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A comparison of extreme conditions at the southern and polar Ural, using frost rings in wood of Siberian spruce

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Introduction

The Ural Mountains, located at about 60° E longitude and extending over 2000 km north-south is the geologic division between Europe and Asia. The Ural has characteristic climatic zoning which is defined by orographic features and geographic location. Climatic distinctions of the Polar and Southern Ural Mountains are great enough that interactions of air masses, seasonal movement of Arctic and Polar fronts, and an oceanic-continental gradient are all characteristic features.

The most important climatic factors in determining the distinction of ecosystems of the Polar and South Urals are the relative distributions of warmth and moisture. Distinction in thermal balance of the Polar and South Ural Mountains is relatively small in the winter, but a strong radiation gradient during the spring and autumn in the South Ural in comparison with the Polar Ural plays a large-role in the length of the growing season. The duration of snow cover on the Polar Ural is greater than that for the Southern Urals. Intensive thawing of snow during spring leads to over wetting and poor aeration of the soil and further reduces the short vegetative season, typical for high latitudes. Additionally, melting of snow in the Polar Ural is slowed down by frequent snowfalls and frosts. In summer, the radiation balance is approximately identical, as the long day-length in the Polar Ural compensates for the lower radiation intensity. Frosts stop in June in the high-mountain areas of the South Ural, but in the Polar Ural frosts are possible during all months and may occur even towards the middle of the growing season. Summer is colder in the Polar Ural, than in the Southern with average summer temperatures being +11.2°C and +17.8°C, respectively.

The role of solar energy in the Polar and the South Ural Mountains can be broadly differentiated. In the southern Urals, up to 60 % of the radiating energy is used in turbulent exchange. The total amount of heat energy for evaporation doesn't exceed 40 %, because of a small amount of precipitation. In the Polar Ural, on the contrary, humidity is great and up to 70 % of heat is spent on evaporation, and for a turbulent exchange up to 30 %. (Ural & Priurale, 1968).

These distinctions broadly define the climatic features of research areas, including influence on the spatial and temporal occurrences of climatic extremes and on distribution of trees. For example, the upper tree line in the Polar Ural occurs at 300 m elevation above sea level, and in the Southern Urals spruce ascends up to 1360 m elevation. (Shiyatov 1986).

Pathological structures in wood of coniferous trees are formed under influence of climatic extreme events. Low-temperature extremes during a vegetative period lead to formation light and frost rings. Light rings represent a disturbance in formation xylem issue because of long influence of low, yet above freezing, temperatures during second half of vegetation period.

Usually such long cold snaps are observed over a wide spatial range. Frost damages, on the contrary, represent damages of xylem cells under influence of short-term decrease of temperature below 0°C during the period of tree ring formation.
Frosts during the vegetative period damage xylem cells of coniferous trees and as result of this influence we can observe formation so-called frost rings within a tree ring (Kaennel & Schweingruber 1995). Frequencies of frost damages, and their position within the limits of the tree ring, characterize the severity of climatic conditions on tree growth (Gurskaya 2002).

The study's aim was to compare extreme climate conditions of the South and the Polar Ural Mountains using frost rings in spruce wood. The following tasks were conducted to understand the spatial and temporal occurrences of frost damage and to quantify the climatic and weather conditions leading to this damage.

1. To determine and record the occurrence of frost rings in spruce trees growing at upper tree line of the Polar and Southern Ural.
2. To compare the tree age when frost rings form, the position of frost injury within tree rings, and the fraction of damaged annual rings for each year.
3. To compare frost rings and daily meteorological data from the nearest meteorological stations to determine conditions when frost rings form.
4. To build and compare chronologies of frosts, based on the share of frost rings, in the Polar and the South Ural during last 100 years.

Material and methods

Research Area

The study was carried out on forest-tundra ecotone at the upper tree line of Ural Mountains (Fig.1). Two transects were made on upper tree line on south-west slopes of the Polar Ural (66° 55′N, 65° 45′E) and the South Ural (54°32′N, 58° 52′E).

