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Pathological Tree-Ring Structures in Siberian Juniper (*Juniperus sibirica* Burgsd.) and Their Use for Reconstructing Extreme Climatic Events

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Abstract—The results of identification and dating of frost, false, and light rings in the wood of living and dead Siberian juniper plants growing at the upper forest boundary in the Polar Urals were used to determine the incidence of these structures over the past 630 years. Based on the data of instrumental observations on daily air temperature, the dates and rates of temperature decrease in the years of pathological tree ring formation were analyzed. The recurrence and intensity of extreme temperature drops during the growing seasons of the past six centuries were reconstructed. The severest frosts occurred in the summer seasons of 1601, 1783, 1857, 1882, and 1968.

Key words: tree rings, pathological structures, *Juniperus sibirica*, climatic extremes, frosts, the Polar Urals

Extreme climatic events have a strong effect on the state, functioning, and stability of ecosystems. At high latitudes, they include frosts and long-term air temperature drops during the growing season. A promising method for reconstructing the history of these events in the past, when instrumental observations had not been performed, consists in the analysis of pathological structures in tree rings. Such studies in the subarctic regions of Siberia and the Urals are even more important because, in contrast to the situation in Europe, there are virtually no records of anomalous climatic events in these regions during the period before the onset of instrumental meteorological observations. Moreover, none of publications available to us deals with the analysis of temporal frequency patterns of pathological structures in subarctic trees and shrubs.

In this work, we describe our first experience in analyzing pathological structures in the wood of Siberian juniper from the Polar Urals and, on this basis, reconstructing the history of weather extremes during the past 630 years.

MATERIALS AND METHODS

Siberian juniper (*Juniperus sibirica* Burgsd.) is a typical arctalpine shrub reaching 1.0–1.5 m in height. In the Polar Urals, it grows under the canopy of light spruce-larch forests, on screes, and in mountain tundras, expanding beyond the upper treeline. Individual plants usually have several branches. Lower branches lie on the ground surface and can take root; thus, the bush can grow aside for 2–3 m. Fragments of branches that died off long ago are found near large juniper bushes.

To analyze pathological structures and their temporal distribution, we chose 34 more or less isolated juniper bushes growing on the eastern macroslope of the Polar Urals (the Rai-Iz Massif, Mount Chernaya) near the upper boundary of light larch forests (200–280 m a.s.l.). In 1997 and 1998, the most developed branches of each bush were crosscut at the base; in addition, crosscuts of dead branches found near the bushes were made. Eventually, 42 crosscuts of living branches and two crosscuts of the same dead branch were chosen for the analysis of pathological structures. The number of annual rings in these samples ranged from 60 to 483. The comparison of individual tree-ring chronologies by cross-dating showed that, in aggregate, they cover the period between 1363 and 1998; however, only two crosscuts of a branch that died off 180 years ago provide the data on the first 150 years of this period.

Wood pathology in tree rings was analyzed throughout their length, distinguishing several types of pathological structures and recording the degree of their expression and location in the ring.

Frost rings. A typical frost ring consists of three zones (Glerum and Farrar, 1966): deformed (bent) tracheids, destroyed cells (an amorphous layer), and subsequently formed tracheids of abnormal size and shape. However, studies on young spruce growth (Nilov and Chertovskoi, 1975) showed that different trees can form either typical frost rings or rings consisting of the first zone only after the same frost. Below, both are referred to as frost rings. Observations performed in nature (Nilov and Chertovskoi, 1975; Stahle, 1990, cited from Schweingruber, 1996) and experimental studies (Glerum and Farrar, 1966) demonstrated that frost rings appear when the air temperature drops to subzero values (usually below –5°C) during the period of cambium activity and xylem cell growth.

Wood density fluctuations (false rings) are manifested in the appearance of a darker cell layer within a tree ring. Cells of this layer differ from neighboring cells in their shape, size, and cell wall thickness. Such structures can appear when a long-term worsening of weather conditions during the growing season (at the upper forest boundary, an air temperature drop) is followed by their normalization (Schweingruber, 1996).

