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Palaeogeography, Palaeoclimatology, Palaeoecology 209 (2004) 155–164
PALAEO
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Extreme temperature events in summer in northwest Siberia since AD 742 inferred from tree rings

Rashit M. Hantemirov*, Ludmila A. Gorlanova, Stepan G. Shiyatov

Institute of Plant and Animal Ecology, 8 Marta 202, Ekaterinburg 620144, Russia

Received 13 January 2003; accepted 21 December 2003

Abstract

Frost and light rings of living and dead individuals of Siberian juniper (*Juniperus sibirica* Burgsd.) and Siberian larch (*Larix sibirica* Ledeb.) growing at the upper (Polar Ural Mountains) and polar (Yamal Peninsula) tree lines in northwest Siberia have been studied to reconstruct summer frosts and abrupt temperature declines during the second half of the growing season over the past 1250 years. The most severe temperature events in both regions were in AD 801, 1109, 1259, 1278, 1466, 1601 and 1783. Comparison of our data with data from other regions of the world shows that there is agreement in the timing of extreme temperature events in AD 800–801, 1109, 1258–1259, 1453, 1466, 1585, 1601, 1783, 1884, 1912 and 1992 between several regions. Most probably, these extremes have been caused by climatically effective explosive volcanic eruptions.

Keywords: Frost rings; Light rings; Extreme temperature events; Upper tree line; Polar tree line; Volcanoes; *Larix sibirica*; *Juniperus sibirica*; Polar Ural Mountains; Yamal Peninsula; Siberia; Russia

1. Introduction

Extreme climatic events have a strong effect on the state, functioning, and stability of ecosystems. At high latitudes, they include frosts and multiday abrupt temperature declines during the growing season. The analysis of anomalous structures in tree rings provides a promising method for reconstructing such events in times before the advent of instrumental meteorological observations. This is of particular importance in the subarctic regions of Siberia and the Urals where, in contrast to the situation in Europe, there are virtually no records of anomalous climatic events in preinstrumental times.

Two types of microanatomical trace have been used for the reconstruction of such short extreme temperature events, namely, frost-damaged layer of cells (frost rings) and thin-walled latewood cells (light rings). A typical frost ring in a coniferous species consists of underlignified, crumpled (deformed) tracheids, collapsed cells, traumatic parenchyma cells, and abnormal tracheids (Glerum and Farrar, 1966; Schweingruber, 2001). Experimental studies (Glerum and Farrar, 1966) and observations performed in nature (e.g., Glock, 1951; Nilov and Chertovskoy, 1975; Stoeckli, 1996; Hantemirov et al., 2000) demonstrated that frost rings appear when the air temperature drops to subzero values during the period of

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* Corresponding author. Tel.: +7-343-2606494; fax: +7-343-2606500.

E-mail address: rashit@ipae.uran.ru (R.M. Hantemirov).

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doi:10.1016/j.palaeo.2003.12.023

cambial activity and xylem cell growth. It has been shown (Nilov and Chertovskoy, 1975; Hantemirov et al., 2000; Schweingruber, 2001) that soon after the frost event, a typical frost ring may be formed, or several rows of damaged (crushed) cells followed by regenerating tracheids growing in an altered direction, or a ring consisting only of deformed (distorted) tracheids. The term 'frost ring' has, on occasion, been applied to each of these structures.

Light rings contain thin-walled (i.e., incompletely lignified) latewood cells. Such rings are formed in the years with unfavourable conditions. In the subarctic zone, light rings may be formed as a consequence of cool and short summers, especially the second half of the summer (Yamaguchi et al., 1993; Wang et al., 2000; Gurskaya, 2000; Gurskaya and Davy, 2001).

2. Material and methods

2.1. Objects

Analyses of frost and light ring frequency have been carried out on the wood of Siberian larch (*Larix sibirica* Ledeb.) and Siberian juniper (*Juniperus sibirica* Burgsd.).

Siberian larch growing at the upper and northern limits of their range has been widely used in dendroclimatic studies, because of the high sensitivity of ring-width and wood-density chronologies to summer temperature changes. Tree-ring structure in larch is often broken by extreme weather conditions such as frosts and abrupt temperature drops (Shiyatov and Gorlanova, 1986; Knufinke, 1998; Gurskaya, 2000; D'Arrigo et al., 2001). However, the sensitivity of trees, including larch, to frost damage decreases with increasing diameter of the tree and bark thickness (i.e., age) (Stoeckli, 1996; Gurskaya, 2002). Therefore, frost rings are formed mainly in the central rings of the stem.

