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Extreme Cold Summers in Western Siberia, Concluded from Light-rings in the Wood of Conifers

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With 7 Figures

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Summary

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Wood samples of larch (*Larix sibirica* LEDEB.), spruce (*Picea obovata* LEDEB.) and pine (*Pinus sibirica* DU TOUR), growing in the northern taiga of western Siberia, were screened for the occurrence of light-rings – an anomaly of tree-ring formation in extreme environments. Light-rings were dated and the resulting species-related light-ring chronologies were used (1) to explore possible causes of light-ring formation and (2) to reconstruct past extreme climatic events. Light-rings in spruce and larch were mainly formed by an unusually cool May, June, August and September, whereas light rings in pine were associated with a cool July. Between 1740 and 1997 we identified seven years when all three species had formed light-rings and 15 years

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when light-rings were formed in larch and spruce, but not in pine. As concluded from linear regression, summer temperatures explained 43 and 50% of the variability of light-ring intensity in spruce and larch, respectively. However, not all light rings were formed in below-average cold summers but in a few cases even in above-average warm summers, indicating the limitation of this approach.

Zusammenfassung

GURSKAYA M. A., HALLINGER M., ECKSTEIN D. & WILMKING M. 2012. Extreme cold summers in western Siberia, concluded from light-rings in the wood of conifers. [Extrem kalte Sommer in West-Sibirien, abgeleitet aus "light-rings" im Holz von Nadelbäumen]. – Phyton (Horn, Austria) 52 (1): 101–119, mit 7 Abbildungen.

Bohrkerne von Lärche (*Larix sibirica* LEDEB.), Fichte (*Picea obovata* LEDEB.) und Kiefer (*Pinus sibirica* DU TOUR) aus der nördlichen Taiga in West-Sibirien wurden auf helle Spätholzzonen ("light-rings") – eine Anomalie der Holzbildung unter extremen Lebensbedingungen - untersucht. Diese light-rings wurden datiert und die daraus folgenden baumart-spezifischen light-ring-Chronologien genutzt, um (1) mögliche Ursachen der light-ring-Bildung zu erkunden und (2) frühere Wetterextreme zu rekonstruieren. Light-rings in Fichte und Lärche wurden zumeist bei ungewöhnlich kühlen Monaten Mai, Juni, August und September gebildet, während light-rings in Kiefer mit einem kühlen Juli in Verbindung standen. Zwischen 1740 und 1997 gab es sieben Jahre, in denen alle drei Baumarten light- rings aufwiesen, und 15 Jahre, in denen Lärche und Fichte, aber nicht die Kiefer light-rings gebildet hatten. Die Analyse der linearen Regression der Sommertemperatur ergab eine Variabilität der light-ring-Intensität von 43 und 50% für Fichte bzw. Lärche. Light-rings wurden jedoch nicht nur in kalten Sommern, sondern in wenigen Fällen auch in warmen Sommern gebildet. Dies weist auf die Grenzen unseres Ansatzes hin.

1. Introduction

Weather extremes such as frosts, droughts or floods can affect the physiology of plants and as a result the distribution of plant species as well as the functioning of ecosystems (GU & al. 2008, JENTSCH & al. 2007). Tracking such extreme events back into the past is a need for a deeper understanding of human history but at the same time a challenge because of the short duration of such weather episodes, the limited number of written records and the lack of climate data. Annual weather changes can be reconstructed from tree-ring width (e. g., COOK & KAIRIUKSTIS 1990, FRITTS 2001, SHIYATOV 1986, VAGANOV & al. 1996), isotope content of the wood (e. g., WATERHOUSE & al. 2000, SIDOROVA & al. 2009, YOUNG & al. 2011), wood density (e. g., WANG & al. 2001, BRIFFA & al. 2002, VAGANOV & KIRDYANOV 2010) or, since recently, from anatomical time series (e. g., FONTI & al. 2010). However, short-term detrimental weather events may occur in summers which have, on the whole, been beneficial for tree growth. One approach to detect such short-term and intense weather events in tree rings is to look out for irregular anatomical tree-ring features, such as frost rings (e. g., LAMARCHE & HIRSCHBOECK 1984, PAYETTE & al. 2010), density fluctuations (e. g., MASIAKAS & VILLALBA 2004) or light-rings (e. g., DELWAIDE & al. 1991). Whereas a frost ring indicates an extreme cold event of hours or days and light-rings relate to extreme events of weeks to months (e. g., DAY & PEACE 1937, FILION & al. 1986, LIANG & al. 1997, GINDL 1999, WANG & al. 2000, GURSKAYA & SHIYATOV 2002), density fluctuations can be attributed to dry episodes during summer (e. g., HOFFER & TARDIF 2009, RIGLING & al. 2002). Reconstructing extreme events from light-rings can turn out to be difficult, as light-rings occur rather infrequently. In northern latitudes, light-rings are usually formed when the growing season temperature drops below a certain threshold (e. g., YAMAGUCHI & al. 1993, GIRARDIN & al. 2009). But there are also biotically-induced light-rings described (LIANG & al. 1997). Drought-induced light-rings have up to now been reported only for semiarid areas (LIANG & ECKSTEIN 2006). Light-rings are characterized by a narrow band of latewood with either normally lignified cell walls (LIANG & ECKSTEIN 2006) or poorly lignified cell walls making the latewood appearing light colored (FILION & al. 1986, SZEICZ 1996, GINDL 1999).