Methods

There are three the altitudinal levels on every profile (Fig.2). The uppermost altitude (1), were single trees grow , was located at 1360 m a.s.l. at the South Ural (SUR) and at 300 m a.s.l. at the Polar Ural (PUR). Here 10 samples of Siberian spruce (*Picea obovata*, Ledeb.) were collected on PUR, and 13 spruces were gathered on SUR. The middle elevational level (2), with generally scattered trees was located at 250 m a.s.l. on PUR and 1300 m a.s.l. on SUR. This elevation has enough trees and here 100 samples at PUR and 92 trees at SUR were collected. The third altitude level (3) represents continuous spruce forest. It is located at 90 m a.s.l. on PUR and 1200 m a.s.l. on SUR. This lowermost level corresponds to the bottom of mountain valley on the PUR. At PUR 100 spruce cores were gathered and 139 samples were chosen at SUR. In total, 210 trees from PUR and 244 trees from SUR were selected for this study.
All sampled trees were growing in forest-tundra ecotone on generally moist sites on south-western slope. Cores were collected 0.2 m above the base of the tree, where the pith was hit for 70 % of the samples. In the cases of a missing pith, the amount of absent rings were

estimated by overlaying a circular grid to more precisely determine the cambial age of all rings. Samples have from 20 up to 110 annual rings with the oldest trees generally found at the uppermost level. The mean age of trees was 80 years.

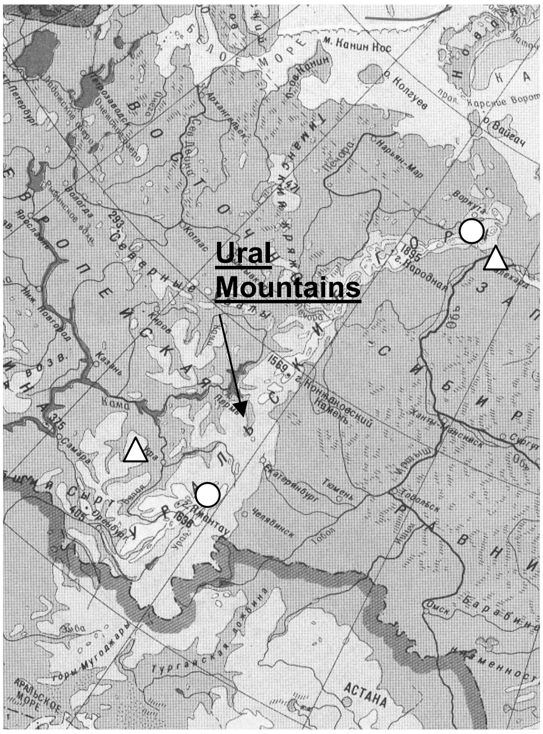

Figure 1: Research area. O: studied sites; - Δ: the nearest meteorological stations

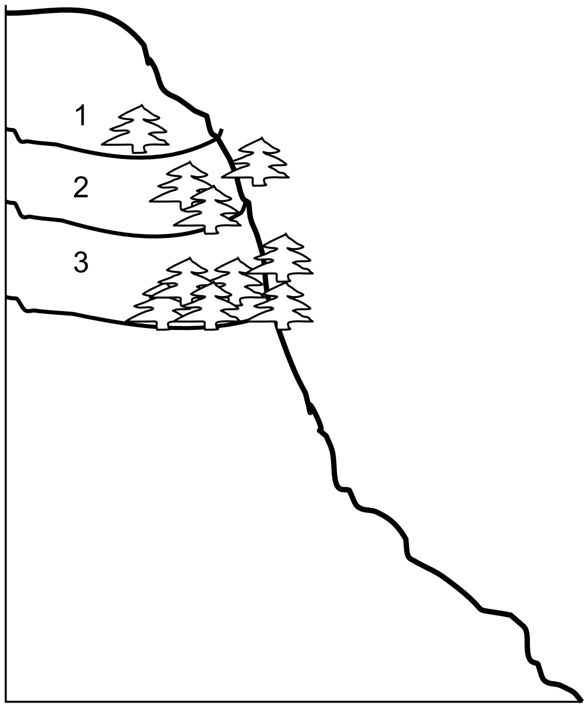

Figure 2: Scheme of transects.

