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Tree ring chronology of *Pinus peuce* from the Pirin Mts and the possibilities to use it for climate analysis

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Abstract. In this article the authors present a 300-year tree-ring chronology of *Pinus peuce* from a treeline site in the Pirin Mts in Bulgaria. The possible climate that influences tree-ring growth is discussed, as well as the reasons for occurrence of frost and light rings. On the basis of our results, we have concluded that radial growth depends mostly on the temperature regime of the preceding vegetation period and the current summer. The reason for formation of frost rings is abnormally sharp cooling at the treeline zone, with temperatures dropping below the freezing point at the end of May or at the beginning of June. Light rings form in years with very low average summer temperatures or short vegetation period. Severe droughts during the growth period may also cause decreased radial growth and consequent narrow rings.

Key words: dendroecology, frost rings, light rings, *Pinus peuce*, Pirin Mts, tree rings

Introduction

Treeline ecosystems are among the most sensitive to environmental changes (Lloyd 1997; Korner 1998; Moiseev 2002; Camarrero and Guitierrez 2004; Esper & Schweingruber 2004). This is one of the reasons, why many studies of the influence of climate and climate change focus on treeline forests. For this purpose, dendroecological methods are some of the frequently used research methods (Fritts 1976; Schweingruber 1996; Briffa & al. 2001). They are based on the concept that tree-ring formation is strongly dependent on environmental factors and especially on the varying temperature and precipitation (Fritts 1976). Trees at treeline grow at limiting temperatures and thus are very sensitive to general variation of temperatures and extreme climate events (Fritts 1976; Tranquillini 1979; Schweingruber 1996; Frank & al. 2005). This, along with the fact that once formed, tree rings do not change with time, makes tree-ring chronologies a "natural archive" containing information on past climate and historic development of individual sites. Those studies that focus on treeline chronologies also benefit from the long life span of tree species, sometimes exceeding 500 years (Fritts 1976; La Marche & Hirschboeck 1984; Motta & Nola 1996; Hantemirov &al. 2004).

It is very important to construct chronologies from trees growing on different sites in the context of increasing need for knowledge about the natural ecosystems, their development in the past, the influence of extreme events such as fires, avalanches, storms, droughts, etc. and the changing climate. Despite this, in Bulgaria there have been only a few attempts at collecting and analyzing such data and especially at basing this type of research on trees from the treeline ecosystems. Along with this, there are still numerous very old trees available in the high mountains. This provides opportunities for constructing long tree-ring chronologies and thus facilitates researches on natural disturbance, climate changes and their influence on the ecosystems.

The objective of the present study is to compose and analyze a 300-year tree-ring chronology of Macedonian pine {*Pinus pence* Griseb.) from a treeline location in the Pirin Mts, Southwest Bulgaria. For this purpose, we studied the ring width variations and specific tree-ring anatomical structures such as "frost rings" and "light rings" in relation to climate data.

Material and methods

The study area is situated on the Northwestern slope of Todorka peak in the Pirin Mts, Bulgaria, 41°45'N, 23°26'E(Fig.l).

The sampled trees are located in the treeline belt (2100-2300m). Since the slope is steep and hardly accessible, the forests have not been subjected to intensive logging or deliberate firing by shepherds in the past. Thus, these ecosystems can be regarded as natural. They are dominated by the Balkan endemic species Macedonian pine *(Pinus peuce),* with limited participation of Scots pine {*Pinus sylvestris* L) and Norway spruce [*Picea abies* (L.) H. Karst] at lower altitudes. Above the treeline, the plant communities are composed mainly of mountain dwarfpine *(Pinus mugo* Turra subsp. *mugo)* and Siberian juniper *(Juniperus sibirica* Burgsd.). According to the Oliver & Larson (1990) classification, the forests are at the old-growth stage. They grow on Umbric and Modic Cambisols formed on granite bedrock.