Light rings contain thin-walled (e.g., incompletely formed) latewood cells. Specialists believe that such rings are formed in the years with the prevalence of low air temperatures during the growing season (Schweingruber, 1996) or in the end of the period of tree growth (Filion *et al.*, 1986).

In addition, we recorded the absence of individual tree rings and the formation of pathological resin ducts and scars.

To reveal the relationship between the formation of pathological structures and climatic parameters, we used meteorological data obtained at the Salekhard station, which is located 50 km east of the study region. Observations at this station have been performed since 1883.

RESULTS AND DISCUSSION

Incidence of Pathological Wood Structures

Of 8218 tree rings studied, 306 rings (3.7%) contained some of the aforementioned pathological structures. Frost rings were the most frequent, accounting for 54% of all the pathological cases (18% in earlywood and 36% in latewood). The analysis of their incidence in Siberian juniper showed that their frequency does not decrease with age, as it occurs in trees characterized by an age-related increase in the thickness of the trunk and heat insulation (bark and bast). Bark in Siberian juniper is 2–5 mm thick, and branches are in the surface air layer; hence, frosts can damage differentiating xylem cells throughout the branch length and at any age. Apparently, frost rings in this species can appear even at air temperatures above –5°C.

Wood density fluctuations and light rings accounted for 38 and 4% of all the pathological structures, respectively. Scars and abnormal resin ducts in Siberian juniper were very rare, as the probability of mechanical damage to branches was low. The complete absence of individual tree rings from crosscuts was virtually never observed.

As these pathological structures were manifested to varying extents, we classified each type of pathology with respect to its severity. In the case of frost rings, three grades were distinguished: weak, limited to changes in the direction of growth of one or several rows of tracheids; medium, with several rows of damaged (crushed) cells followed by regenerating tracheids growing in an altered direction; and strong (typical frost rings). Wood density fluctuations within a tree ring were put into two categories: the first included false rings with a slight increase in wood density (smaller cells with thicker walls in earlywood tracheids); in the second category, this increase was significant. Wood density in false rings of our samples never reached the level characteristic of normal latewood. Light rings in different tree species are of two types: in the first, latewood consists of thin-walled cells; in the second, only one or two latewood cell rows have thin walls. Samples of Siberian juniper wood contained light rings of the first type only. It should be noted that latewood in this species is weakly developed, accounting for no more than 15–20% of the total ring width.

Chronology of Pathological Wood Structures

Figure 1 shows the temporal distribution of pathological structures formed in juniper tree rings over the past 630 years. Dates refer to the years characterized by the occurrence of tree-ring pathologies in no less than 15% of samples.

As the number of samples characterizing different periods of time ranged from 2 to 39, the frequencies of pathological tree-ring structures formed during these periods were difficult to compare. Nevertheless, a high incidence of these structures in the second half of the 19th century is noteworthy. All of the types of wood pathology occurred with high frequencies in the 20th century, which is apparently explained by a great number of samples included in analysis. The most remarkable years, in which the formation of pathological structures in tree rings was revealed in no less than one-half of the samples, were 1601, 1783, 1857, 1882, and 1968. The year 1466 was excluded from this list because the data on it were obtained from only two crosscuts of the same dry branch.

Figure 2 shows the types of pathological structures formed in juniper wood in summer seasons of the years indicated in Fig. 1 and characterized by a significant proportion of samples containing such structures. It is noteworthy that, in the same year, different pathologies proved to appear in different plants. Although this can be attributed to the influence of different external factors, a more logical explanation is that the same factor, depending on the microenvironment and individual features of plants (e.g., bark thickness, bush density, and cambium activity in a given moment), exerted different effects on differentiating xylem cells and induced the formation of different pathological structures. This assumption is confirmed by the fact that, in several samples, the same tree ring represented two types of these structures: a frost ring in one sector and wood density fluctuations in another sector. Such a situation can be explained by differences in the growth