Siberian juniper is a typical arctoalpine shrub with a height of up to 1.0–1.5 m. An individual juniper bush usually consists of several branches; branches can form adventitious roots and old individuals are cushion-like with a diameter of 2–3 m. Frost rings are the most frequent anomalies in the wood of these northern junipers (Hantemirov et al., 2000). It is important to note that their frequency does not decrease with age, as the juniper branches are covered by thin bark (no more

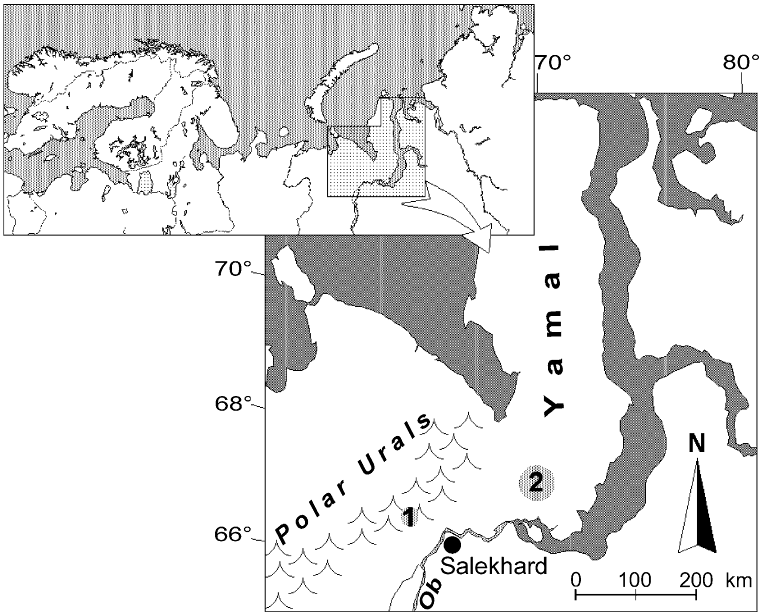

Fig. 1. Region of research. Areas in Polar Urals (1) and Yamal Peninsula (2) shown as grey circles.

than 2–5 mm). Moreover, these branches are in the surface air layer where frosts are more pronounced. On the other hand, light rings are very rare in the wood of Siberian juniper, in contrast to larch, because latewood of this species is usually weakly developed, i.e., “light”. Therefore, rings that appear lighter than normal are rare.

The oldest living larches in the north of Western Siberia reach an age of 400–500 years. The oldest living branches of Siberian juniper we found in the Polar Urals were 840 years old. To prolong chronologies beyond the age of the oldest living larches and junipers, samples from dead trees and shrubs have been used. There is a large amount of dead-and-down larches and junipers near and above the upper limit of the open larch forest distribution (200–280 m above sea level) in the foothills of Chernaya Mountain and the Rai-Iz Massif (eastern slope of the Polar Urals), located in the area approximately at 66°48′N and 65°46′E (Fig. 1). In the southern Yamal Peninsula, sandy alluvial deposits of Holocene age contain a large amount of subfossil tree stem remnants. By far, the greatest proportion of these trees is made up of Siberian larch (95%). The collection of subfossil wood samples in the southern Yamal Peninsula was carried out in the basins of small rivers that traverse the plain located between 67°00′ and 67°50′N and 68°30′ and 71°00′E (Fig. 1).

2.2. Material

Several dozen samples from each site and each species have been used for the analysis reported here (Table 1). In the case of juniper, discs from the most well-developed branch of each bush were selected. For larches, mainly discs from stems have been used. In the Polar Urals, increment cores from stems of living trees and discs from roots of dead larches have also been used.

The determination of calendar dates of tree-ring formation was carried out by cross dating with pre-existing ring-width master chronologies. For dating dead larches from the Polar Urals, the 1350-year-long chronology developed by Shiyatov (1986, 1995) was used. For dating junipers from the same site, the 1359-year-long chronology by Shiyatov et al. (2002), and for larches from Yamal, the 4000-year-long chronology by Hantemirov (2000), and Hantemirov and Shiyatov (2002) have been used as master chronologies.

The evaluation of the relationship between the formation of frost rings and light rings and climatic parameters was based on the 117-year record of meteorological observations from the meteorological station at Salekhard (1883–1999), which is situated 60 km southeast of the research area in the Polar Ural Mountains and 150–200 km southwest of the research area in the Yamal Peninsula (Fig. 1).

3. Results

3.1. Frequency of frost and light rings

The frequencies of different types of wood structure anomalies are shown in Table 2.