Frost rings were identified on the surface of well polished cores. It is known that frost rings form under the influence of spring and summer frosts. To make the analysis more detailed and accurate, tree rings were divided into three parts: the beginning of earlywood (first 1-2 rows of tracheids, EW0), the remaining portion of the earlywood (EW1), and the latewood (LW). Usually, frost damage, located in the beginning of earlywood, indicate late spring frosts, in the "late" earlywood they reflect early summer frosts, and frost damages in latewood reflect summer frosts (Gurskaya 2002).

Analysis

All wood samples were measured and cross-dated using TSAP. Missing rings were found in some of the older trees. The occurrence and position of frost rings were visually determined.

Meteorological data from the nearest weather stations were used (Fig. 1). In the Polar Ural Salekhard's weather station (66°32'N 66°32'E, 16 m above sea level) is located 60 km from the study site and has observations between1883 to 2006. Ufa's weather station (54.7° N 55.8° E, 136 m above sea level, with data between1900-1995) is located in 160 km from the South Ural site. Average June, July and August temperatures (mean summer temperature) were used to compare conditions of research areas. Days with minimal air temperature during June-July were identified for each year since 1900 to 1995. Minimum, mean and maximum daily temperatures of these days were analyzed.

In this article, we refer to the duration of frosts as the number of continuous days for which the minimal temperature was below 5°C. This temperature corresponds to that when many physiological processes are strongly reduced or cease in trees. It is know, that temperature data were collected in weather stations fixed 2 m above the grounds surface, whereas ground temperatures are generally lower by 2-7°C. The temperature data were not corrected to the altitude of the investigated sites.

Years between 1900 and 2000 were divided into four groups based on the different amounts of frost damage. The first group represents years without frost rings (0 %). Years when less than 10 % of the trees were injured formed the second group, from 10 – 40% were in the third group, and years with injuries in more than 40% of the trees were classified in group four. The following parameters of frosts were analyzed using Student's T-test in the STATISTICA program to test for significant differences between means: minimal, average, and maximal daily temperatures at 2 m height, diurnal daily temperature range per day with frosts, duration of frost (in days), date of beginning of frosts, and average monthly temperatures of June, July and August.

Results

Many researchers mention that frost rings are commonly formed in the xylem of trees during their first 20-30 years (Glerum & Farrar 1966, Stoeckli & Schweingruber 1996, Knufinke 1998, Block & Treter 2001, Gurskaya & Shiyatov 2006). Comparison of tree age, when frost damages stop to form in wood of studied spruces, has shown that this age is characteristic at different elevations along the transect. The longest sensitivity period to frosts is shown for the uppermost level where single trees grow. Frosts damages 70-80 year-old trees on PUR at the first level, and at the third level 35 year-old trees are already capable of resisting frost damage (Fig.3). On SUR differences in the ages of the trees damaged by frosts are not as big as at PUR, but tree age decreases down the slope as well.

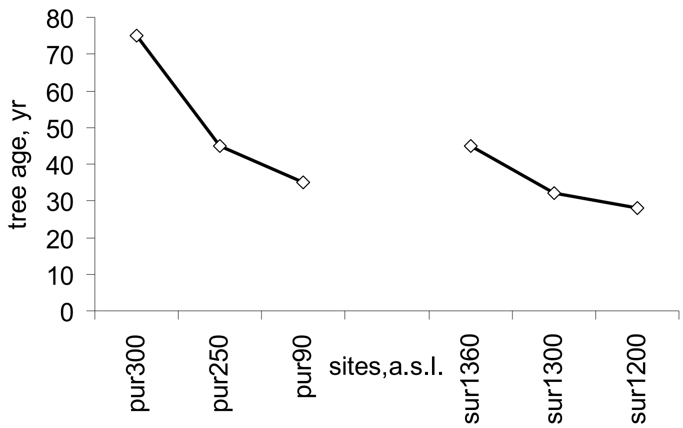

Figure 3: Tree age, after which frost rings in the xylem are no longer found.