The climate in the region is typically mountainous, with strong influence of Mediterranean air masses. The mean annual temperature (Vihren chalet climate station, 1970m) is 3.5°C. It ranges from a mean monthly temperature of-4.7°C in January to +12.2°C in August. The annual temperature at the treeline, obtained by extrapolation from the Vihren chalet data, is 1.6 °C, 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; Dakov & al. 1980; Korner 1998) and is an additional indicator that the forests on the Northwestern slope of Todorka peak were not disturbed intensively in the past. The annual precipitation amounts to 1378 mm, with a maximum in autumn and winter. Deep snow covers are characteristic for the region. It is appropriate to note that the absolute maximum snow depth for Bulgaria (472 cm) was recorded at Vihren chalet station.

A total of 57 samples, one core per tree, were collected with increment borer. They were taken at breast height (1.3 m) from dominant trees. Cores were mounted on wooden boards and sanded to make possible the distinguishing of separate cells. Ring widths were measured at the Dendrochronology Laboratory in the University of Forestry in Sofia. In order to facilitate further statistical analysis, tree rings with specific anatomic features (e.g. "early- and latewood frost rings", "light rings", "wounded rings", "rings with reaction wood") were recorded, photographed and coded with number codes. Obtained tree ring-width series were crossdated to assign the calendar year of formation of each annual ring with the use of visual clues (Stockes & Smiley 1968) and the computer program COFECHA (Holmes 1983). Then the data was standardized with the software package ARSTAN (Cook 1985) using modified exponential and liner functions. The final chronology was composed by calculating bi-weighted robust means of annual ring widths. This, as well as the calculation of standard descriptive parameters, was performed with the ARTSAN software.

Fig. 1. Geographical position of the study area.

The event years with narrow or wide tree rings, which can be particularly useful to analyse the influence of extreme climate events, were identified according to a methodology proposed by Cropper (1979). Event value indexes were calculated by dividing residuals from a five-year moving average for a specific year by the standard deviation of the same period. Indexes with values below -0.75 or above 0.75 were selected as possible indicators of pointer years (i.e. years with narrow or wide rings in the majority of samples from the site). After validation with tree-ring series as a threshold level for determining a year as a "pointer year", a limit of 50% was selected (i.e. years, in which more than 50% of samples displayed an "event year"). This methodology enables the statistical determination of rings, which visually look as "narrow" or "wide" in comparison with the neighboring ones and thus the obtained pointer years can also be used in the procedure of crossdating new cores.

Climate data for the analysis was obtained from Bansko (936 m) and Vihren chalet (1970 m) climate stations. The first one is at the foot of the valley, 10 km off the study area and provides continuous data for a period of more than 70 years (since 1931). The second was situated at the base of the Northwestern slope of Todorka peak and operated for 25 years. Data from it was used to obtain average temperature and precipitation values and more precise information about some specific climate situations like frost days in the summer, intensive snowfalls, etc. Data from Sofia climate station (550 m), which has the longest climate record in Bulgaria (since 1887), was used for comparison with pointer years prior to 1931. Although this station is about 100 km away from the study area, it is representative for the general meteorological situations in West Bulgaria and especially for cases with severe droughts and unusually cold periods.

The analysis of the climate-growth relationship was performed with DENDROCLIM2002 software (Biondi & Waikul 2004), using average monthly temperatures and precipitation sums for months from June of the year prior to growth to September of the current year.

Results

The chronology (Fig. 2) was composed of cores from 27 trees that showed no signs of avalanche disturbance (e.g. without broken stems, reaction wood, and numerous growth decreases) (Table 1). Cores from trees with such signs were used only for obtaining data for frost ring occurrence. The first year included in the chronology is 1700. Segments before that year were disregarded in order to avoid low replication. The oldest studied tree had 614 tree rings in its core. Segments before 1700 AD from such samples were used only for detection of tree rings with specific anatomical structures like frost rings and light rings.

Table 1. Main statistical and descriptive parameters of the chronology.

Year span	305
First year	1700
Last year	2004
No. of trees	27
Mean ring width (mm)	0.114
Standard deviation	0.040
Autocorrelation (1 st)	0.771
Mean sensitivity	0.175

Pointer years with narrow ring (negative pointer years) estimated by the methodology of Cropper are: 1734, 1776, 1836, 1867, 1876, 1909, 1919, 1929, 1947, 1960, 1977, 1982, 1989, and 2000.