In north-west Siberia, frost and cold spells are among the most frequent extreme weather events usually affecting large geographical areas. As meteorological stations are rare and most meteorological records extend back only to the 1930s and are sometimes incomplete, climate reconstructions based on tree-ring width, stable isotopes or wood density are an important source of annually resolved past climatic variability for this region. So far, climate reconstructions as well as research on light-rings in western Siberia have mainly been done at altitudinal and latitudinal tree lines (BRIFFA & al. 1998, HANTEMIROV & al. 2004, ESPER & al. 2010). But little is known about weather extremes in the northern taiga of western Siberia, south of the northern tree line.

Our study is, therefore, aimed at (1) exploring the climatic causes for light-ring formation of three coniferous tree species in the northern taiga of western Siberia, (2) establishing species-specific, discontinuous light-ring chronologies, and (3) using the occurrence of light-rings for the reconstruction of cold summers.

2. Material and Methods

2.1. Study Area

Our research area is situated at the transition between the taiga and the southern forest tundra in western Siberia (Fig. 1). The climate is influenced both by arctic air masses from the Arctic Ocean moving southward along the Ural Mountains without any topographic barrier as well as by the warm water of the Ob River moving from south to north making the regional climate comparatively mild. The amount of water runoff can indirectly influence the annual wood formation of trees growing in that region by changing the air temperature and microclimatic conditions (AGAFONOV 1995, BOGDANOV & AGAFONOV 2001). The soil is characterized by permafrost

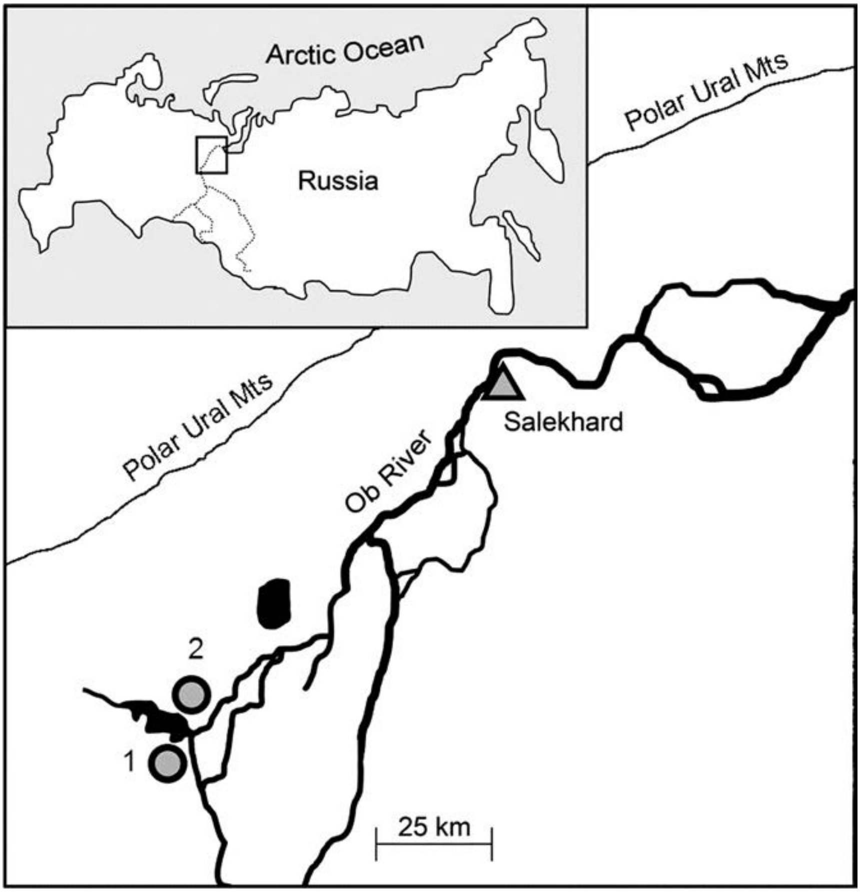


Fig. 1. Contour map of Russia (inset in the upper left corner) showing the location of the study area near the mouth of the Ob River [with the meteorological station Salekhard (grey triangle) and the study sites (grey circles)].

whereby the seasonal thawing does not exceed 50–150 cm in depth. The average annual air temperature at the Salekhard weather station is –4.8 °C, with +14.9 °C in July and –22.0 °C in January. The number of days with temperatures above 0 °C or 10 °C is on average 135 and 67, respectively. The snow cover lasts for around 220 days per year (AGAFONOV & al. 2004). The region is only little disturbed by man. Moreover, insect outbreaks were never registered here. This makes the Ob River floodplain area very interesting for climatic studies.