Despite the fact that in the Polar Ural trees have a longer period of frost sensitivity than those in the Southern Ural, the total amount of damaged rings for this period of tree life is less. On PUR the share of the damaged rings varies from 2 –7%, and on SUR between 8 – 10 % of the total amount of the rings during the tree's period of sensitivity to frost. The total share of frost damages on every elevation level is greater in the South Ural in comparison to the Polar Ural (Fig.4).

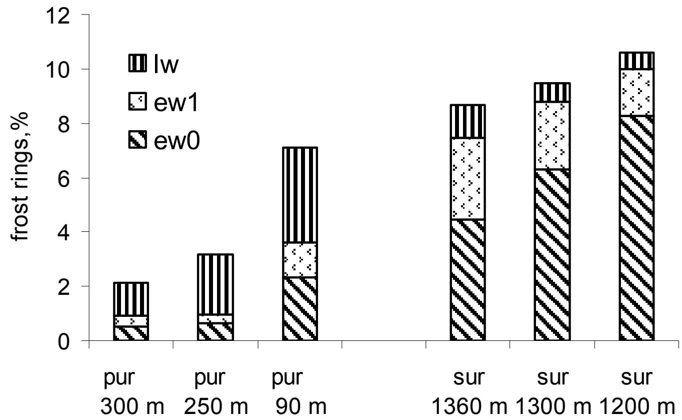

Figure 4: Percentage of frost damage on study's two profiles.

The frequency of damaged tree rings increases down slope at both locations. With the greatest quantity of frost damages found at the lowest site on SUR. On PUR maximum frost damages are also found on the lowest altitude. Here, the total amount of damages is about 2 times greater in comparison with the uppermost and middle elevations. These trends in quantity are systematic for all ring sub-divisions (EW0, EW1, LW). In spruce on PUR, frost damages in LW are more prevalent in comparison to those in EW0 or in EW1. The sum of frost damages in EW0 and EW1 is comparable to the quantity in LW alone. PUR's two top levels have a few years when frost rings are obtained but not found in the lowermost site.

On the contrary, in tree rings of spruce from the South Ural frost damages are most prevalent in the EW0 zone. The greatest contribution to the increase in quantity of damages downhill on SUR is reflected in EW0 damage. Frost injuries in EW1 zone of tree ring are much more rare in comparison to the EW0 frost rings. In SUR's LW the amount of such damages is lower in comparison with frost damages in EW1 zones and frost damages in LW in wood of trees from the Polar Ural.

Considering the highest frequency of frost rings, only the third altitudinal levels of the studied profiles were taken to develop subsequent frost ring chronologies. Frost ring chronologies are constructed in the following way. The maximal tree age, when frost damages are no longer found, has been determined for each profile at the lowermost (third) level. This age is 35 years on PUR, on SUR it is 30 years old. The amount of rings in these age-classes is known and is then considered as the sample size for each year. The number of such tree ages for every year was 20-30. Finally, the percentage of damaged tree rings from the total amount of "juvenile" rings for every year has been calculated.

A comparison of the resulting PUR and SUR frost-ring chronologies is shown in figure 5. There are periods when frost damages occur often and synchronously both on PUR and on SUR, but also periods when frost damages form only on one of the two profiles. Furthermore there are also periods with a very low incidence of frost damage.

