H and the majority of trees in site HIGH formed LRs.

Visually distinguishable narrow rings (NR) occurred most frequently in the sites at the boundaries of the species distribution range (i.e., sites HIGH and LOW, Table 4). Yet, there were differences in their distribution pattern: the highest NR frequencies at the low altitude sites were found in years with higher occurrence of light rings (Fig. 6), but at the higher altitude sites, NRs were also frequent in years with low occurrence of light rings (i.e., 1987 and 1988 at site MID-H; 1989 and 2000 at site HIGH). Our composite analysis revealed that years with NRs in sites LOW, MID-L and MID-H co-occurred with lower than average summer (June–August) precipitation amounts (Fig. 8), whereas NRs at site HIGH were common in years with higher precipitation. An exception was the exceptionally dry summer of 2000 in which NR frequency was also increased at site HIGH.

IADFs were more frequent at the sites at lower altitudes and did not occur at the highest altitude site. At site LOW, several trees produced IADFs in 1902, 1908, 1910 and 1918. At site MID-L, IADF frequencies were remarkable in 1950 and 1952, years with very low PDSI and dry summer conditions (Table 5). A detailed review of the daily meteorological records revealed long periods without precipitation or with sporadic and limited rainfalls in June–July in the years with IADFs. In 1950, there was a total of 3 mm precipitation from 8 June to 16 July followed by a dry spell at the end of July and throughout the month of August (a total of 9 mm for the period from 21 July to 30 August). Comparable conditions were found for 1952 with total precipitation of 6 mm from 28 May to 20 June, limited precipitation between 21 and 24 June (15.5 mm) and 1.9 mm from 25 June to 18 July.

Approximately 1 % of all tree rings at sites LOW, MID-L and MID-H were EwFRs and at site HIGH their occurrence was up to three times higher (Table 4). In chronology LOW, there was no specific year when this type of anomaly was dominant (Fig. 6). More than two trees had EwFRs in 1915, 1916, 1917 and 1923. Most EwFRs in the MID-L site were concentrated in 1941. In chronology MID-H, frost rings were found in 1941, 1942, 1947 and 1952. Yet, all the frequencies of EwFRs in sites LOW, MID-L and MID-H were low, but in site HIGH all trees produced frost rings in some years (Fig. 6). The F_s values at site HIGH were highest in 1944 and then gradually decreasing in 1952, 1955 and 1962. In all years with frost rings, there was a period with low temperatures in May or early June. In the cases when site LOW produced EwFRs the temperatures in Sofia were about +2.0 °C (Table 5). Because our study site is at the foot of the mountain and 200 m higher than the meteorological station we can expect that the temperatures in the region of the plantation were close to 0 °C or negative. In the years in which mountain climate stations operated, the frost situations were characterized with slightly negative or positive temperatures in Sofia station (−0.5 to +6.0 °C, Table 5). At the same moments at the region of the local treeline temperatures ranged from −2.0 to −5.0 °C (Aleko hut station), while at Cherni vrah peak station temperatures were from −7.8 to −11 °C (Table 5).

Discussion

Altitude influence on climate-growth relationships

Chronologies from the lower-altitude sites on Vitosha Mountain (LOW and MID-L) were mainly dependent on the hydrothermal regime at the beginning and in the middle of summer (May, June and July) with positive influence of moist conditions and negative of dry periods. The high rate of cambial growth in years with moist early summer months can be explained by the higher availability of water in the soil, which enables normal cambial activity and the production of wide tree rings. May–June is the period in which most of the tracheids are produced (Gruber et al. 2010) and favorable conditions during this period ensure a higher rate of cell production and thus wider tree rings. In contrast, in years when precipitation was abnormally low and temperatures were higher than usual, most trees formed narrow rings. Our findings are in line with recent detailed intra-annual studies of *P. sylvestris* tree-ring formation (Gruber et al. 2010; Oberhuber and Gruber 2010; Eilmann et al. 2011), which confirmed previous conclusions (Antonova et al. 1995; Rigling et al. 2001; Eilmann et al.