Pointer years with wide rings (positive pointer years) are 1788, 1807, 1822, 1852, 1870, 1874, 1877, 1889, 1910, 1917, 1928, 1956, 1970, 1973, and 1999.

Years in which earlywood frost rings were found (Fig. 3) are 1548, 1818, 1824, 1860, 1888, 1903, 1921, 1928, 1933, 1947, 1952, 1955, 1962, 1989, and 1997.

Years, in which frost rings were detected in more than two cores are 1921,1928,1933,1947,1952, 1962, and 1989 (Table 2). These years are of particular interest for the analysis, since this information can be taken as a sign of reaction, which can be considered specific for the site rather than for a single individual.

Years with light rings (Fig. 3) are 1933, 1959 and 1976. Of these, very prominent is 1976 in which light rings were found in 29 % of all cores.

The correlation analysis (Fig. 4) shows statistically significant positive influence of temperatures on

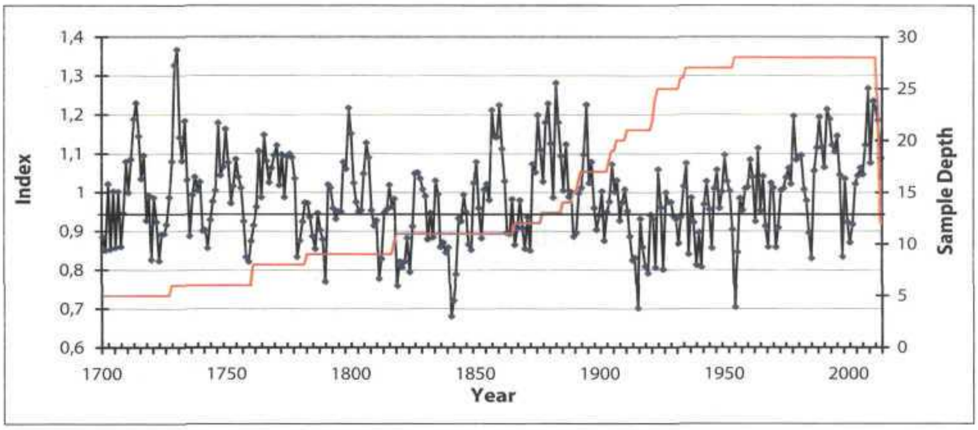

Fig. 2. Chronology of *Pinus peuce* from Todorka peak, Pirin Mts.

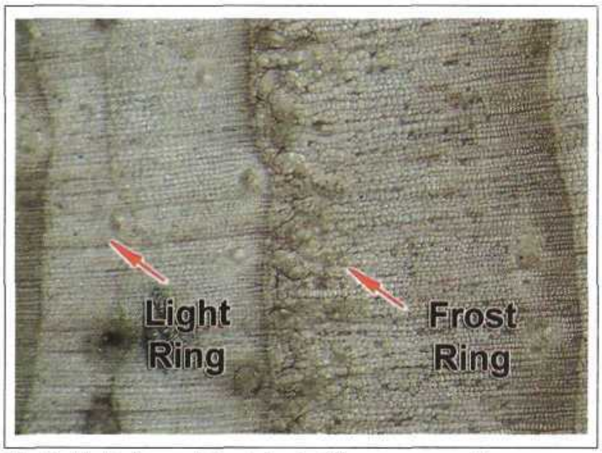

Fig. 3. Light ring and frost ring in *Pinus peuce* wood.

Table 2. Earlywood frost rings and light rings.