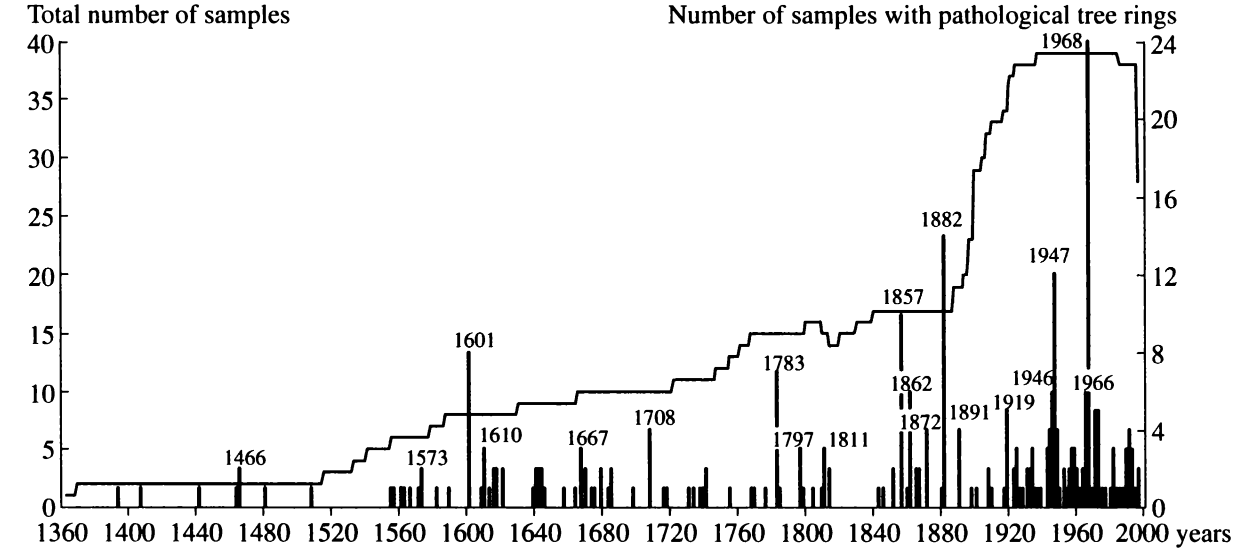

Fig. 1. Dates of pathological tree ring formation in Siberian juniper. The broken line shows the number of samples analyzed, bars show the number of samples with pathological rings formed in a given year. Dates above bars refer to the years characterized by a high incidence of pathologies in samples.