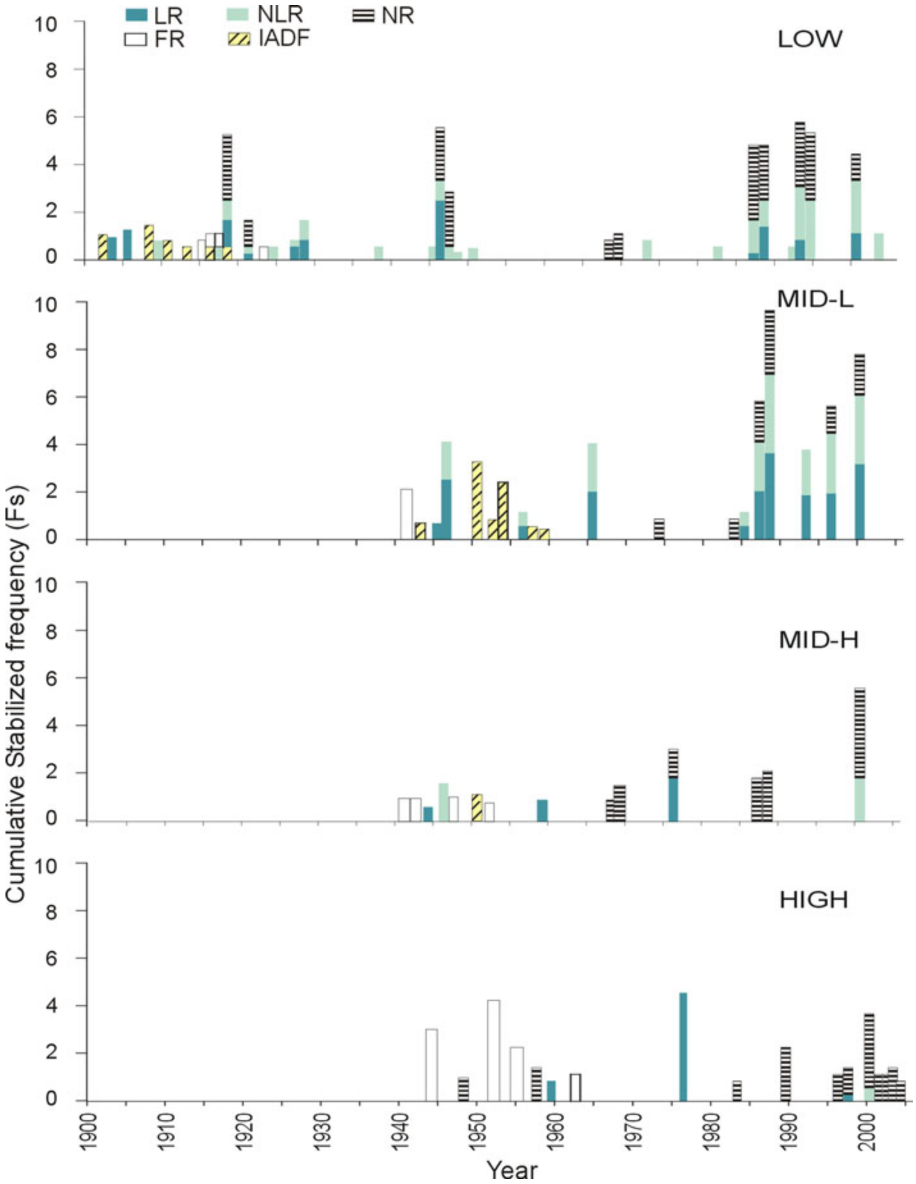

Fig. 6 Stabilized frequencies (F_s) of tree ring features. Used abbreviations are: *LR* light ring, *NLR* narrow-latewood light ring, *NR* visually distinguishable narrow rings, *IADF* tree rings with intra-annual density fluctuation, *FR* frost rings

2006; Thabeet et al. 2009) that drought stress hinders cell production in *P. sylvestris* and thus may have profound effects on tree-ring width. The effect of moisture deficiency on tree-ring width in our study sites was most pronounced during several known drought periods—namely in 1917–1919, 1945–1948 and 1984–1994. The first of these periods made an impression on foresters at the beginning of the twentieth century and was among the reasons for the earliest studies on drought impact on tree growth in Bulgaria (Zahariev 1930). The negative social effects of the 1917–1919 and 1945–1946 droughts were probably masked by the post-World Wars economic crises. Yet, historic (Ilchev 2005) and economic (Limpe 1986) studies reveal that wide spread famine in Bulgaria in 1918 was also due to crop failure associated with an unfavorable climate. In 1945–1946 the post-war crisis escalated due to low agriculture production (Limpe 1986), which was caused by one of the harshest droughts of the century (Koleva et al. 2004). The unusually low precipitation in the 1984–1994 period caused serious economic losses in the agriculture sector in Bulgaria and led to vitality decrease in coniferous forests at low altitudes (Raev et al. 2003).