Year	Number of sampled trees	Percent of sampled trees that have frost ring	Percent of sampled trees that have light ring
1921	40	13	–
1928	43	5	–
1933	43	5	10
1947	47	7	-
1952	48	19	-
1959	50	-	8
1962	50	18	-
1976	52	–	29
1989	57	5	–

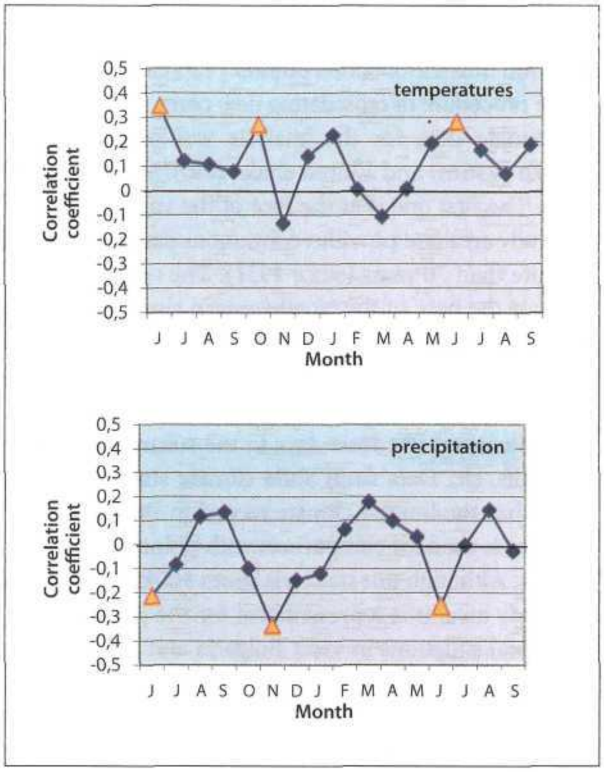

Fig. 4. Correlation coefficients for the tree growth–climate relationship. Statistically significant values are marked with triangles.

growth from the beginning and the end of the previous vegetation season (June and October) and the respective summer (June). Influence of high precipitation during the growth period is negative. This is most probably due to the negative relationship between precipitation and temperatures values (correlation of average June-August monthly temperatures to precipitation sums is -0.52, $p<0.05$), especially in years with extremely high precipitation in summer, such as 1940, 1947, 1949, 1959, 1976, 1983, 1989, 1995, and 2002.

Discussion

Chronology characteristics and climate forcing

The chronology descriptive parameters show that the average tree ring width is relatively low (0.140mm). This reflects the fact that the majority of the cores were taken from older trees that have overpassed the initial period of intensive radial growth. The 1-st order autocorrelation (0.771) indicates a strong influence of growth from the previous year on the radial increment of the present one. This is typical for some treeline species (Fritts 1976). The mean sensitivity (0.175) that expresses the variability between adjacent annual rings is close to the one of *Pinus cembra* chronologies from the Italian Alps (average value 0.100, ex Motta & Nola 1996) - a tree species that is systematically close to *Pinus peuce* and grows in ecosystems in similar climate conditions.

The correlation analysis indicates that the temperature regime of the vegetation season is of major importance for the radial growth. This is expected at treeline and falls in agreement with studies on radial growth of trees in this zone (Fritts 1976; Schweingruber 1996). Positive influence of high temperatures from the beginning and end of the previous growth season shows that the length of the vegetation period affects tree development in the following season. Accumulation of carbohydrates and other substances needed for radial growth and development of more buds stimulates fast growth start at the beginning of the next vegetation season and thus the formation of wide tree rings (Fritts 1976).

The chronology shows consecutive periods with high and low radial growth rate, with several more distinct and longer periods with low indices: at the second half of the 18th century (1770s and 1780s), the first half and the middle of the 19th century (1810s, 1830s and 1860s), and the first half of the 20th century (1910s). Another Macedonian pine chronology (Vakarelov & al. 2001) also indicates low growth at the first half of the 20th century, but does not show the same trend in the first half of the 19th century. This is possibly due to the use of less sensitive (from the valley bottom) and younger trees in the composition of that chronology and consequent lack of a distinct reaction to possible unfavorable growth conditions in the stages of youth of the trees.