2.2. Site Characteristics

In 1996 and 2000, we sampled increment cores from 60 larch (*Larix sibirica* LEDEB.), 24 pine (*Pinus sibirica* DU TOUR) and 15 spruce (*Picea obovata* LEDEB.) trees at two sites (Fig. 1). Site 1 is located on the southwest side of the Vojkar Sor Lake (65°39′N, 64°20′E, 10 m a. s. l.). The trees are growing in a mixed larch-pine forest (Fig. 2) in a moist habitat with a loamy soil cover and an understory of marsh Labrador tea (*Ledum palustre* L.). In the early 1980s, a fire has burned most of the young trees whereas the old trees survived. The pine trees were on average 270 years and the larch trees 230 years old. Site 2 is located on the northeast bank of the lake (65°41′N, 64°36′E, 5 m a. s. l.). These trees are growing in a mixed spruce-larch forest on a long narrow sandy cape extending into the lake. We did not find any traces of fires here because the site seemed to be well protected by the water. Dogrose (*Rosa* sp.), grey alder (*Alnus incana* L.), dwarf birch (*Betula nana* L.) and marsh Labrador tea are forming the underbrush. All sampled trees were 15–17 m high and 40–45 cm in diameter at breast height. The spruce trees were on average 170 years and the larch 270 years old.

2.3. Climate Data

We used monthly mean temperatures (AD 1883-1997) and monthly sums of precipitation (AD 1890-1997) recorded at the Salekhard meteorological station (Fig. 1) (66°32′N 66°32′E, 16 m a.s.l.), 120 km northeast of our study area; this is the longest continuous meteorological record in the area.

2.4. Light-rings

We identified light-rings under a microscope with incident light by comparing the color and width of latewood as well as cell shapes with adjacent rings. Light-rings with both, narrow latewood of thick-walled tracheids as well as broad latewood of thin-walled tracheids, were identified for spruce, larch and pine (Fig. 3). Since both types occurred in any given year in different trees of the same species, we did further-on not differentiate between them. Several larch trees had tree rings of only 1–2 cell rows, especially in the beginning of the 19th and during the 20th century, what made the identification of light rings difficult. Nevertheless, we rejected the possibility that such narrow rings were caused by insect attacks since no insect outbreaks have been mentioned in the records. We also faced difficulties with Siberian pine whose tree rings were characterized by a narrow latewood band of very often thin-walled cells so that they could not be clearly distinguished from light-rings. This phenomenon has well been elaborated by Volney & Mallett 1992 for jack pine (*Pinus banksiana* Lamb.) in Canada showing that light-rings may be a source of error in determining tree ages, particularly in older stands.

Species-specific light-ring chronologies were derived as percentage values of light-rings compared to the total number of rings in a given year. Henceforth only those parts of the chronologies consisting of at least three trees were analyzed (spruce, back to 1797; for once, we included the year 1783 because it is a well-known and distinct light-ring year throughout the northern hemisphere (Jacoby & al. 1999, Hantemirov & al. 2011); larch, 1620; pine, 1664). The period covered by instrumental temperature measurements (back to 1883) and used for correlating climate with light-ring formation was represented by a nearly constant number of trees (spruce, 13; larch, 35–37; pine, 24).

Then, these light-ring chronologies were correlated with the contemporaneous monthly temperature and precipitation to identify the climatic signal contained in

Fig. 2. Study site 1 with young *Larix sibirica* LEDEB. and *Betula pubescens* EHRH. subsp. *tortuosa* (LEDEB.) NYMAN.