With an increase in altitude, the negative influence of moisture deficiency in the summer period decreases. This is demonstrated by the change in the correlation strengths of the climate-growth relationships for the chronologies from sites MID-H and HIGH. The influence of high summer temperatures was negative for the MID-H chronology, but not significant for the HIGH chronology. We consider this to be related to a gradual precipitation increase and a temperature decrease. The effect of such changes in the hydrothermal regime is a decrease in the potential for

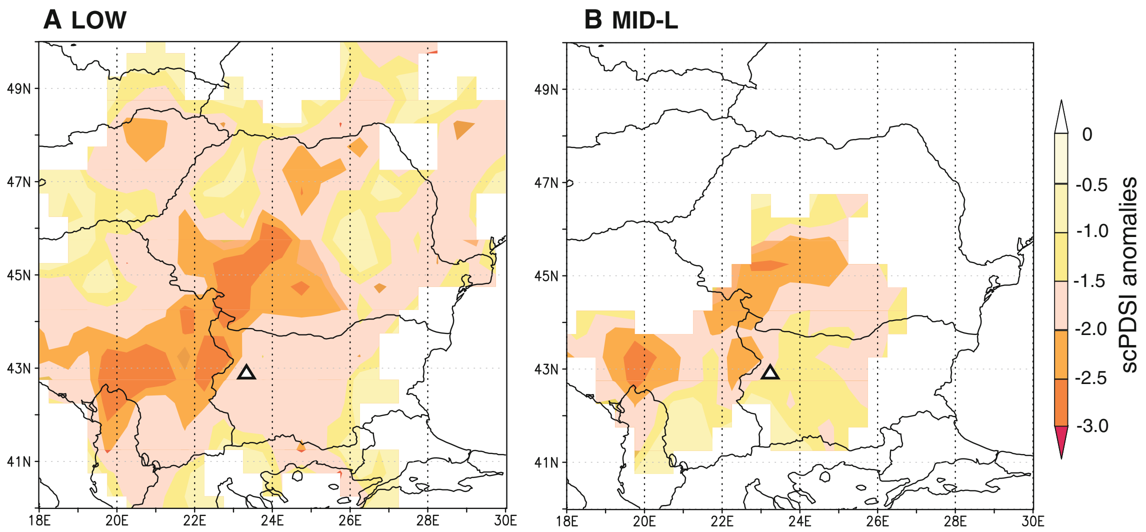

Fig. 7 Composite maps for gridded scPDSI anomalies in years with high stabilized frequencies of light rings (LR) in: **a** chronology LOW; and **b** chronology MID-L; study area is marked with *triangle*

drought-induced growth stress. However, in a year with exceptionally dry mid-summer (i.e., 2000), the higher altitude sites also had high frequency of NRs. The precipitation-free August of 2000 was already found to have triggered production of narrow tree rings in other species at the Bulgarian treeline (Panayotov 2007; Panayotov and Yurukov 2007), thus demonstrating that the observed reactions were not restricted to our study sites.

As expected, the precipitation limitation we found at lower elevations diminished with increasing elevation, but it is not clear why the correlation coefficients of the relationship between summer temperatures and tree-ring widths were not statistically significant for the HIGH chronologies. A strong influence of summer temperature is often found at high altitude sites (Fritts 1976; Camarero et al. 1998; Rossi et al. 2008). Yet it is sometimes recorded not in tree-ring width, but in other parameters such as maximum latewood density (Trouet et al. 2012). A likely explanation is that other factors rather than summer temperatures were limiting tree growth. Such limiting factors could include snow damages and rime accumulation in winter, which are typical for the region (Panayotov 2007), or fungal diseases and insect attacks. They can cause sudden and long-term growth decreases during which trees do not reveal a clear climate-forced signal (Swetnam et al. 1985; Schweingruber 1996). Stefanoff (1939) reported serious fungal damages in high altitude *P. sylvestris* afforestations on Vitosha Mountain during the first decades after planting and suggested that they could compromise future growth. In our study period, we did not observe clear signs of fungal or insect attacks, but we cannot exclude their presence in previous decades.