The periods of low and high growth are most probably associated with long and short-term variability of temperatures as shown by a number of studies (Fritts 1976; Briffa & al. 2001; Esper & al. 2005; Frank & al. 2005). Some of them may be related to large volcanic eruptions like the one of Tambora (1815) and consequent cold years in Europe (e.g. "1816 - the year without a summer", ex. Rampino & al. 1988). In the presented chronology, 1815 has a very low index of radial growth and this trend remains until 1820. Since the Tambora eruption had an effect on the climate of most of the Northern Hemisphere and had caused serious cooling (Rampino & al. 1988; Mann & al. 2000), probably the low radial growth during the period 1815-1920 in the presented chronology is related to it. Another negative pointer year that might be associated with a large volcanic eruption is 1836. It is one growth season after the large eruption of the Cosiguina volcano. These two eruptions are with very high volcanic explosivity indexes (VEI), which is closely related to the amount of sulfate aerosols injected in the atmosphere and stratosphere and to the subsequent short-term summer cooling in the Northern Hemisphere (Robock 2000).

At the same time, some atmospheric processes might have different influence over the neighboring regions and therefore cause dissimilar short-term climate variation. For example, the summer of 1976 was the coldest one in the Bulgarian mountains for the whole 20th century. It was characterized by higher than normal precipitation, while the year was noted as very dry in Central Europe (Schweingruber 1996). The effect of these cold and wet summer conditions was the production of narrow "light rings" in many *Pinus peuce* trees. The reflection of such short-term climate differences in the neighboring regions in tree-ring characteristics makes possible the studying of climate variations by comparing local tree-ring chronologies.

To obtain more precise information about the climate influence on the tree-ring formation, it is very useful to analyze not only the overall relationship of ring-width variability with climate data, which is expressed by the correlation analysis, but also to study the pointer years of different types (e.g. very narrow or wide rings, light rings, frost rings). Often, they present a clue for extreme values of temperature or precipitation and for unusual climate events (La Marche & Hirschboeck 1984; Schweingruber et al. 1990; Stockli & Schweingruber 1996; Gindl 1999; Hanetemirov & al. 2004).

Climate significance of pointer years

In order to obtain information about the relation of negative or positive pointer years to climate, we have reviewed the available climate data records. Special attention was dedicated to temperatures at the beginning or the end of the preceding and the respective vegetation periods. As it has been already demonstrated by the correlation analysis, they have the strongest overall influence on the radial growth.

The negative pointer years in the chronology are associated either with the very low temperatures in June or July of the respective year (e.g. 1960 and 1989), or of the preceding summer (e.g. the negative pointer years of 1960 and 1977 after the cold summers of 1959 and 1976). In one case (2000) the low growth might be associated with an extreme and unusual drought. In that year the overall June-August precipitation (78 mm) in Bansko was much lower than the normal (119mm). This resulted mostly from the low July precipitation (14.5 mm at a norm of 38 mm) and the lack of any precipitation in August. Since there are no data for other possible reasons for the low growth as, for example, insect attacks, the long period with low precipitation is a logical explanation of the frequent narrow tree rings. That particular summer was generally very dry in the whole country and caused low growth also in other treeline species like Norway spruce (Panayotov 2006). On the basis of our data we cannot identify the possible reasons for the low growth in 1947 and 1982. In 1947, there was high precipitation in June and July, but no extreme values were recorded. The temperatures in the high mountains were not lower than normal. The June-August precipitation of the two preceding years (1945 and 1946) which were considered drought ones in Bulgaria (Koleva & al. 2003) was lower than that of the adjacent years. At the same time it is uncertain whether this could be the only reason for a negative pointer year in cores from a treeline forest, growing on a shady NW slope. In 1981 and 1982, the temperatures and precipitation were close to the normal values. Yet, 1982 was with high frequency of narrow tree rings. That year was famous as an "El Nino" year, but the review of climate records does not reveal any unusual values. Nevertheless, since we were able to analyze only the mean monthly temperatures and the total monthly precipitation sums for that period, we cannot be sure whether there was not a longer period with low precipitation, which could be lost as information in a monthly sum due to a single more intensive rainfall.

The positive pointer years can be associated with normal winter and summer temperatures and precipitation (e.g. 1956, 1970, 1973, 1999), combined with higher spring temperatures (e.g. 1970) or higher temperatures during the preceding summer (e.g. the pointer years of 1956 and 1999 after the warmer summers of 1955 and 1998).

