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RESEARCH ARTICLE

Specific peculiarities of woody-tree radial growth in icing areas of the Altai mountains

Nikolay I. Bykov[1], Natalia V. Rygalova[1], Anna A. Shigimaga[1]

1 *Institute for Water and Environmental Problems, Siberian Branch, Russian Academy of Sciences, 1 Molodeznaya st., Barnaul, 656038, Russian Federation*

Corresponding author: Nikolay I. Bykov (nikolai_bykov@mail.ru)

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Abstract

The following features of the radial growth of *Picea obovata* L., *Larix sibirica* L., and *Pinus sibirica* Du Tour in the icing areas of Altai were analyzed: changes in growth along the trunk height, synchronicity of individual tree-ring chronologies, and sensitivity of generalized chronologies. The dependence of the width of the annual rings of the studied trees using such indicators as the volume and area of icing, the date of gathering of icing and the index of the intensity of icing formation was established. For the analysis, data from the state hydrometeorological station, remote sensing of Earth, literary sources, and materials from our own dendrochronological works were used.

Keywords

Altai, icing, tree rings, woody plants

Introduction

Icing is understood to be layered arrays of ice masses on the surface of the earth, comprised of ice or highly organized ice structures formed during the freezing of periodically erupting (precipitating) and man-made waters (Alekseev 1987). Depending on what waters take part in the formation of ice, such as atmospheric, surface, and groundwaters (Alekseev 1987). In regions with long-term and deep seasonal freezing of ground and soils, as well as in regions with perennial unfrozen rocks, icings occupy a significant area and have a great influence on all components of the natural complex.

Vegetation cover in areas of icing development show signs of external influences in their growth. The periodic release of icing waters onto the ice surface and their subsequent freezing causes cell ruptures in plants, heaving and wedging of fibers, the formation of cracks in woody plants, as well as peeling of bast (phloem) and bark. Horizontal and vertical movements of icing, which arise from a result of gravitational pressure, thermal expansion and compression of ice, as well as heaving, cause mechanical damage or death of plants. Longer-term gathering of icing during the warm period causes a delay in the phenological development of plants in icing areas (Alekseev and Novitskaya 1985; Bykov 1999), a change in the species composition of plants, and, in the case of the development of thick icing, the complete disappearance of plant cover.

In view of geosystem significance of icings, as well as the need to assess the risk of icing formation for engineered structures, such as woody plant tissue, the question of predicting these phenomena arises. However, long-term observations of the icing regimes are practically absent, except for random polygons, so there is a need to resolve data on this phenomenon using indication methodologies. One of these indication methods is using tree-rings as indicators, which is based on identifying the relationship between the parameters of tree rings and indicators of the observed phenomenon. A study of ice deposits on woody plants was carried out by several Russian authors (Alekseev 2005; Pomortsev et al. 2007; Nikolaev et al. 2004). For remote areas, based on field studies, relationships were established between small tree rings and the thickness of icing (Alekseev 2005), and significant differences in tree-ring chronologies (TRCH) and dendrochronological measurements from trees from one icing area were identified (Nikolaev 2010). Based on the studied connections, spatiotemporal reconstructions of individual icings were adopted (Efremov, Nikolaev 2005; Nikolaev 2010; Pomortsev et al. 2017). On the territory of the Altai mountains, an attempt was made to reconstruct their effects of long-term regime on woody plant growth in the Central and Eastern Altai (Bykov 1991; Bykov 1998; Bykov 1999; Savchuk et al. 2021).

The purpose of this study is to investigate the natural radial growth of trees in icing areas of the Altai mountains and to analyze the possibility of using tree-ring indicators to reconstruct the history of long-term icing regimes. The objective of the study is to analyze the similarity of natural tree-ring chronologies (TRCHs) in individual icing areas and explore the possibility of constructing standardized or generalized TRCHs, as well as to test the relationship of TRCHs with the area and volume of icing, the dates of gathering of icing and the index of the duration of icing formation.