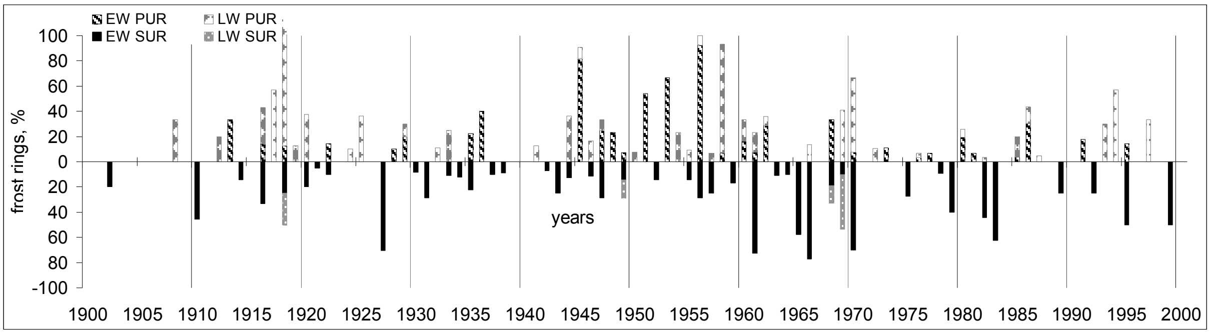

Figure 5: Comparison of frost damages between PUR and SUR chronologies.

Overall, in the Polar Ural frost damages occur more often than in the Southern Ural. On third level of PUR, 70% of the years for the last 100 years are characterized by conditions severe enough to lead to frost ring formation. In the Southern Ural, 40 % of years are characterized by such extreme conditions. Thus, years with extremely strong frosts (when frost damaged more than 40 % of trees) are more often observed on the Polar Ural. Frost damage was most frequent and intense in both chronologies during the following decades: 1910-1920, 1940-1950, 1960-1970. In each of these periods, frost rings were observed synchronously at the Polar and Southern Urals in at least three years. However, in the 1950s many frost rings were formed on the Polar Ural, but not on the South Ural.

There are 18 years with synchronous formation of frost rings: 1916, 1918, 1920, 1922, 1933, 1935, 1946, 1947, 1949, 1955, 1956, 1957, 1961, 1968, 1969, 1970, 1982 and 1995. Most of these years occur during the periods with a high frequency of damages. During other periods, namely in 1900-1910, 1920-1940, 1970-1980, frost damages were seldom formed in spruce wood. In these periods, synchronous frost damage are seldom observed at PUR and SUR. During the last 20 years (1980-2000) there are many frost rings, but few of these are common to PUR and SUR.

These data were compared with average summer temperature data received from Salekhard and Ufa meteorological stations. The variations in average summer temperature for the Polar and the South Ural is shown in figure 6. Cold periods are: 1910-1920, 1940-1950, 1960-1980, warm periods are 1900-1910, 1920-1940, 1950-1960, and 1980-1990 for SUR and 1990-2000 for PUR. These periods coincide with the decades showing the greatest intensity and frequency of frost damage. Thus, frost rings form frequently and synchronous for two study's sites in cold periods and rarely in warm periods.

The 1950s were a warm period for both sites, but only for the Polar Ural many frost rings were observed. The period between 1960 and 1970 was one of the coldest times of the 20th century. In this period frost rings were not as abundant on PUR, as on SUR. In the Polar Ural tree rings tend to be very narrow; frost rings rarely form in narrow tree rings (Gurskaya, 2002). However, during this period three common years with frost rings exist.

In 1980s and in 1990s, the thermal conditions during the summer months on PUR and SUR became somewhat anti-phased. Therefore, in these two periods, despite the frequent observations of frost damage at the investigated profiles, the amount of common frost years is not as great as during other times.