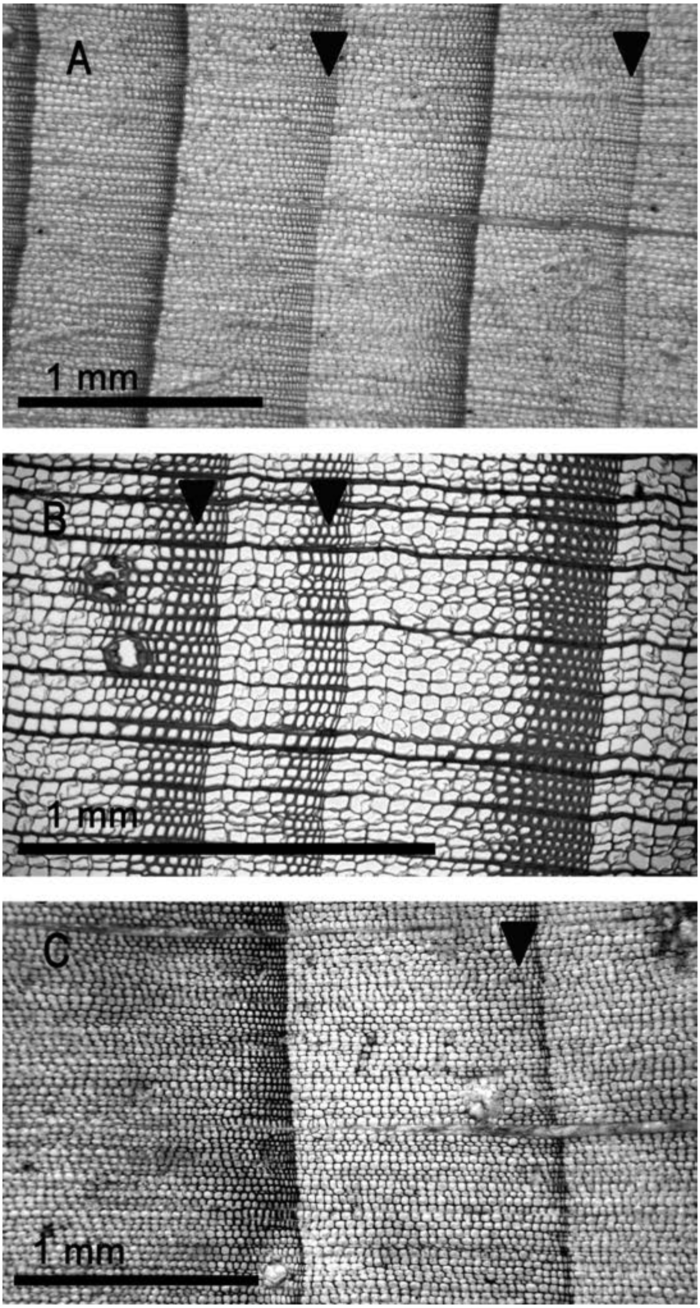


Fig. 3. Light-rings (arrow heads) in coniferous trees in the northern taiga in Russia. – A spruce. – B larch. – C pine.

light-rings and thus to explore their potential to reconstruct extremely cold summers.

Finally, all light-rings were ranked according to their frequency in a given year into three groups: (1) >30% light-rings, (2) between 30–10% and (3) <10%. To validate the spatial extent and synchrony of years with extreme weather conditions, we compared our data with light-ring chronologies for the Yamal peninsula (300–400 km north of our study area) and for the Polar Ural Mts. (150 km apart from our study area) (HANTEMIROV & al. 2004). These are the nearest regions where climatic extremes and in particular light-rings have been studied.

3. Results

3.1. Light-ring Chronologies

In the Ob River flood plain, the light-ring frequency related to the total number of tree rings was 2.9% in spruce, 2.8% in larch and 1.5% in pine.

Light-rings were unevenly distributed over time in all three species (Table 1, Fig. 4). In the 20th century, light-rings were formed in 14 years in spruce, 24 years in larch and seven years in pine, whereas in the 19th century we identified 12, 23 and 17 light-ring years, respectively. In the 18th century, we noticed 10 light-ring years in the larch chronology and 19 light-ring years in the pine chronology; the spruce chronology was not considered in this period of time because it was covered by only two trees.

Seven years with light-rings were common to all three tree species (1783, 1797, 1857, 1862, 1879, 1882, 1926) (Table 1). The two chronologies with the highest percentage of light-rings (larch and spruce) showed a high light-ring synchrony, that means, light rings common for larch and spruce were identified for 22 years.

The width of light-rings and non-light-rings were statistically not different; the mean values and standard deviations are 0.7 ± 0.2 vs. 0.6 ± 0.2 mm for spruce, 0.6 ± 0.2 vs. 0.6 ± 0.2 mm for larch and 0.4 ± 0.2 vs. 0.5 ± 0.2 mm for pine.

Table 1. Light-ring years in three conifer species (*Picea obovata, Larix sibirica* and *Pinus sibirica*) in the northern taiga of western Siberia. <10% (+); 30–10% (++); >30% (+++) light-rings.

Years	Spruce	Larch	Pine		Spruce	Larch	Pine
1559		+++		1848			+
1575		+++		1849		+	
1583		+++		1852	++	+++	
1585		+++		1857	+++	+++	+
1591			+++	1858	++	++	
1620		+++		1860			+
1621		+++		1862	+++	++	++
1627			+++	1863		+	