Materials and methods

Altai is a vast mountainous region, parts of which differ significantly from each other in physical and geographical terms. In this regard, icings are distributed extremely unevenly in Altai. They occupy the largest areas in the South-Eastern, Central and Eastern Altai, the major physical-geographical “provinces” of Altai, the climate of which is characterized by the highest index of winter continentality (Revyakin 1981). Here, a significant proportion of icings is occupied by groundwater icings, the release of which is, among other things, is due to cryogenic pressure arising as a result of seasonal freezing of ground and soils. Some ice dams consisting of icings can be several meters thick at their maximum development. This inevitably entails the transformation of natural complexes under the influence of icing formation. However, their influence is determined by many other factors: the thickness of the ice on the icing-covered area, the altitude of the area above sea level, the slopes and exposure of the slopes, etc. This sometimes results in multidirectional effects of icings on vegetation, including woody plants (Bykov 1999). For example, the same thickness of icing on slopes of northern exposure can lead to the elimination of tree stands, and on steppe slopes of southern exposure it can promote the development of woody plants. Similar changes are noted along the altitudinal gradient: in the mountain-forest belt, icings eliminate the tree stand, and in the mountain-forest-steppe and mountain-steppe, on the contrary, they support it.

To assess the influence of icings on the radial growth of woody plants, we selected icing areas of the Kubadra river basin (left tributary of the Bashkaus river) and the Akru river basin (left tributary of the Chuya River), as well as the Tyurgun stream (right tributary of the Chuya River) (Fig. 1). Since trees are rare in many icing areas, the number of samples taken was uneven and sometimes insignificant (Table 1). From the trunks of living trees, samples in the form of drill cores were taken at a height of 30 and 130 cm, and from a small number of dead trees, cuts were taken at several levels. This was done to establish the influence of icing in direct contact with the tree. Measurements of the width of tree rings were carried out using a semi-automatic Lintab 6 installation with an accuracy of 0.01 mm (Shiyatov et al. 2000). Standardization and generalization of dendrochronological series was carried out in the ARSTAN program. To estimate tree-ring chronologies of specific sites, EPS (The Expressed Population Signal) was used, and for generalized chronologies, mean sensitivity was used (Speer 2009). Generalized chronologies for sites were constructed if the EPS value was equal to or higher than 0.85. The sensitivity coefficient characterizes the variability of growth from year to year. The sensitivity coefficient characterizes the variability of growth from year to year. It is considered satisfactory at a value of 0.3 and above.

There are practically no published data on the long-term dynamics of icings in the study area, with the exception of a 12-year series of observations in the Aktru Valley (Narozhny 1997). Here, observations were made on the periglacial icings "Maly Aktru" and the icing "GMS", which includes all the other icings of the trough part of the Aktru valley. Two dendrochronological sites were laid out on the icings of the HMS – 12Np and 13Np. For all studied areas, the dates of gathering of icing were established in 2013–2021, according to satellite data (Sentinel and Landsat satellites).