Table 2
Frequency of frost and light rings

Site	Species	Frost rings	Light rings
Polar Urals	*Juniperus sibirica*	642 (2.2%)	60 (0.2%)
	Larix sibirica	433 (0.8%)	5310 (9.8%)
Yamal	*Larix sibirica*	337 (1.2%)	3667 (13.5%)

Fraction of total rings analyzed in this study shown in parentheses (see Table 1).

Table 1
Description of material used for analysis

Site	Species	No. of used samples		Period covered		Total rings analyzed
		Living	Dead	Total	n>4	
Polar Urals	*Juniperus sibirica*	57	39	641–1999	988–1999	28,711
	Larix sibirica	148[a]	281[b]	643–1999	745–1999	54,044
Yamal	*Larix sibirica*	13	217	644–1996	742–1996	27,112

[a] Including 138 increment cores.

[b] Including 133 discs from the base of roots.

It was mentioned above that, in juniper, frost rings can be formed throughout the life span of a branch. This is the reason for the higher frequency of frost rings in the wood of juniper in comparison with larches. The greater frequency of frost rings in larch from the Yamal Peninsula compared to those in the Polar Urals can probably be explained by the greater proportion of samples from young trees in the Yamal material. This would be consistent with the tendency for frost rings to be formed more frequently in young wood in larch.

Analysis of the incidence of tree ring anomalies revealed a somewhat ‘‘blurred’’ picture.

This results from there being many cases when only one or a few trees showed frost or light rings. Thus, 213 of the 1012 years (21%) studied have such

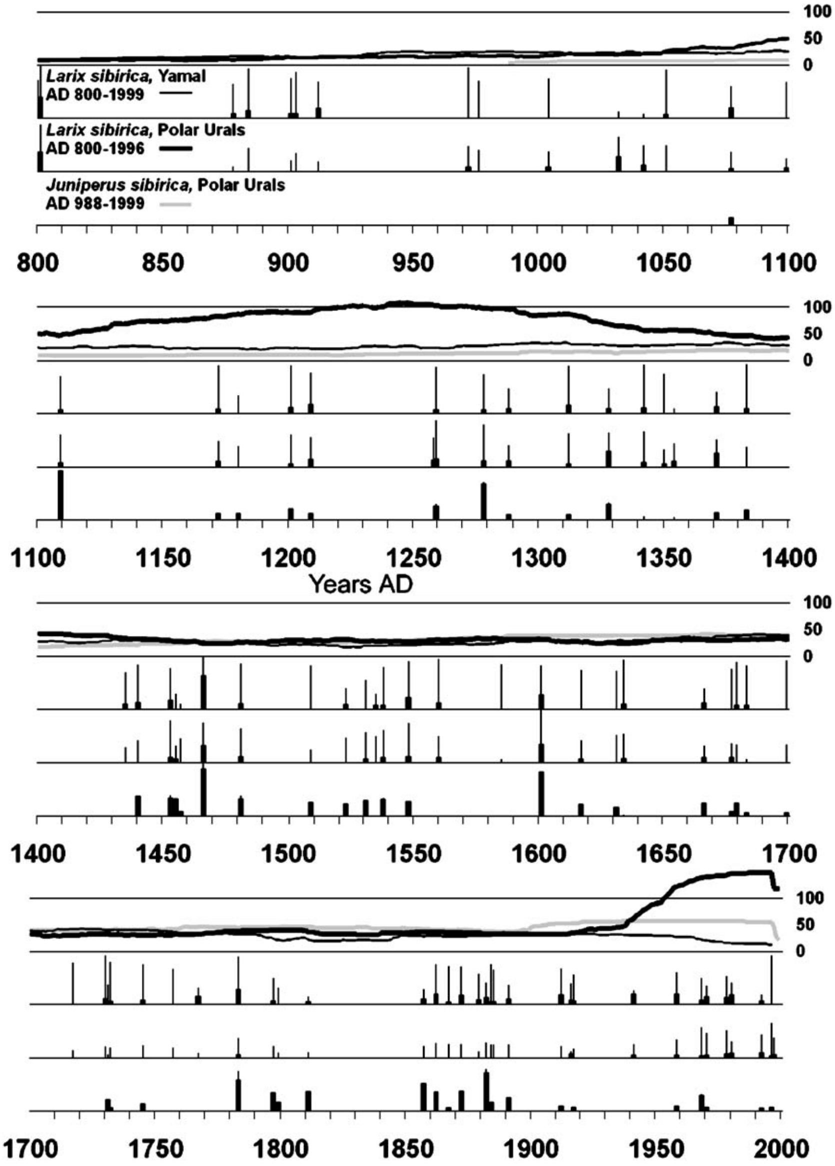

Fig. 2. The proportion (%) of frost rings (bold part of bars) and light rings (thin part of bars) in the wood of juniper and larch from the Polar Ural Mountains and Yamal Peninsula. The height of each band is 100%. The broken lines above bars show the replication.

a feature in at least one juniper specimen. In the case of larch, this applies to 921 of the 1255 years (73%) in the Polar Urals, and 890 of 1255 (71%) on the Yamal Peninsula.