Years	Spruce	Larch	Pine		Spruce	Larch	Pine
1630		+++		1866		++	+
1633			+++	1868			+
1642			+++	1872	+++	+++	
1644			+++	1873		++	
1683			+++	1875		++	
1687			+++	1878	++	+++	
1696			+++	1879	++	+	+
1699			+++	1880	+		
1706		+++		1882	++	++	+
1708			+++	1884	+++	+++	
1717		++		1885		++	
1730			++	1886		++	
1731			+	1891	+++	++	
1732			++	1895		+	
1740			+	1901	+		+
1742			+	1905		++	
1744			+	1906			+
1745		++	++	1908	+		
1746			++	1912		+	+
1747		++	++	1914			+
1752		++		1916		++	+
1761			+++	1917	+	++	
1764			+	1918	+++	++	
1766			++	1921		+	
1772			+	1924		+	
1780			+	1925	+	+	
1783	+++	+++	+++	1926	++	+	+
1786			+	1929	+		
1792	+++	++		1933	++	+	
1794			+	1939		+	
1797	++	++	+	1942		+	
1798		++		1943		+	
1799		+++		1944	+++	++	
1800			+	1952	++		
1804			+	1958	+++	++	
1808			++	1964			+
1810			+	1968		+	
1811			+	1969	+++	+	
1818			+	1970	++		
1819			+	1971		+	
1825		++	+	1978	+++	++	
1831	++		+	1982		+	
1832		++		1983		+	
1843		++		1992		+	
1844		+		1994		++	
1847		+		1996		++	

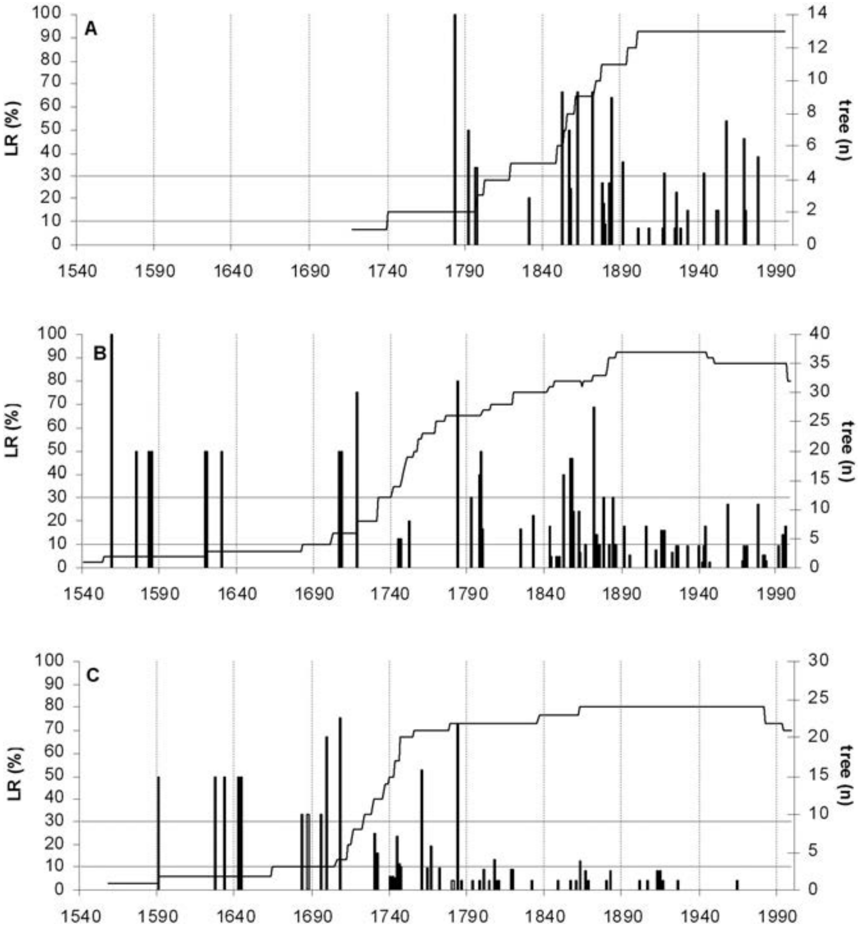


Fig. 4. Distribution of light-rings over time. – LR light-rings (bar). – A spruce. – B larch. – C pine. – Stepped line: number of trees; horizontal lines: 10 and 30% of light-rings, respectively.

3.2. Climatic Response of Light-rings Between 1883 and 1997

The intensity of spruce light-rings (altogether 16) correlated negatively with May, June, August and September mean temperatures (Fig. 5). In the seven years with more than 30% of light-rings, the temperatures in May, August and September were on average by 2.8/2.0/0.7 °C below their long-term means, calculated from the 120-year climate record. If all 16 spruce light-rings were taken into account, 43% of the variability of their intensity was explained by May, August and September temperatures (Fig. 6 A); June temperature was by 1.8 °C below its long-term mean, but explains only 9% of the variance of the light-ring intensity.

The intensity of larch light-rings (altogether 29) correlated also negatively with May, June, August and September mean temperature (Fig. 5). The highest correlation, accounting for 50% of the variability, was found for August-September temperature (Fig. 6 B) whereas May and June temperatures accounted for only 5 and 9%, respectively. In years with more than 10% of light-rings, the temperatures in August and September were on average by 1.5/0.7 °C, respectively, below their long-term means.