Tree-ring features and climate extremes

The occurrence of light rings in our tree-ring series can provide an additional and more detailed insight in the effect of unusual climate events such as droughts or exceptionally cold periods. At the LOW and MID-L sites the highest frequencies of light rings (e.g., 1946, 1993 and 2000) occurred in years, in which the August PDSI values were the lowest (Fig. 9). Yet, there were years with high frequencies of light rings that were not matched by low PDSI values (e.g., 1918, 1928, 1987, 1988, 1996 and 2003). In most of these cases, the PDSI index calculation routine did not show continuous dry periods either because monthly data failed to adequately represent actual precipitation-free periods, as in 1918, 1928, 1987, 1996 and 2003, or precipitation quantities were higher and temperatures lower in July (e.g., 1988). A review of daily meteorological records for these years (Table 5) showed that there were long precipitation-free periods with a duration of at least 1 month, mainly in July–August. The precipitation data at monthly resolution, however, did not show low extremes because rainfall occurred at the beginning of 1 month (e.g., July) and in the middle or end of the next one (e.g., August). A possible explanation for the high frequencies of NLRs in dry years is that moisture deficiency in the period when latewood cells were forming and lignification was being completed, seriously affected these processes. Water shortage and stress are known to strongly influence cell metabolism and division and thus have an impact on tree-ring formation (Whitmore and Zahner 1967; Antonova et al. 1995). In analogy with studies of tree-ring formation in coniferous species at sites with similar ecological conditions, we expect that latewood cell production

Table 5 Climate anomalies in years with high frequencies of tree rings with unusual anatomical structure

Tree ring feature	Years	Chronology	Climate anomaly				
			August PDSI value	Rank August PDSI		Precipitation free period in June–August	Frost event in May–June
				Positive ranking	Negative ranking		
Light rings	1905	LOW	−1.72		24		
	1918	LOW	−3.81		4	15 July–13 August	
	1928	LOW	−2.48		13	No precipitation July	
	1946	LOW; MID-L; MID-H	−4.26		1		
	1965	MID-L	−1.52		26	21 July–16 August	
	1976	MID-H; HIGH	4.97	4			
	1987	LOW; MID-L;	0.39	45		19 June–12 August	
	1988	LOW; MID-L;	−1.92		22		
	1993	LOW; MID-L;	−3.45		6		
	1994	LOW	−2.76		10		
	1996	MID-L	0.85	34		15 June–15 July	
	2000	LOW; MID-L; MID-H	−3.88		2	No precip. August	
	2003	LOW	−1.44		27	14 July–27 August	
Narrow rings	1918	LOW	−3.81		4	15 July–13 August	
	1957	HIGH	1.00	30			
	1969	LOW; MID-H	−0.88		39		
	1987	LOW; MID-L; MID-H	0.39	45		19 June–12 August	
	1988	LOW; MID-L; MID-H	−1.92		22		
	1989	HIGH	0.68	39			
	1993	LOW	−3.45		6		
	1994	LOW	−2.76		10		
	1996	MID-L	0.85	34		15 June–15 July	
	2000	LOW; MID-L; MID-H; HIGH	−3.88		2	No precip. August	
	2003	HIGH	−1.44		27	14 July–27 August	
IADF	1950	MID-L	−3.12		7	8 June–18 July; 17 July–21 August	
	1952	MID-L	−3.46		5	28 May–20 June 25 June–17 July	
Frost rings	1915	LOW					19.05; Sofia +2.0 °C
	1916	LOW					22.05; Sofia +2.6 °C
	1917	LOW					24.05; Sofia +2.4 °C
	1941	MID-L; MID-H					14.05; Sofia −0.6 °C; Aleko −5.0 °C
	1942	MID-H					6.05; Aleko −6.5 °C
	1944	HIGH					24.05; Aleko −7.6 °C
	1947	MID-H					09.05; Sofia +6.0 °C; Aleko −2.0 °C
	1952	HIGH					19.05; Sofia −0.5 °C; Cherni vr. −11.0 °C
	1955	HIGH					24.05; Sofia +1.4 °C; Cherni vr. −8.7 °C
	1962	HIGH					09.06 Sofia +3.5 °C; Cherni vr. −7.8 °C