Frost or light rings may have been produced in one or a few trees in a particular year as a result of those individuals starting growth unusually early, and hence being more susceptible to frost damage in spring. Alternatively, they may result from the particular microclimatic features of the sample site. To exclude such "casual" frost and light rings we have applied the following procedure. We have assumed that any anomaly may occur by chance. We then calculated the theoretical frequencies of binomial series by random appearance of these anomalies within the observed periods (1255 years for larches from Polar Urals and Yamal and 1012 years for juniper). As a critical level, we have considered the number of anomalies in one year (for the given sample size) for which the expected number of years with this amount of anomalies (for the given length of chronology) is less than 1. Years where the number of frost rings or light rings reaches the critical value in at least one species or site we considered to be "extreme".

These years are shown in Fig. 2 and Table 3. The chronology in Fig. 2 begins with AD 800, though reliable larch data are available from 742, because in the period from 742 to 800 there were no extreme years.

The extreme years tend to co-occur in both species and at the various sites. Although the sites are all within approximately 200 km of one another, they represent very different situations—mountains, valleys and plains. Thus, the observed degree of synchroneity in the frost and light rings suggests that the climate phenomena causing them had at least a regional extent.

3.2. Weather extremes responsible for the formation of frost and light rings

Using daily air temperature data we have shown (Hantemirov et al., 2000), that in Siberian juniper, the presence of frost lesions in tree rings provides evidence for frosts that occurred in late June or in the first half of July. Frost rings that formed in 1891 apparently resulted from a cold spell on July 5–7, which was probably accompanied by frost on the soil surface. In 1968, more strongly expressed frost lesions formed in a significant number of junipers because of frost (temperature below 0 °C) on the night of July 10–11.

The frost rings in larch in our study areas of research are formed by frosts occurring at the same time of year, from June 20 to July 20 (Gurskaya, 2002). As to light rings, the comparison with meteorological data indicates that formation of light rings in the larch coincides with extreme low mean July–August air temperature, i.e., during the middle and end of summer (Fig. 3). Thus, Fig. 2 can be considered as a reconstruction of temperature extremes.

Although frost rings are almost always also light rings, and are associated with cold periods, we cannot exclude the possibility that they might be formed independently in the same year.

4. Discussion

Frost and light rings may be related not only to regional climate extremes, but also to global phenomena. The occurrence of frost and light rings has been shown to correspond fairly closely with cooling after major volcanic eruptions (e.g., LaMarche and Hirschboeck, 1984; Filion et al., 1986; Briffa et al., 1998).

It is impossible to conclude whether an event was of global scale from data derived in one region. Therefore, we have compared our data with the data of other authors who have reconstructed the occurrence of such extreme cold events. Our aim was to determine the spatial scale of the events. We compared these records with the years in which we found significant numbers of frost and/or light rings in our materials (Table 3). As the climate effects of a volcanic event often appear in 1 or 2 years after the eruption and may have different lags in regions remote from the volcano, we have also noted cases, when the cooling in other regions was 1 year before or after the extreme year in northwest Siberia. We comment on several years in which many samples form our collections show frost or light rings, and place them in the context of other similar records.

The event of AD 800–801 resulted in frost or light rings in almost all larch sampled from the Polar Urals and Yamal Peninsula. Both samples of juniper from the Polar Urals available for this period have frost

Table 3
Dates of extreme years in northwest Siberia and other regions of the world