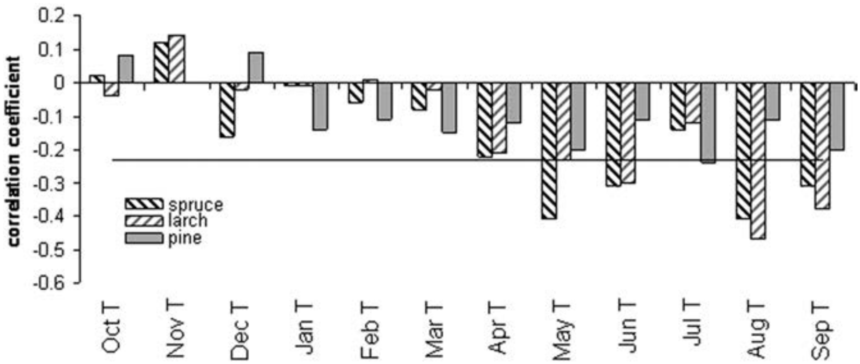


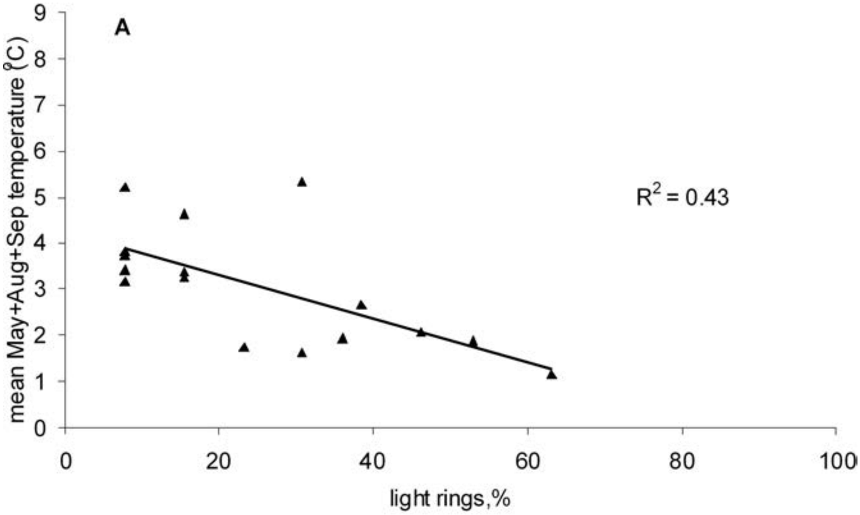
Fig. 5. Correlation between light-rings and air temperature, separated by tree species; values significant at the 95% confidence level go below the horizontal line.

The pine light-ring chronology correlated weakly, but significantly, only with July mean temperature (r = –0.22), thus explaining 5% of the variability of the light-ring intensity.

A comparison between the highly significant temperature variables (May/Aug./Sept. for spruce; Aug./Sept. for larch) registered from 1883 to 1997 and the temperature derived from the light-rings – according to the regression equations in Fig. 6 – is given in Fig. 7. The temperature reconstruction, based on the larch light-ring chronology, was stronger associated with the measured temperature than the temperature reconstruction, based on the spruce light-ring chronology.

3.3. Extreme Summers Between 1740 and 1997 Concluded from Light-rings

The highest frequency of light rings was identified for seven years (1783, 1797, 1857, 1862, 1879, 1882, 1926), when up to more than 30% of all tree rings in all three species were light-rings. In these years the summers are considered to have been extremely cool in the area. However, not in all years with a cold onset and end of the vegetation period a light-ring was formed. For example, in 1901 and 1986 light-rings were missing in larch although these years were characterized by low temperatures during the



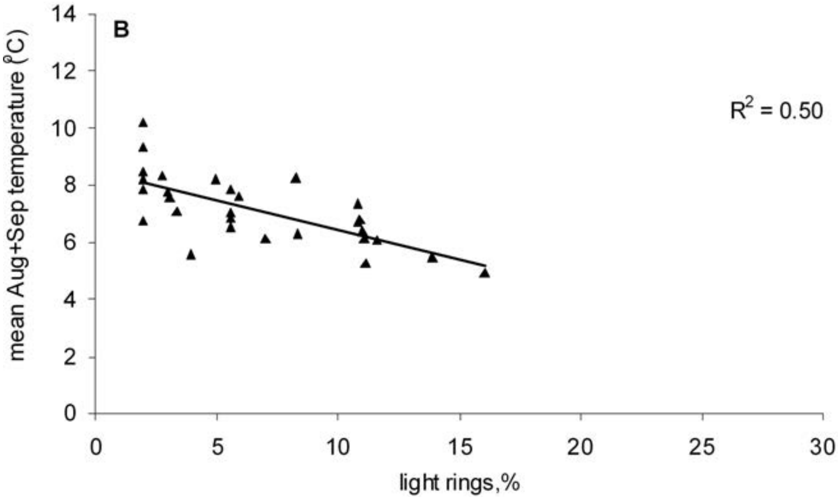


Fig. 6. Linear regression between temperature per group of months and light-rings. – A spruce, y = –0.047x + 4.266. – B larch, y = –0.206x + 8.505. – All correlations are significant at $p < 0.05$.

entire growing season and extremely low temperatures in August-September (according to the meteorological record of the Salekhard weather station). Only in spruce, we observed a few light-rings in 1901. Light-rings were even occasionally formed in summers warmer than the long-term mean temperature.