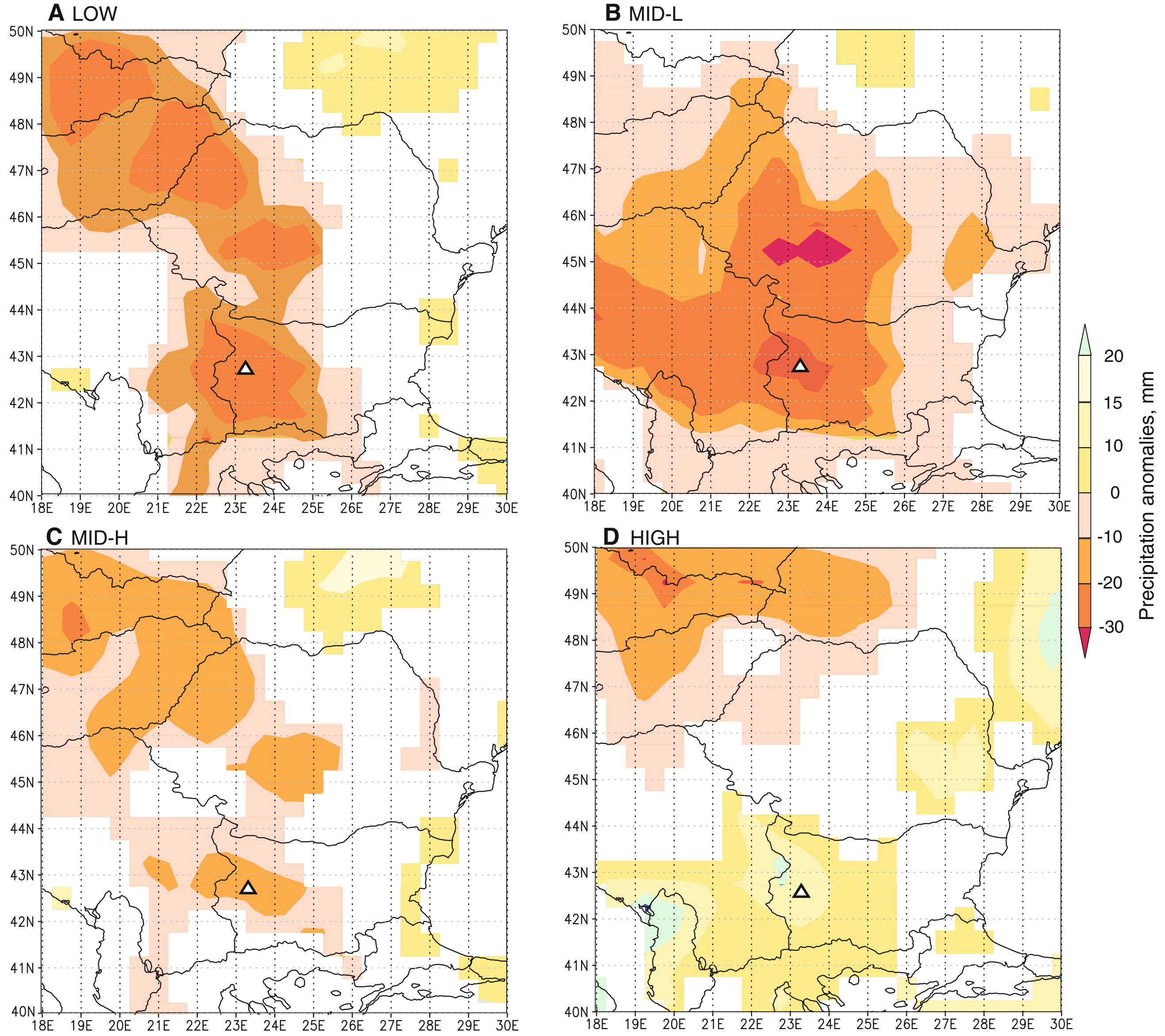

Fig. 8 Composite maps for gridded precipitation anomalies in years with high stabilized frequencies of Narrow rings (NR) in: **a** chronology LOW; **b** chronology MID-L; **c** chronology MID-H and **d** chronology HIGH. Study area is marked with *triangle*