NW Siberian extreme years 742–1999	Western USA *Pinus longaeva* & *P. aristata* Frost rings 3435 BC – 1993 AD	Eastern Canada *Picea mariana* Light rings 695 – 1994	NW Canada *Picea glauca* Light rings 1186–1989	NE Siberia *Larix cajanderi* Ring width 1400–1994 (20 coldest years)	Northern Hemisphere Latewood density 1400–1995 (30 coldest years)	NW Siberian extreme years 742–1999	Western USA *Pinus longaeva* & *P. aristata* Frost rings 3435 BC – 1993 AD	Eastern Canada *Picea mariana* Light rings 695 – 1994	NW Canada *Picea glauca* Light rings 1186–1989	NE Siberia *Larix cajanderi* Ring width 1400–1994 (20 coldest years)	Northern Hemisphere Latewood density 1400–1995 (30 coldest years)
800						1548		+			
801		+1				1560		–1			
878	–1					1585		+	+	+	
884		–1 +1				1601	+	+	+		+
901		–1				1617			+		
903	+					1631		–1	+		
912						1634		+			
972	+1					1666			–1		+
976		+				1677	+		+		
1004	–1					1679	+1	+1		+1	
1032		–1				1683	+				
1042						1699	+1	–1	+	–1	+
1051	+	+				1717	+1	–1	+		
1077	+	–1				1730	+	+	–1		
1099	+	+				1731					
1109		+				1732	+	+	+1		
1172	–1	–1 +1				1745		+			
1180						1757		+			
1201	–1	+1				1783		+1	+		+
1209	–1	+1				1797					
1258		+				1799		+1	+		
1259	+1					1811			+1		
1278		+1				1857			+		
1288		+				1862		+	+		
1312			–1			1867	–1	+	+1		
1328	+1	+1				1872		–1	–1		
1342	–1	–1				1879	–1	–1			
1350						1882	+				
1354		+1	+1			1884	+	+	+		+
1371		+				1885					
1383	+	–1				1891					
1435						1912	+	+	+		+
1440		+	–1			1916			+		
1453	+	+	+		+	1917		+1	+		
1455		+				1941	+	+	+		
1457		+	+			1958		–1	+1		
1466		+	+			1968		–1 +1	–1 +1		+
1481	+	–1				1970		–1	–1		
1509		+				1978		+	+		+
1523		–1				1980					
1531		+				1992		+		+	+
1535		+				1996					
1538		+	–1			1997					

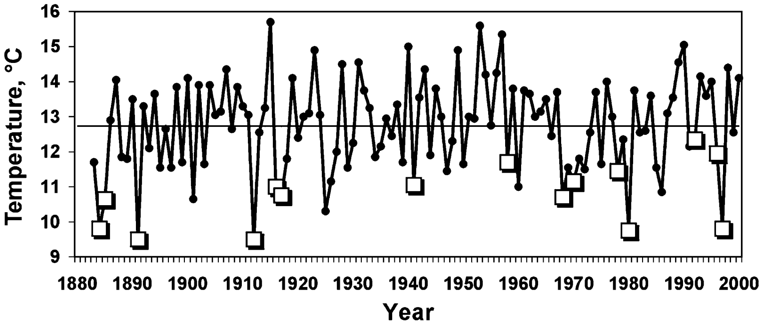

Fig. 3. July–August mean air temperatures from Salekhard weather station (1883–1999 period). (□) mark years when a significant proportion of trees formed light rings.

rings in both of these years. There are historical data for an eruption of Fuji, Japan in April AD 800 (Simkin and Siebert, 1994) with a Volcanic Explosivity Index (VEI) = 4. There are records of several other major eruptions, e.g., Dakataua, Papua New Guinea (VEI > 4), Popocatépetl, México (VEI > 3), that dated much less precisely to around AD 800 (Simkin and Siebert, 1994). However, apart from Fuji, we have not found any well-dated records mentioning traces of large volcanic eruptions at this time. Nevertheless, AD 800 was among the five coldest years in Fennoscandia during last 1400 years (Briffa et al., 1990); and in Quebec in AD 802, the majority of trees sampled formed a light ring.

In AD 1109 in Quebec, as well as in Western Siberia, light rings occurred in a significant fraction of the trees sampled, and it too was one of the five coldest years in Fennoscandia (Briffa et al., 1990). This may have resulted from the eruption of Hekla (Iceland) in about AD 1104.

The next two remarkable years are AD 1258 and 1259. In northwest Siberia, 1259 was most strongly expressed. In 1258 in eastern Canada, a significant fraction of spruce rings was light. Furthermore, in Mongolia (D'Arrigo et al., 2001), in both of these years, frost rings occurred in Siberian pine. Moreover, Russian chronicles mentioned frost during the summer of 1259 (Borisenkov and Pasetsky, 1988). Stothers (2000) described in detail the climatic and demographic consequences of the massive volcanic eruption in beginning of 1258. Oppenheimer (2003) dated this eruption as mid-1257. It was probably the world's largest volcanic eruption of the past millennium, or probably the last seven millennia (Zielinski, 1995), and was recorded in ice cores from both polar regions. Although this eruption clearly had global effects, its identity is unknown.

In 1278, a majority of larch and juniper samples from northwest Siberia showed frost or light rings. There is no other evidence of extreme climate events in tree rings. There is a trace of an eruption of an unknown volcano dated about (before) 1286 AD (Zielinski, 1995).