Based on only spruce and larch light-rings, extremely cool summers may have additionally occurred in the years 1792, 1872, 1884, 1891, 1958, 1969, and 1978 (Table 1). Years in which less than 10% of all tree rings were light-rings partly occurred during periods of positive June-July temperature anomalies. Still, May, August and September temperatures of these years were lower than the long-term mean.

3.4. Light-rings Formed in Warm Summers

Occasionally, light-rings were even formed in summers warmer than the long-term mean temperature, for example, one light-ring each in 1908, 1944 and 1952 in spruce, or in 1905 in one larch. But this occurred in one tree or, at maximum, two trees of either pine or spruce or larch, never in two or three species at the same time. Currently, the data basis is too small to decide whether this phenomenon is restricted to individual trees growing under specific, at present unknown, micro-site conditions. In any case, the occurrence of such rare cases of light-rings indicates some limitation of our approach. At least a sufficient number of trees must be investigated.

4. Discussion

4.1. Light-rings and Reconstruction of Extreme Events in the Ob River Floodplain

In the Ob River floodplain, the weather conditions during the growing season of most years vary within a narrow band so that the cambium and its derivative cells do not show any distinctive features. In cold summers, however, with a short growing season when light-rings are formed, cambial cell division either begins essentially later than usual or stops earlier, i. e., as soon as the weather conditions become unfavorable. Temperatures at the end of the growing season (August-September) seem to be of high importance for light-ring formation in larch, while the temperature both at the beginning (May) and end of the growing season (August and September) were triggering light-ring formation in spruce. The lower negative correlation between larch light-ring formation and early summer temperatures (May-June), compared to spruce, might result from the yearly renewal of the photo-assimilation system in larch. Because of the small number of light-rings in pine during the period of instrumental temperature measurements, no clear climate/growth relationship with specific months could be established for the light-ring formation in pine.

We found seven years with a high percentage of light-rings in spruce and larch (and to a moderate extent in pine): 1783, 1857, 1872, 1884, 1958, 1969 and 1978. The year 1783 is known as one of the most extreme years for the growth of conifers within the last 400 years (Briffa & al. 1998, Jacoby & al. 1999) because the eruptions of the Icelandic volcanoes Laki and Grímsvötn with a volcanic eruption index (VEI) of 4 caused a cold northern hemisphere summer and subsequently the light-ring formation in our study trees. The cold summer of 1857 was triggered by the eruptions of the volcanoes Sheveluch, Kamchatka, in 1854 (VEI=5) and Komaga-Take, Japan, in 1856 (VEI=4). Two volcano eruptions in 1872 (Sinarka, Kuril Islands and Merapi, Java, Indonesia; VEI=4) could have led to the light-ring formation in 1872. The light-ring in 1884 could have been induced by the explosion of the volcano Cracatoa, Indonesia in 1883 (VEI=6) (SIMKIN & SIEBERT 1994). The light-ring in 1958 appears to be associated with the directed blast eruption of the Bezymianny volcano, Kamchatka, in 1956 (VEI=5) (BELOUSOV & al. 2007), whereas the light-ring in 1969 can be attributed to the eruptions of the Kelut and Awu volcanoes, Indonesia, in 1966 (VEI=4) and of the Fernandina volcano, Galápagos Islands, in 1968 (VEI=4) (HANTEMIROV & al. 2004). Finally, the light-ring in 1978 may have been induced by the largest historical basaltic eruption of Tolbachik, Kamchatka, in 1975-1976 (VEI= 4) (FEDOTOV 1984) and the eruption of Augustine, Southwestern Alaska, in 1976 (VEI=4).

Interestingly, there are also years of eruptions with VEI=4 without any light-ring formation in our study area. For example, eruptions with VEI > 6 in 1815 (Tambora, Lesser Sunda Islands, Indonesia) and in 1912 (Novarupta, Alaska Peninsula) did not lead to light-rings in the following 2–3 years. For 1816-17 though, light-ring formation has been reported for black spruce in Northeast America (YAMAGUCHI & al. 1993) indicating large-scale heterogeneities in the expression of unfavorable growing conditions. In these years, our three coniferous species in the Siberian northern taiga reacted by displaying frequently narrow or missing rings. It therefore seems that in years that are generally cold, all physiological processes are slowed down but ring formation as such stays normal. Thus, light-rings seem to form only when there is a temperature gradient from cold to warm or vice versa during the growing season. The temperature gradient in and after 1815 or 1912 was probably too weak to result in light-ring formation. It is commonly observed in most light-ring studies, that not all cold summers reaching the temperature threshold for light-ring formation (FILION & al. 1986, GIRARDIN & al. 2009, SZEICZ 1996, YAMAGUCHI & al. 1993) actually provoke the formation of light-rings. In our study area, light-rings also occurred in years warmer than the long-term mean (1840–60) probably caused by cold periods of shorter duration that did not affect the mean temperature of the respective year. In general, tree growth as concluded from our study seems more susceptible to episodes of cold within warm periods (GU & al. 2008).