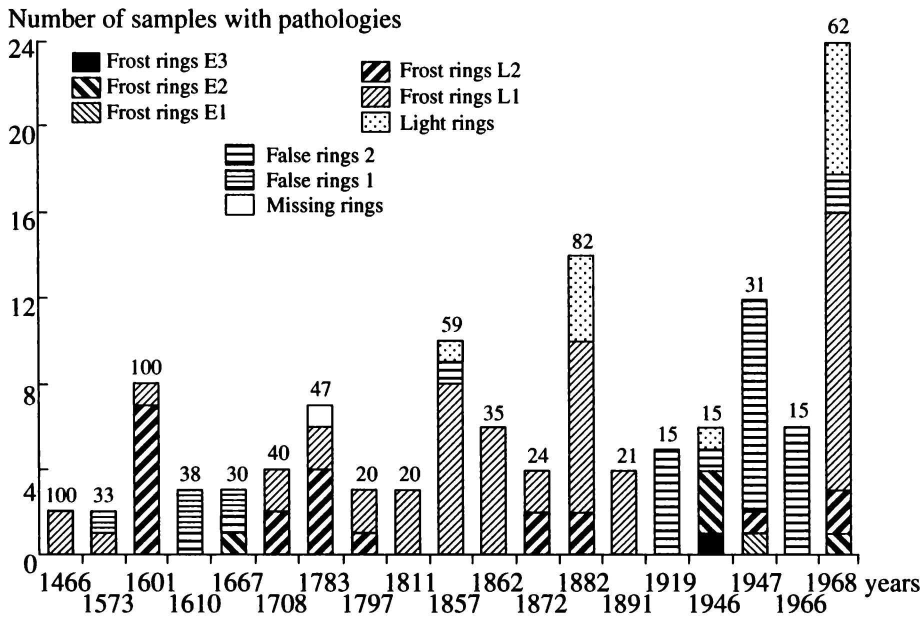

Fig. 2. Types of pathological tree rings formed in Siberian juniper in the years characterized by a high incidence of pathologies in samples. Letters E and L refer to pathologies in earlywood and latewood, respectively, with numerical indices (1–3) showing the degree of their expression (in decreasing order). Figures above bars show proportions of samples with pathologies in corresponding tree rings (%).

rate or bark thickness between different parts of the same branch.

Weather Extremes Responsible for the Formation of Pathological Wood Structures

As noted above, the three most frequent types of wood pathology (frost, false, and light rings) usually arise upon a considerable temperature drop during the growing season. As we had data on the average and minimal daily air temperatures during the period between 1883 and 1998, it was possible to estimate actual weather conditions providing for the formation of these tree-ring structures in Siberian juniper. As an example, we chose the years 1891, 1919, 1946, 1947, 1966, and 1968.

It was necessary to take into account that juniper wood samples were taken at elevations of 200–280 m a.s.l., whereas the meteorological station is at an elevation of only 35 m. To estimate corresponding temperature differences, we used the data obtained by S.G. Shiyatov. In June and July 1961, he measured the air temperature in the region of our research three times a day, at 7 a.m., 1 p.m., and 7 p.m. The results of analysis showed that air temperature in this region and at the station changed synchronously (correlation coefficient 0.95) and had close absolute values. Using linear regression coefficients determined for these two data sets, we recalculated temperature values recorded in Salekhard (Fig. 3) and obtained results that differed from the initial values by no more than 1°C. It should be taken into account, however, that juniper branches virtually lie on the ground surface, where temperature during frosts is lower than that at the level of a meteorological cabin.

The analysis of possible factors responsible for the formation of pathological wood structures in Siberian juniper is difficult because the available data on its seasonal growth pattern, including dates of the onset and cessation of cambium activity, are approximate. Growth in this species does not begin until the plants emerge from under the snow cover, which averages 1.5–2.0 m within the species range. In the study region, such a thick cover melts in the second half of June (Shiyatov, 1965). The time when radial growth ceases can be estimated by analyzing the relationship between growth indices and the air temperature in summer months (Hantemirov *et al.*, 1999). It was shown that the August average temperature has no effect on the width of the tree rings. This is evidence that the formation of an annual wood layer is completed by early August, and the cell walls of latewood are formed somewhat later. The onset of latewood formation is more difficult to estimate. It appears that latewood in Siberian juniper, as in trees, is formed in the second half of July.

After making the necessary comments, we can begin the analysis of conditions under which pathological tree-ring structures had been formed in Siberian juniper.

Well-manifested signs of frost damage in earlywood were found in four bushes in the rings formed in 1946. As follows from Fig. 3, frost occurred on June 28 of that year. It is noteworthy that the nine days before this frost were fairly warm, and this could stimulate the onset of cambium activity in some juniper plants.

Frost damage to latewood occurred in 1891 and 1968. In the former year, this damage apparently resulted from a significant decrease in minimal air temperatures on July 5–7, which was probably accompanied by frost on the soil surface. In 1968, similar lesions formed in 16 of 39 samples because of frost on the night of July 10–11. As follows from this example, the lower the temperature, the greater the number of damaged bushes.

Thus, we conclude that, in Siberian juniper from the Polar Urals, the presence of frost lesions in earlywood and latewood provides evidence for frosts that occurred in late June or the first days of July and in the first half of July, respectively. The degree of their expression depends on the rate of the temperature drop and the phase of seasonal wood growth in individual plants during frost.