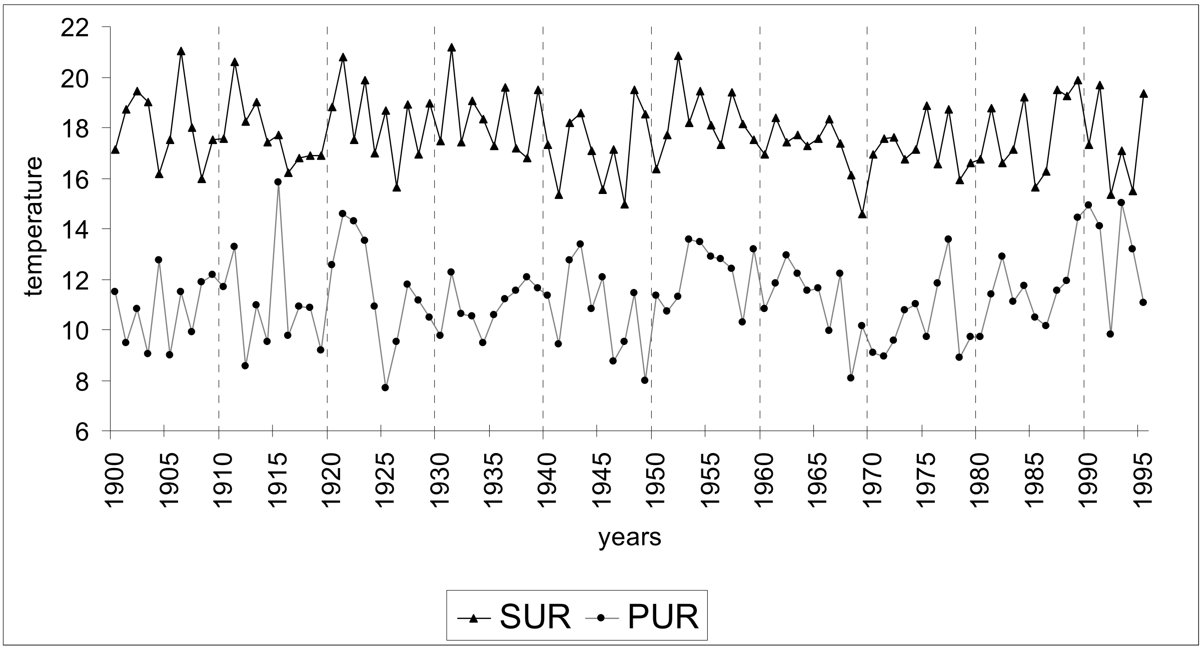

Figure 6: Mean summer temperature on Salekhard (for PUR) and Ufa (for SUR) weather stations, from 1900 to 1995.

Analyzing the 18 years which have common frost rings, shows that in only 6 years the frosts are classified as having the same position within the three differentiated zones. These six years (1916, 1935, 1951, 1956, 1969 and 1995) had strong frosts, as confirmed by the high percentage of trees having frost damage over a large territory. These years were characterized by a cold growing season, when mean summer temperature was lower than the long-term temperature mean. Only 1956 was characterized as a warm summer.

Despite the synchronism of frost damages during some decades, the similarity of two profiles shows that the formation of frost injuries occurs under influence of the different independent factors (i.e. spring or summer frosts). Climate extreme conditions on PUR are not necessarily found on SUR's climate and vice versa.

Furthermore, various instrumental parameters were analyzed to determine which of them most directly triggers frost damage, their threshold values, and which of them can be used for reconstruction of extreme climatic phenomena. The most obvious relations are found for 'minimal temperature' and the 'duration of frost' (Fig.7).

Other relationships, such as correlation between frost rings and mean monthly temperature, mean summer temperature, maximum daily temperature, diurnal temperature range, precipitation, date of frost beginning, and beginning of the tree growing season were not evident. For example, a diagram showing the relationship between maximum daily temperature on frost ring formation in figure 7 shows no clear statistically significant relationship.