Growth anomalies in the 1453 ring are not especially extreme in the Polar Urals and Yamal, but are marked almost everywhere else. There are historical records (Borisenkov and Pasetsky, 1988) of a cold rainy summer in this year and during the subsequent 4 years in the European part of Russia, and also early autumn frost. The conventional reason for a global fall in temperature in 1453 is the Kuwae eruption, Vanuatu (Briffa et al., 1998).

AD 1466 is the most extreme year in the West Siberian chronology (excluding AD 801, for which

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Notes to Table 3:

Shadowed rows indicate years when extreme rings were formed in three or more regions. " − 1" and " + 1" indicate cases when the cooling in other regions was 1 year before or after the extreme year in northwest Siberia.

Data for Western USA from LaMarche and Hirschboeck (1984); Brunstien (1996); for east Canada from Filion et al. (1986); Delwaide et al. (1991); Yamaguchi et al. (1993); Wang et al. (2000); for northwest Canada from Szeicz (1996); for northeast Siberia from Hughes et al. (1999); for Northern Hemisphere from Briffa et al. (1998).

there are not enough data from juniper). All of the junipers from the Polar Urals and larches from Yamal showed frost or light rings in this year. There is historical information (Borisenkov and Pasetsky, 1988) that in this year in European Russia, snow covered ground even on May 26. On August 18, frost had already occurred, and the winter and following summer were cold. This year's event was reflected in tree rings of spruce from eastern Canada, light rings being found in almost all spruce examined (Wang et al., 2000). These effects were probably caused by the climatic consequences of the eruption of some as yet unidentified volcano. In the Greenland Ice Core GISP2 high peaks of volcanic aerosols were found in the ice layers for 1460 and 1461 (±2 years) (Zielinski, 1995). One possible source is volcanic eruption of Kuwae, Vanuatu, mentioned above. Therefore, this eruption was probably responsible for one of the global coolings, in 1453 or 1466.

The formation of light rings in many regions of the world in 1585 could be associated with the eruption of the volcano Billy Mitchell (SW Pacific).

Anomalous tree rings were formed in many regions in 1601. A large proportion of the samples from the Polar Urals and Yamal Peninsula have frost or light rings in 1601. Interestingly, our reconstructions of summer temperatures, based on tree-ring width data, for the Polar Urals (Hantemirov et al., 1999; Shiyatov et al., 2002) and Yamal Peninsula (Hantemirov and Shiyatov, 2002) showed that the average summer temperature of 1601 was at the long-term mean level. Nevertheless, some global event left its trace in tree rings of woody plants in this region. This was probably the climatic consequence of the eruption of Huaynaputina, in Peru at the beginning of AD 1600, the world's greatest eruption over the past 500 years (de Silva and Zielinski, 1998).

AD 1783 was noteworthy. The existence of a severe cold spell this year has been established by several authors (see Stothers, 1996), causing dry fog, and observed from England to the Altai Mountains. Cold weather reached Alaska (Jacoby et al., 1999), where lakes and rivers froze over in midsummer. This anomaly was caused by the eruption of Laki in the same year. In the wood layers formed in 1783 in the Polar Urals and Yamal Peninsula the frost and light rings were formed in the majority of trees and shrubs sampled. Moreover, the radial growth of tree rings from this region in 1783 was the least for the last 500–600 years (Shiyatov et al., 2002; Hantemirov and Shiyatov, 2002).

In 1884, the eruption of Krakatau (Indonesia) most probably caused the formation of anomalous tree rings in many regions of the world. Double frost injuries were found in spruce tree rings from northwest Siberia (Gurskaya and Shiyatov, 2002). In 1912, the Katmai eruption (Alaska) lowered summer temperatures abruptly, and in 1992, Pinatubo (Philippines) had a similar effect. However, our anomaly-based reconstruction did not show these years to be especially extreme.

5. Conclusion

The analysis of frost and light rings provides a promising method for reconstructing extreme temperature events in times before the advent of instrumental meteorological observations. In contrast to ring width, growth anomalies are produced by very short term events, and in some cases they occur within seasons that were not reconstructed as cold using ring-width data. In other words, this method enables us to obtain important information about past climate that is unachievable by other proxies.

Weather extremes in the Polar Ural Mountains and Yamal Peninsula, reconstructed by analysing anomalous structures in tree rings of Siberian juniper and Siberian larch, not only reflect global climatic anomalies most likely caused by major volcanic eruptions. They also record regional anomalies resulting from the specific processes of atmospheric circulation.