at our sites starts in July, and cell wall thickening and lignification continues into October (Gindl et al. 2001; Camarero et al. 1998; Rigling et al. 2001; Eilmann et al. 2011), but may be terminated earlier due to dry conditions (Thabeet et al. 2009; Gruber et al. 2010; Eilmann et al. 2011). Thus, droughts in July and August may considerably influence the stages of latewood cell production and development. This could result in the production of unusually narrow and “lighter” (in macro observation) latewood and explain the dominance of the NLR subtype of LRs. These results agree with the conclusions of Liang and Eckstein (2006) who showed that, at arid sites in Northern China, light rings with very narrow latewood were formed in years with severe summer droughts.

With an increase in altitude the climatic anomalies that cause the formation of light rings change. In site MID-H the light ring frequencies were high in only 3 years: 1946, 1976 and 2000. All light rings in 1946 and 2000 were of the NLR subtype, but of the LR subtype in 1976. NLRs in these years were caused by the exceptionally dry end of the summers, revealed also by very low PDSI values in our dataset. In contrast, the coldest summer at the Cherni Vrah climate station was recorded in 1976. The average June–August temperature in this year was 5.2 °C, which was 2.3 °C below the mean for the period 1961–1990 (Panayotov 2007). The August value (3.9 °C below the mean temperature) was the lowest on record. This year was also notable for very high summer precipitation and

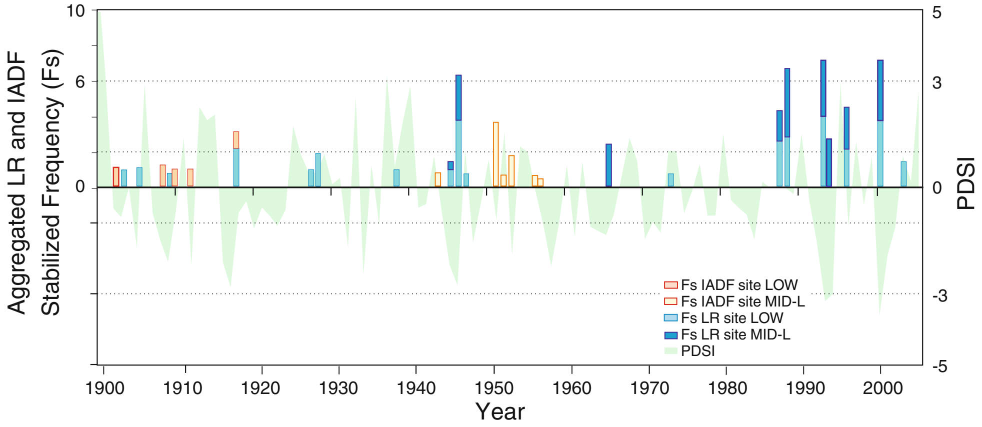

Fig. 9 August Palmer Drought Severity Index (PDSI) values calculated for Sofia climate station and stabilized frequencies (F_s) of light rings (NLR) and tree rings with intra-annual density fluctuations (IADF) at sites LOW and MID-L

consequently for very high PDSI values (Fig. 9). We therefore consider a short growing season with unfavorable (e.g., cold and cloudy) climate conditions to be the probable reason for light ring production in 1976, as also demonstrated by other studies of light ring formation at high altitude or latitude sites (Filion et al. 1986; Yamaguchi et al. 1993; Gindl 1999; Hantemirov et al. 2004). An increase in the 1976 LR frequency from site MID-H to site HIGH, where most of the trees formed LRs, supports this hypothesis. The other year with higher LR frequency in site HIGH (1959) has also been described as a year with a colder than usual summer, which caused production of light rings at treeline locations (Panayotov and Yurukov 2007).