Information about the climate data in the pointer years agrees with the conclusions drawn from the correlation analysis. They also confirm the opinion of Vakarelov & al. (2001) that ring-width variation in Macedonian pine is highly dependent on thermal conditions during the vegetation period. At the same time, this analysis reveals that strong droughts may have a negative impact on the radial growth of treeline trees, which is concealed in the correlation analysis.

Climate significance of frost rings

The climate situations at the beginning of the growth season (May and June) were examined for those years with high frequencies of earlywood frost rings. For this purpose were used the bulletins published by the National Meteorological Institute, with daily temperatures (07,14 and 21 h) for the years from 1887 to 1984. Data for the periods before the 1930s (when the climate stations in the high mountains started to function) were used for Sofia climate station only.

A review of the climate situations in the years with earlywood frost rings shows periods with unusual cooling at the end of May, or at the beginning of June.

In 1962, the temperatures in May were normal for the month, while at the beginning of June there was a sudden cooling with a drop of temperatures down to 3.2 °C in the valleys (07.06.1962, Sofia climate station, 550 m a.s.l.) and -12 °C in the highest parts of the mountains (Moussala peak, 2925 m). In the treeline zone, the temperatures were under -6 °C (Vihren chalet climate station, -5.5 °C). In our opinion the normal climate in May had favored the start of the cambial growth. Then the sudden and sharp cooling at the beginning of June caused frost and injury of the cambium and the newly-formed tracheids. This resulted in the occurrence of the characteristic for the frost rings layer with buckled cells as a separate isolated stripe inside the earlywood (Fig. 5). The beginning of May 1952 registered normal temperatures for that period of the year. Then on 19th May there was a sharp cooling with temperature drop in the valleys down to 0.4 °C (Sofia climate station) and -15°C in the highest parts of the mountains (Moussala peak climate station). The frost injury is found at the beginning of the earlywood (Fig. 6), which could be explained by the earlier date of the temperature anomaly.

In 1947 the meteorological situation was quite similar to the one in 1962. It was characterized with normal temperatures in May and frost conditions in the beginning of June (-6.3 °C on 08.06.1947, Moussala peak station). Data for 1933 are limited to records collected in the valleys and several mountain stations. They show decrease in

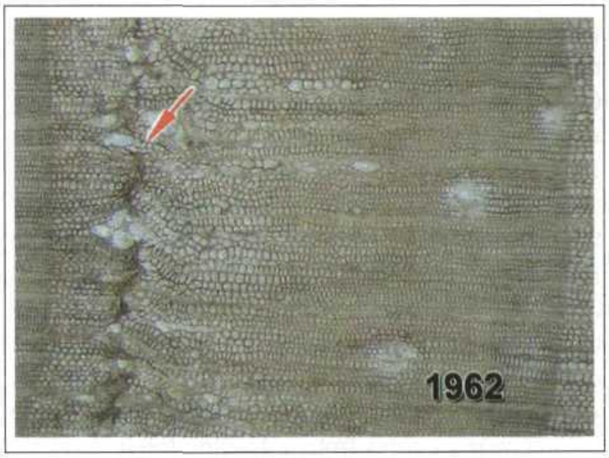

Fig. 5. The 1962 earlywood frost ring.

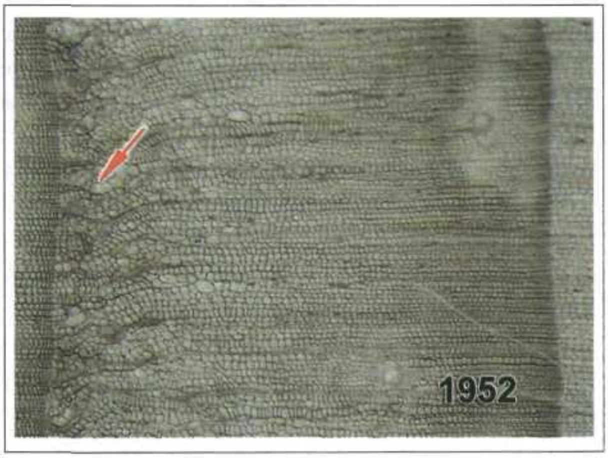

Fig. 6. The 1952 earlywood frost ring.