Tree rings formed in 1919, 1947, and 1966 were mainly characterized by fluctuations of wood density (false rings). Diagrams of daily average temperatures in those years are wavelike, reflecting very warm weather in mid-July followed by a sharp temperature drop (by 12–18°C) and subsequent gradual warming by the end of the month. False rings could be formed due to these changes of temperature. Thus, a long-term and pronounced temperature drop in the middle of a very warm period in the second half of July is the factor responsible for fluctuations of wood density in tree rings.

Light rings, formed in 1946 and (in greater number) 1968, are unlikely to be a consequence of insufficient heat supply at the end of the growing season, as was proposed by Filion *et al.* (1986). More probably, their formation reflects the persistence of very low air temperatures throughout this season. Indeed, the summer of 1968 was among the coldest summers registered during the period of instrumental observations.

Reconstructing the History of Temperature Extremes

Based on the relationships between the formation of pathological wood structures and temperature drops during the growing season, we reconstructed the history of temperature abnormalities in the Polar Urals during the past 600 years. The following events were dated (the severest frosts occurred in the years written in boldface): frosts in late June and early July (1667 and 1946); frosts in July (1466, 1573, **1601**, 1708, **1783**, 1797, 1811, **1857**, 1862, 1872, **1882**, 1891, and **1968**); and long-term and pronounced temperature drops in mid-July, preceded and followed by very warm periods (1610, 1919, 1947, and 1966).

The fact that an extreme temperature drop was recorded in summer does not necessarily mean that the corresponding summer season as a whole was extremely cold. However, such a situation occurred in 1783, 1862, 1882, 1891, and 1968: according to the data of instrumental observations and tree-ring reconstructions (Shiyatov, 1995; Hantemirov *et al.*, 1999), average summer temperatures in these years were significantly below the norm. Relatively low summer temperatures were also recorded in virtually all of the years listed above except for 1708: our reconstruction showed that the temperature in the summer of this year slightly exceeded the long-term average value.

Global Climatic Events and the Formation of Pathological Wood Structures

In some studies on the incidence of light and frost rings (LaMarche and Hirschboeck, 1984; Filion *et al.*, 1986), the authors paid much attention to the analysis