The IADFs at sites LOW and MID-L were not so frequent but give additional insight in drought-induced growth limitations at lower altitudes. In the years with the highest frequencies of IADFs (1950 and 1952), August PDSI values were anomalously low, -3.49 and -3.39, respectively. IADFs, named “false rings” in earlier studies (Cherubini et al. 2003), have been attributed to water deficiency (Schulman 1939). Rigling et al. (2001) reported that cool-moist conditions in July and August following a drier period earlier in summer were one of the primary reasons for IADF formation in a dry inner Alpine valley. A study of De Micco et al. (2007) confirmed that IADFs are formed during drought periods and the authors pointed out that the cells in the IADF zone looked like typical latewood cells, but differed from latewood in having a significantly higher content of δ^{13}C and suggested the reason for this was drought-induced stomatal closure during their formation (De Micco et al. 2007). The IADFs in our samples occurred as a distinct layer within the latewood (Fig. 3c, d) and we hypothesize that the water-shortage conditions that caused this intra-annual feature must have occurred within the period of active cell division or the period of latewood lignification. A detailed review of the daily meteorological records for 1950 and 1952 revealed very low precipitation in June and at the beginning of July, followed by short precipitation and then another dry period at the end of July and the entire month of August (Table 5). It is questionable why IADFs, but not NLRs, formed in these years, as in other dry summers. A possible explanation is the long precipitation-free periods at the beginning of summer, followed by short periods with rain, as suggested by Rigling et al. (2001). This could lead to reduced cambial activity, resulting in a decreased rate of cell production in June, when *Pinus* trees in xeric sites are normally in a phase of active tracheid formation (Gruber et al. 2010; Eilmann et al. 2011), followed by a recovery after the moist conditions in the second half of the summer. Later, the dry conditions in August might hinder the normal lignification of cell walls and thus cause the light band in the latewood of the tree rings. In contrast, the years with NLRs were often characterized by normal precipitation in June (with exception of 1987) and long dry periods in July and August (Table 5).

Changes in frost ring frequency provide additional evidence for increased influence of the temperature regime at the higher-altitude sites. FR frequencies were rather low in LOW, MID-L and MID-H sites, but they were higher in the HIGH chronology. The meteorological data from years with frost rings in our chronologies showed that they occurred when there was a sudden temperature decrease in May and, in rare cases, at the beginning of June (Table 5). In order to injure the newly formed tracheids, these frost events must have happened after the start of cambial activity (Glerum and Farrar 1966; Hantemirov et al. 2004). We did not study the onset of cambial activity in detail, but in analogy with other studies we expect it to start after the middle of April at xeric sites (Antonova et al. 1995; Gruber et al. 2010; Eilmann et al. 2011) and at the beginning of May at high altitude sites (Rossi et al. 2003, 2008; Gruber et al. 2009). This is why we consider that frost events recorded at the beginning of May at lower altitude sites or in the middle of May at higher altitudes could have damaged cambial cells and newly formed tracheids. This would explain the usual position of the zone with buckled cells at the beginning of the tree rings (Fig. 3e). The exceptional position of the layer with deformed cells in 1962 (Fig. 3f), which was found within the earlywood but not at its beginning, is an indication of a later frost event. Indeed, in this year, the frost happened on 9th June, which was about 15 days later than the other cold spells that triggered frost rings at the treeline zone (Table 5). FRs were also found in tree-ring series from other species (*Picea abies* L. and *Pinus peuce* Griseb.) from high altitude locations in Bulgaria, thus providing an indication that the observed frost deformations were not specific only to the described sites or species (Panayotov 2007; Panayotov and Yurukov 2007).

Conclusions

Our study demonstrates that tree-ring width analysis alone may be limited in its recording of the actual impact of climate on tree growth and physiology. Tree-ring morphology, i.e., wood anatomical structure, better reflects extreme climatic events than ring width, because the short duration of such events may only affect a portion of the produced cells in the tree-ring, thus causing a specific feature.

In our study, summer drought caused formation of light rings with very narrow latewood, narrow rings and rings with intra-annual density fluctuations at low-altitude sites, whereas at mid-altitude mountain sites, it induced the production of narrow tree rings with normal latewood. The period during which the drought occurred was decisive for the type of cambial reaction and resulting anatomical feature. Frosts at the beginning of the growing period mostly affected trees at higher altitudes, causing frost ring formation. Unusually cold temperatures in July and August were the most likely reason for light ring production at these sites. Often these climatic extremes were reflected in tree-ring morphology, but not revealed in monthly climate data.

Our results show that simultaneously analyzing tree rings at the lower and upper distribution limit of a species, in our case *P. sylvestris*, may provide information about the occurrence of extreme climatic events of different types. Such data could be particularly valuable for obtaining proxy records for periods without instrumental measurements and for further understanding climate variability in a specific region.

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