Frost and light rings in juniper and larch from northwest Siberia provide an invaluable aid in cross-dating tree-ring records from this region. Such "pointer years" as 800–801, 1109, 1258–1259, 1278, 1466, 1601, 1783 are very good markers for dating subfossil, historical and archaeological wood.

Acknowledgements

We thank Alexandr Surkov for his assistance in collecting wood samples, Prof. Malcolm Hughes and three anonymous reviewers for valuable comments on an earlier version of this paper, and again Prof. Malcolm Hughes for improving the English. This research was supported by the Russian Foundation for Basic Research (grants 01-05-65218 and 02-06-08004).

References

Borisenkov, E.P., Pasetsky, B.M., 1988. Tysyacheletnyaya Letopis' Neobychaynykh Yavleniy Prirody. Mysl, Moskva. 522 s (in Russian).

Briffa, K.R., Bartolin, T.S., Eckstein, D., Jones, P.D., Karlen, W., Schwengruber, F.H., Zetterberg, P., 1990. A 1400-year tree-ring record of summer temperatures in Fennoscandia. Nature 346 (6283), 434–439.

Briffa, K.R., Jones, P.D., Schweingruber, F.H., Osborn, T.J., 1998. Influence of volcanic eruptions on Northern Hemisphere summer temperature over the past 600 years. Nature 393 (6684), 450–455.

Brunstien, F.G., 1996. Climatic significance of the bristlecone pine latewood frost ring record at Almagre mountain, Colorado, USA. Arct. Alp. Res. 28 (1), 65–76.

D'Arrigo, R., Frank, D., Jacoby, G., Pederson, N., 2001. Spatial response to major volcanic events in or about AD 536, 934 and 1258: frost rings and other dendrochronological evidence from Mongolia and Northern Siberia: comment on R.B. Stothers, "Volcanic dry fogs, climate cooling, and plague pandemics in Europe and the Middle East" (Climatic Change, 42, 1999). Clim. Change 49, 239–246.

Delwaide, A., Filion, L., Payette, S., 1991. Spatiotemporal distribution of light rings in subarctic black spruce, Quebec. Can. J. For. Res. 21 (12), 1828–1832.

de Silva, S.L., Zielinski, G.A., 1998. Global influence of the AD 1600 eruption of Huaynaputina, Peru. Nature 393 (6684), 455–458.

Filion, L., Payette, S., Gauthier, L., Boutin, Y., 1986. Light rings in subarctic conifers as a dendrochronological tool. Quat. Res. 26, 272–279.

Glerum, C., Farrar, J.L., 1966. Frost ring formation in the stem of some coniferous species. Can. J. Bot. 44 (7), 879–886.

Glock, W.S., 1951. Cambial frost injuries and multiple growth layers at Lubbock, Texas. Ecology 32 (1), 28–36.

Gurskaya, M.A., 2000. Pathologicheskie struktury v drevesine listvennitsy sibirskoy proizrastayuschey v poyme r. Yadayachady-Yacha, poluostrov Yamal. Ekologia poym sibirskih rek i Arktiki. Trudy 2 soveschania, Tomsk, 24–26 noyabrya 2000 g. STT, Tomsk, pp. 76–84. In Russian.

Gurskaya, M.A., 2002. Morozoboinye povrezhdeniya ksilemy khwoynyh derev'ev v lesotundre Zapadnoy Sibiri i Polyarnogo Urala. Avtoreferat Dissertacii na Soiskaniye Uchenoy Stepeni Kandidata Biologicheskikh Nauk. Uro RAN, Ekaterinburg. 24 s (in Russian).

Gurskaya, M.A., Davy, N.M., 2001. Svetlye kol'tsa v drevesine khvoynykh derev'ev na priobskom severe. Sovremennye Problemy Populyatsionnoy, Istoricheskoy i Prikladnoy Ekologii. Akademkniga, Ekaterinburg, pp. 59–62. (In Russian).

Gurskaya, M.A., Shiyatov, S.G., 2002. Formation of two xylem frost injuries in one annual ring in Siberian spruce under conditions of Western Siberian forest-tundra. Russ. J. Ecol. 33 (2), 73–79.

Hantemirov, R.M., 2000. 4309-letnyaya khronologiya dlya Yamala i eyo ispolzovanie dlya rekonstrukcii istorii klimaticheskikh izmeneniy na severe Zapadnoy Sibiri. Problemy ecologicheskogo monitoringa i modelirovaniya ekosistem. Gidrometeoizdat, Sankt-Peterburg. T. 17, 287–301. (in Russian).

Hantemirov, R.M., Shiyatov, S.G., 2002. A continuous multi-millennial ring-width chronology in Yamal, northwestern Siberia. Holocene 12 (6), 717–726.