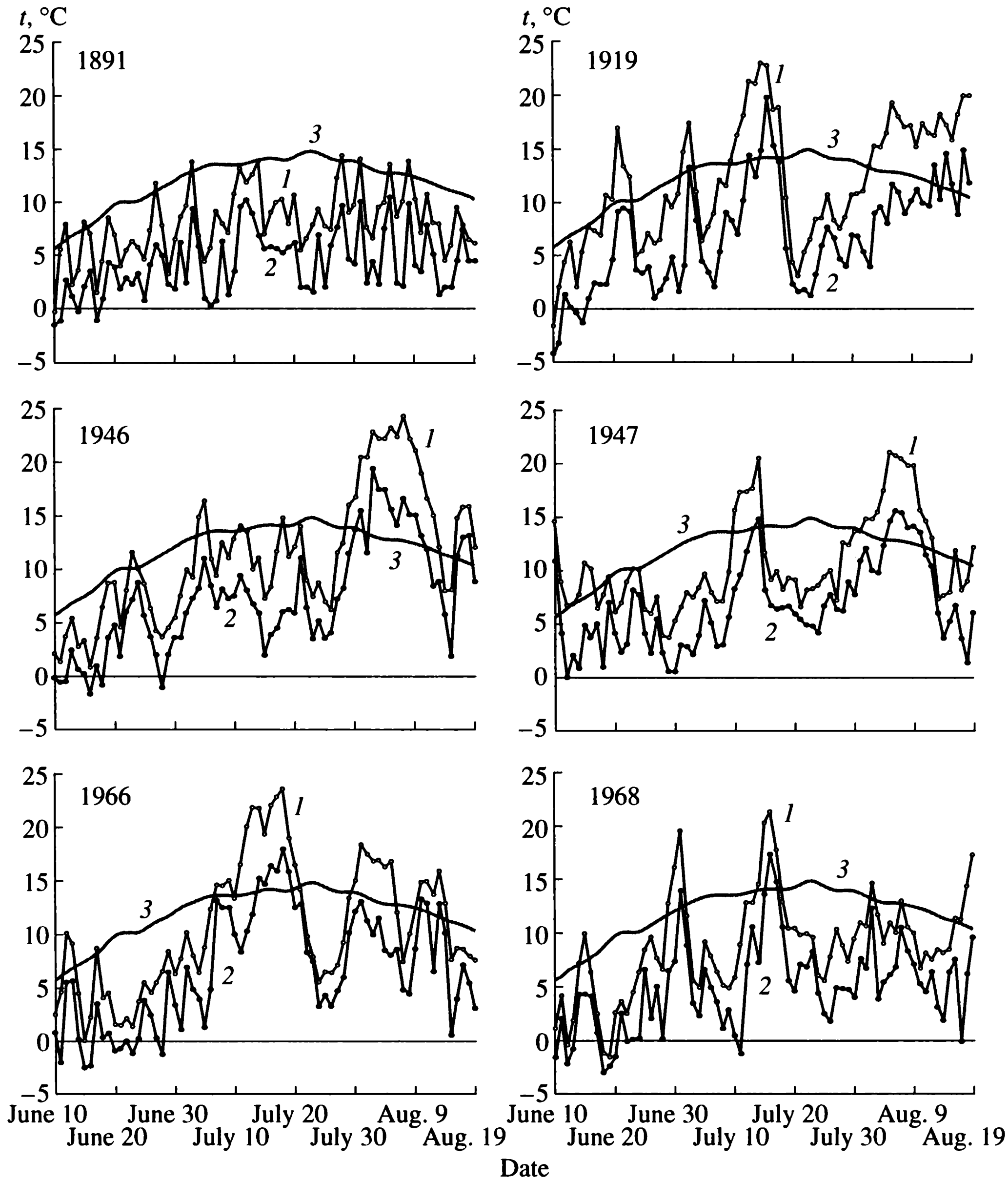

Fig. 3. Dynamics of daily air temperatures in the region studied (recalculated from the data on the Salekhard meteorological station) in the years characterized by a high frequency of pathological tree ring formation in Siberian juniper: (*1*) average daily temperature, (*2*) minimal daily temperature, (*3*) long-term average daily temperature over the period between 1883 and 1998.

of relationships between the formation of these structures and the global decreases of air temperature after major volcanic eruptions. Such an analysis should be performed cautiously, as virtually any case of wood pathology can be attributed to a certain eruption, the more so that the latter effect can manifest itself after an indefinite period of time (one to three years). Nevertheless, it was interesting to correlate our data on the formation of pathological wood structures and similar data obtained in other regions of the Northern Hemisphere, both characterizing the five severest years noted above.

Frost rings formed in 1601 were found in each sample of Siberian juniper from the Polar Urals (100% incidence). In the same year, frost rings (LaMarche and Hirschboeck, 1984) and light rings (Filion *et al.*, 1986) appeared in pine and spruce trees growing in North America. Uncommon natural phenomena were observed in Europe: in England, June was very cold, with frosts occurring every morning (Pyle, 1998); in northern Italy, the weather remained cold until mid-July, and the sky was clouded almost throughout the year (Pavese *et al.*, 1992). In European Russia, severe frosts began unusually early and destroyed all the grain and vegetable crops. The resulting famine was devastating: in Moscow alone, 120000 people died during the next three years (Borisenkov and Pasetskii, 1988).

By analyzing wood density in tree rings, Briffa *et al.* (1998) reconstructed the dynamics of summer temperatures in the Northern Hemisphere. In particular, this study showed that the summer of 1601 was the coldest during the past 600 years. Interestingly, both this reconstruction and our data based on the analysis of variation in tree ring width in Siberian larch and Siberian juniper (Shiyatov, 1995; Hantemirov *et al.*, 1999) showed that the average summer temperature of 1601 in the north of European Russia and Western Siberia was at the long-term average level; nevertheless, a certain global event left its trace in the annual rings of trees growing in this region. Recently, de Silva and Zielinski (1998) found that this cold spell was caused by the Huaynaputina volcano eruption in Peru (February–March 1600), the world's greatest eruption over the past 500 years.