4.2 Validation of the Reconstruction by Other Data of Extreme Events

A comparison of the spatio-temporal distribution of light-rings at the West-Siberian latitudinal and altitudinal tree line (HANTEMIROV & al. 2004) and in the northern taiga (our study area) showed many common years characterized by cold air-mass circulation during the vegetative season,

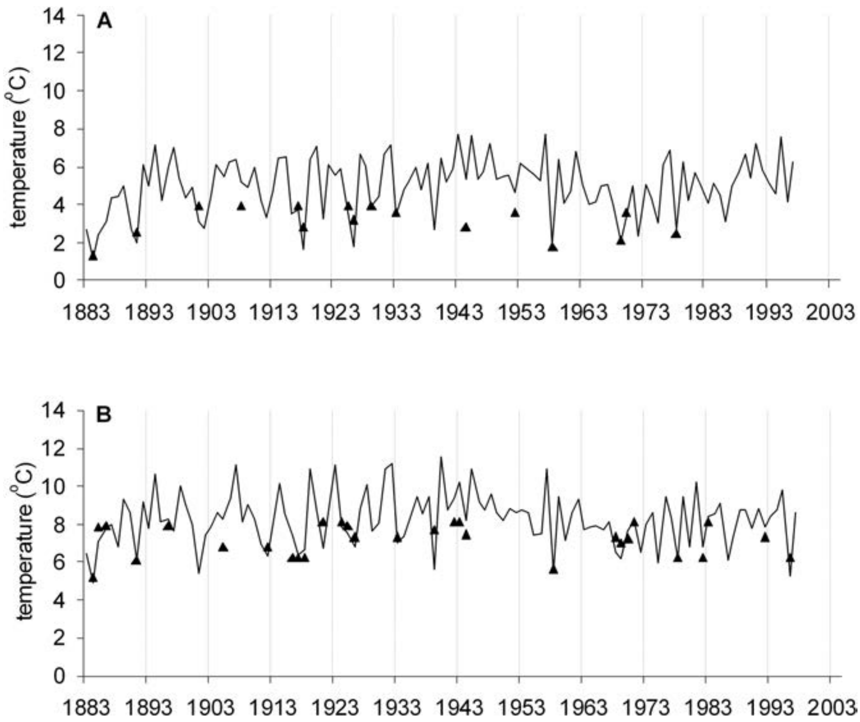


Fig. 7. Comparison between temperature measured (line) and temperature concluded from light-rings (black triangles). – A spruce light-rings vs. average May/Aug./Sep. temperature. – B larch light-rings vs. average Aug./Sept. temperature.

especially during cold periods. During warm periods, however, asynchronous formation of light-rings could be observed (e.g. 1920–1930 and 1980–1990): In the 1920s, many light rings formed in northern taiga trees, but not so intensely and frequently in trees in the river floodplain of the Yamal Peninsula. In the 1980s, the opposite situation occurred with rare occurrence of light-rings in the northern taiga, but frequent light-rings on the Yamal Peninsula. At this point, we can only guess why this decoupling during generally warm periods occurred; a more in-depth analysis of the spatio-temporal pattern of light-ring formation in northern Eurasia is envisaged.

Our light-ring-based summer temperatures (Fig. 7) calculated for the northern taiga resembled tree-ring width/density based temperature reconstructions in western Eurasian regions, such as the Yamal Peninsula and the Polar Ural Mountains (SHIYATOV & al. 1996, 2002, HANTEMIROV & al. 2011), Fennoscandia (BRIFFA & al. 1990) and North-Eurasia (JONES & MOBERG 2003, SIDOROVA & al. 2007). Most low-temperature anomalies that were characteristic for high latitude Eurasia are synchronous with years of light-ring formation in our tree species of the northern taiga zone.

5. Conclusions

Our exploratory study underlined the possibility of assessing extreme climatic events in Siberia, such as a cold onset or a cold end of the vegetative season, from the climatic footprint contained in light-rings of different tree species, since each species reacts to a different set of monthly drivers. Light-ring formation in larch was caused by August-September temperatures below the long-term mean of these months. Light-rings in spruce showed a joint effect of low temperatures during the onset and end of the growing season. However, it is obvious that despite significant correlations between temperature and light-ring occurrence, light-ring formation does not follow simple causalities and therefore merits further research. The study of light-rings and other anatomical tree-ring anomalies remains promising as it has the unique potential to unveil past weather or climate events that are of too short duration to be tracked by any other climate proxy.

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