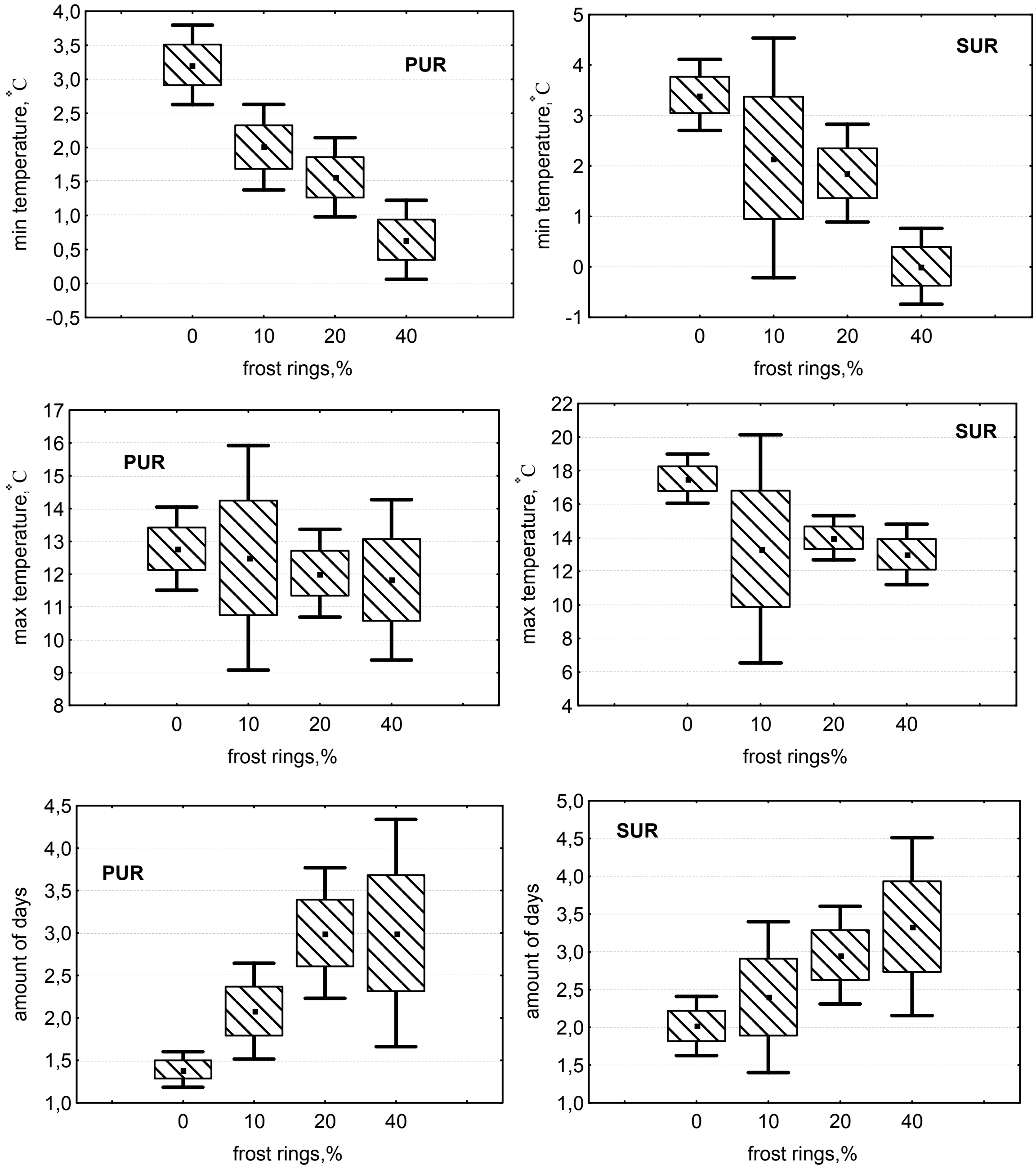

Figure 7: Some meteorological characteristics in relation to the percentage of frost damage.