In 1783, in addition to the formation of frost rings in a significant proportion of samples, the lowest radial increment of juniper was observed in the Polar Urals. Our reconstruction (Hantemirov *et al.*, 1999) showed that the summer of this year was the coldest summer in the Polar Urals over the past six centuries. A significant deficiency of summer heat in 1783 was characteristic of the Northern Hemisphere in general (Briffa *et al.*, 1998). According to the data cited by Borisenkov and Pasetskii (1988), "dry fog" covered the territory extending from Norway to Syria and from England to the Altai Mountains between May 24 and October 8; in St. Petersburg, sunlight in June was weaker than the light of the full moon. This anomaly was probably caused by the eruptions of volcanoes (Laki in Iceland and Asamayama in Japan) which occurred in the same year. In North America, no frost rings of that year were revealed, and light rings appeared in a considerable proportion of spruce trees in Quebec in 1784 (Filion *et al.*, 1986). As shown by the spatial tree-ring reconstruction of summer temperatures in subarctic Asia (Vaganov *et al.*, 1996), the zone affected by the 1783 summer cold spell extended from the Urals to 90° East.

Pathological structures formed in 1857 were revealed in one-half of Siberian juniper bushes studied in this work. Extreme climatic events recorded in the summer of this year were as follows: in the Vologda province, temperature in June decreased to –5°C; in the Arkhangelsk province, frosts occurred in the first half of August (Borisenkov and Pasetskii, 1988). As no pathological tree rings of this year were revealed in North America, it appears that the corresponding weather extreme was regional.

The next extreme in the Polar Urals occurred in the summer of 1882. According to Brunstein (1996), frost rings of that year were formed in 2% of bristlecone pine trees studied in Colorado, United States. However, neither tree-ring records nor documents provide evidence that any other region of the Northern Hemisphere suffered from frosts in 1882. Global climatic anomalies were observed in 1884, after the violent Krakatau eruption in 1883. In the Polar Urals, the summer of 1884 was cold. In 1882, however, the summer season in this region was even colder (Hantemirov *et al.*, 1999): as follows from a high frequency of frost rings in juniper, the minimal air temperature dropped far below zero. This anomaly was probably local. However, there is evidence (P.A. Moiseev, personal communication) that frost rings formed in both 1884 and 1882 occur with a high frequency in Siberian larch and Siberian stone pine trees from different regions of the Kuznetski Alatau. According to the reconstruction of summer temperatures in subarctic Asia (Vaganov *et al.*, 1996), the 1882 summer cold spell affected the zone of 60–90° East.

The summer of 1968 in the Northern Hemisphere is regarded as one of the coldest (Briffa *et al.*, 1998). However, there are no data on the formation of frost rings in other regions of the world in 1968, and no volcanic eruptions were recorded in the preceding years.

Thus, weather extremes in the Polar Urals, reconstructed by analyzing pathological wood structures in Siberian juniper, reflect both global climatic anomalies caused by major volcanic eruptions (summer seasons of 1601 and 1783) and regional anomalies resulting from specific processes of atmospheric circulation over the vast expanses of the Urals and Western Siberia (summer seasons of 1857, 1882, and 1968). To reveal the regions affected by weather extremes in these and other years, it is necessary to perform large-scale studies of pathological structures in tree rings, primarily in the Asian part of Russia.

CONCLUSION

Pathological wood structures, such as frost, false, and light rings, are easily identifiable in Siberian juniper growing at high latitudes and in highlands. Hence, this species can be used for reconstructing extreme climatic events (frosts and cold spells during the growing season), which strongly affect the functioning of different ecosystem components. Moreover, variation in the width of annual rings in Siberian juniper provides the basis for reconstructing spring and summer temperatures. This species is widespread, long-lived, and tolerant to a broad range of environmental conditions. In aggregate, these properties make it a promising object of dendroclimatic research.

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