temperatures at the beginning of June (06.06.1933, Sofia station, +2.9°C; Boeritsa chalet station, 1700m, -3.2°C). There are no data for the highest mountain stations, but since the temperatures below the treeline (Boeritsa chalet) were negative, it could be expected that in the treeline zone they were even lower. The information for 1928 (available only for the climate stations in the valleys) shows a strong decrease in temperatures, down to +2.8°C in Sofia (15.05.1928). Analogically to the other years with frost events, it can be expected that at in the treeline zone the temperatures were negative.

Data on the climate situations during formation of the frost rings fall in agreement with the conclusions drawn by other studies focusing on earlywood frost rings from trees at the treeline or higher-latitude sites (Stockli & Schweingruber 1996; Hantemirov & al. 2004). These studies show that this anatomical feature forms in periods with unusually cold early summer. Our conclusions based on this first analysis of frost rings in Bulgaria also show that such data from tree-ring chronologies can be successfully used to obtain information about events with unusually cold periods at the end of May, or at the beginning of June. This could be particularly useful for years without instrumental climate measurements.

Climate significance of light rings

Light rings are characterized by reduced cell wall thickness and lignification in the latewood (Filion & al. 1986; Gindl 1999). Studies have shown that in the treeline zones these tree rings occur in years with low summer or early spring temperatures and, possibly, reduced radiation (Filion & al. 1986; Gindl 1999; Hantemirov & al. 2004). This is the reason why light rings were used as indicators of such growth conditions.

The most prominent light ring in the series from Todorka peak is found in 1976. That year was notable for its very cold summer. It was characterized by the lowest August monthly temperature for the entire period of climate data recording. The June and July temperatures were also lower than normal. The precipitation in August was also very high: 167 mm were recorded in the nearby Vihren chalet climate station. This amount was more than twice higher than the average 67 mm. In our opinion, the combination of much lower than normal summer temperatures and higher precipitation is the reason for limited growth in the period of latewood cell formation, cell-wall thickening and lignification.

Climatic data for 1933 were available for Sofia climate station only. They show a much colder September (14.1 °C at a norm of 16.1 °C), a slightly colder July and August and unusually heavy precipitation in May (169 mm at a norm of 73 mm). Several trees have formed frost rings. This, as discussed above, is an indicator of frost conditions at the beginning of summer. This climate situation slowed down the cambial activity and tree-ring formation and increased the effect of low early-autumn temperatures on the process of latewood cell-wall lignification.

In 1959 the temperatures of June, August and September were lower than the normal ones. That slowed down the overall rate of cell-wall formation and completion and therefore caused the light ring formation.

Our data show that the years with light rings were characterized by lower average summer temperatures, or shortened growth periods. This agrees with the conclusions of other researches about the causes of light ring formation at the tree line (Filion & al. 1986; Gindl 1999; Hantemirov & al. 2004).

Conclusions

This study is a step towards the establishment of longer and reliable treeline chronologies from the Bulgarian mountains. It demonstrates the influence of temperature and precipitation regime and especially of their extremes on tree-ring formation. Particularly important are the temperatures from the previous growth season and the beginning of the present one.

The analysis of frost and light rings indicates that in the Bulgarian mountains these tree rings were formed at similar conditions as in other high mountains in the world. This makes possible to compare the climate situations in different geographic regions, which could be particularly useful for periods without instrumental measurements.

The list of frost rings, light rings, negative and positive pointer years may prove particularly valuable for future dendroecological research, since these are among the most widely used types of tree rings for the procedures of crossdating.

Finally, we state that further collection and adding of more cores from older trees will extend the chronology and make it more reliable. This will allow various analyses of the climate change on the Balkan Peninsula, forest ecology in old-growth forests, and restoration of the regime of disturbance events, such as avalanches, fires and windthrows.

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