The minimal air temperature at 2 m height, when in tree rings some frost damage (less than 10 % of total tree rings) is observed approaches +1.5°C. Further decrease of this temperature leads to an increase in severity of the damage. However, this dependence is not linear in character. It has been observed that maximal temperatures during frost days don't reflect the formation of frost damages. However, even the maximal temperatures during this period may be around +1-2°C. The duration of frosts when a minimum quantity of damages is formed in xylem appears to be 2 days. A one-day frost, when minimal temperature falls below +5°C, doesn't lead to the formation of frost damage in coniferous wood. Prolonged frosts of 3-4 days lead to substantial frost damage.

Thus, the formation of frost damage is most closely related to two factors: minimal daily temperature and duration of frost. This pattern is observed both on the Polar and on the

Southern Ural. The differences in minimal temperature means are caused by differences in the elevation of meteorological stations and also by the elevation of sites along the transect. By analyzing such data, it is possible to reconstruct frost events and various intensities of frost and related synoptic conditions (minimal temperature and duration of frosts).

Discussion

Frost damage occurs in wood of coniferous trees under influence of cold climatic extremes during the growing season. In high mountains of Urals these extremes are often observed. Despite the fact that the studied territories represent the upper tree-line of spruce and that the sampled trees grew in similar habitats, the frequency and intensity of the extreme climatic phenomena on the Polar and South Ural are different.

A decrease in the cambial age for which trees are susceptible to frost damage downhill is connected with a general increase of width of tree rings and as a consequence also with an increase spruce trunk diameters. Larger trunks are characterized by higher thermal capacity which allows larger trees to become more resistant to spring and summer frosts. In addition, climate conditions at the upper tree-line of the Polar Ural are harsher, than on the Southern Ural. This greater severity of conditions in higher latitudes results in more damage to older trees on the PUR in comparison with lower levels and with SUR.

The increasing quantity of frost damage downhill is a result of the influence of cold air which flows down slope and remains caught in the lower elevations. This is reflected by the greatest percentage of frost rings at the lowest site of both transects (the third level).

Intrusion of cold air masses that cause damage to tree rings is characteristic for the Polar and South Ural Mountains. However, years with frost damages both the Polar and the South Ural under influence of the same cold air mass is seldom observed (up to 20% of cases). More local frosts seem to more often influence the trees in the study region rather than vast cold air masses.

A greater incidence of frosts in the beginning of the vegetation season is more characteristic for the South Ural in comparison with the Polar Ural. Frost damage to the EW0 zone, reflecting late spring frosts, are largely responsible for the greater percentage of frosts at SUR. Frosts during summertime rarely injure trees on the upper tree line of the South Ural, as demonstrated by the low frequency of frost damage in the LW zone. On the Polar Ural, in contrast, most frost damage is observed in the latewood (zone LW), indicative of strong frosts during the growing season in the summer.

Detection of instrumental records that are related to frost damage on PUR and SUR was not always possible. The most important factors are decreases in minimal air temperatures and the duration of minimum temperatures, being two or more days. These comparisons are complicated by differences in location and elevation between the instrumental stations and the tree sites.

In conclusion, the upper tree-line of the forest tundra ecotone on the Southern Ural, where very few trees grow (the first level), is characterized by extreme climatic events such as strong late spring frosts. But on the Polar Ural, the cold vegetation season passes without any strong frost. Strong summer frosts, which limit the vegetation season to only several weeks at the Polar Ural, can be most readily observed on the bottom of the mountain valley (the third level). Overall, Polar Ural Mountains frosts occur more often in comparison to the Southern Ural. However, on the South Ural frosts have more catastrophic consequences for trees.

Frost rings allow determining extreme climate conditions for similar ecosystems (for example, spruce growing on the upper tree-line on the forest-tundra ecotone) across different geographic zones. The frost rings can be used to show periods of common climate forcing and also to illustrate differences in the location, timing, and local nature of cold air masses.

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