Hantemirov, R.M., Shiyatov, S.G., Gorlanova, L.A., 1999. Dendroklimaticheskiy potencial mozhzhevelnika sibirskogo. Lesovedenie 6, 33–38 (in Russian).

Hantemirov, R.M., Gorlanova, L.A., Shiyatov, S.G., 2000. Pathological tree-ring structures in Siberian juniper (*Juniperus sibirica* Burgsd.) and their use for reconstructing extreme climatic events. Russ. J. Ecol. 31 (3), 167–173.

Hughes, M.K., Vaganov, E.A., Shiyatov, S., Touchan, R., Funkhouser, G., 1999. Twentieth-century summer warm in northern Yakutia in a 600-year context. Holocene 9 (5), 629–634.

Jacoby, G.C., Workman, K.W., D'Arrigo, R.D., 1999. Laki eruption of 1783, tree rings, and disaster for northwestern Alaska Inuit. Quat. Sci. Rev. 18, 53–59.

Knufinke, A., 1998. Frostringe in Lärchen (*Larix decidua* Mill.) und deren Beziehung zu Wetter und Standort. Dargestellt an Material aus der Waldgrenz-Aufforstung Stillberg, Davos, Schweiz. Diplomarbeit an der Universität Bielefeld. Fakultät für Biologie. 112 s.

LaMarche Jr., V.C., Hirschboeck, K.K., 1984. Frost rings in trees as records of major volcanic eruptions. Nature 307 (5946), 121–126.

Nilov, V.N., Chertovskoy, V.G., 1975. O deystvii zamorozkov na podrost yeli. Ekologiya 4, 47–52. (in Russian).

Oppenheimer, C., 2003. Ice core and palaeoclimatic evidence for the timing and nature of the great mid-13th century volcanic eruption. Int. J. Climatol. 23 (4), 417–426.

Schweingruber, F.H., 2001. Dendroökologishe Holzanatomie. Anatomishe Grundlagen der Dendrochronologie. Haupt, Bern, Stuttgart, Wien. 472 pp.

Shiyatov, S.G., 1986. Dendrokhronologiya Verkhney Granicy Lesa na Urale. Nauka, Moskva. 136 pp. (in Russian).

Shiyatov, S.G., 1995. Reconstruction of climate and the upper timberline dynamics since AD 745 by tree-ring data in the Polar Ural Mountains. In: Heikinheimo, P. (Ed.), International Conference on Past, Present and Future Climate: Proc. of the SILMU Conf. Helsinki, Finland, 22–25 August 1995. Publication of the Academy of Finland, vol. 6/95, pp. 144–147. Helsinki.

Shiyatov, S.G., Gorlanova, L.A., 1986. Patologicheskie struktury v drevesine listvennicy sibirskoy. Botanitsheskie Issledovaniya na Urale. UNC AN SSSR, Sverdlovsk, p. 71. (In Russian).

Shiyatov, S.G., Hantemirov, R.M., Gorlanova, L.A., 2002. Millennial reconstruction of the summer temperature in the Polar

Urals: tree-ring data from Siberian juniper and Siberian larch. Archaeol. Ethnol. Anthropol. Eurasia 9 (1), 2–5.

Simkin, T., Siebert, L., 1994. Volcanoes of the World, 2nd ed. Geoscience Press, Tucson, Arizona. 349 pp.

Stoeckli, V.B., 1996. Tree rings as indicators of ecological processes: the influence of competition, frost and water stress on tree growth, size, and survival. Inaugural dissertation. Basel. 90 pp.

Stothers, R.B., 1996. The great dry fog of 1783. Clim. Change 32, 79–89.

Stothers, R.B., 2000. Climatic and demographic consequences of the massive volcanic eruption of 1258. Clim. Change 45, 361–374.

Szeicz, J.M., 1996. White spruce light rings in northwestern Canada. Arct. Alp. Res. 28 (2), 184–189.

Wang, L., Payette, S., Bégin, Y., 2000. A quantitative definition of light rings in black spruce (*Picea mariana*) at the arctic treeline in northern Québec, Canada. Arct. Antarct. Alp. Res. 32 (3), 324–330.

Yamaguchi, D.K., Filion, L., Savage, M., 1993. Relationship of temperature and light ring formation at subarctic treeline and implications for climate reconstruction. Quat. Res. 39, 256–262.

Zielinski, G.A., 1995. Stratospheric loading and optical depth estimates of explosive volcanism over the last 2100 years derived from the Greenland Ice Sheet Project 2 ice core. J. Geophys. Res. 100 (D10), 20.937–20.955.