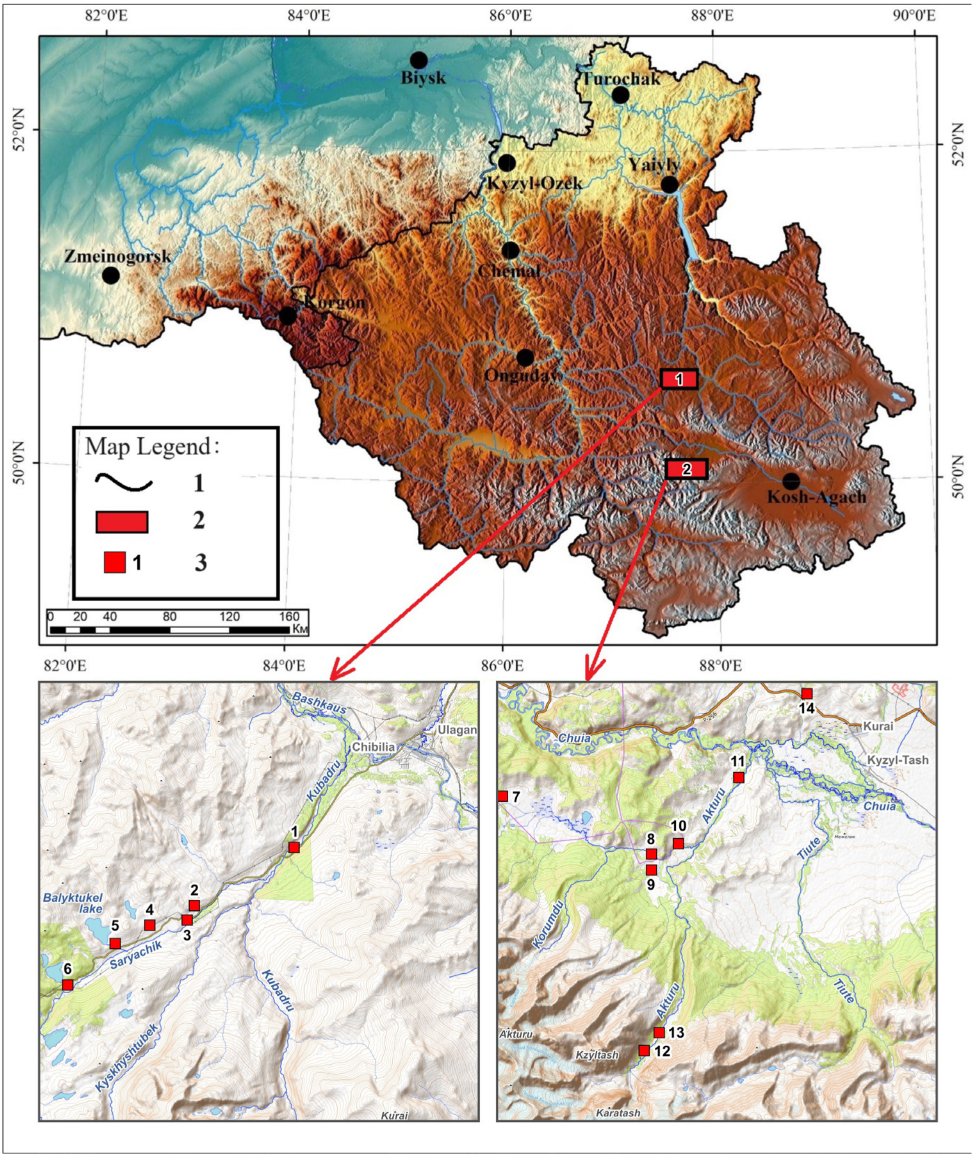

Figure 1. Geographical location of research areas. Legend: 1 – State and administrative boundaries; 2 – Research areas (1 – Kubadru river basin; 2 – Aktru river basin); 3 – Numbers of districts.

Table 1. Geographical location of the studied ice areas and characteristics of the studies trees

Site number	Coordinates	Absolute elevation of the terrain, m	Species	Number of samples	Height of icing salt deposits, cm
			Kubadru River Basin		
Np1	50.5749 87.8569	1350	*Picea obovata* L.	30	45–130
			Larix sibirica L.	6	
Np2	50.5436 87.7784	1640	*Picea obovata* L.	12	20–40
			Larix sibirica L.	12	
			Pinus sibirica Du Tour	2	
Np3	50.5400 87.7736	1665	*Larix sibirica* L.	10	60–150
Np4	50.5338 87.7459	1760	*Larix sibirica* L.	12	25–70
Np5	50.5275 87.7167	1810	*Larix sibirica* L.	10	40–100
Np6	50.5088 87.6765	1930	*Larix sibirica* L.	8	50–150
			Aktru River basin		
Np7	50.1983 87.6727	1805	*Larix sibirica* L.	10	35–40
Np8	50.1694 87.7779	1655	*Larix sibirica* L.	10	150–155
			Picea obovata L.	2	
Np9	50.1657 87.7850	1640	*Larix sibirica* L.	2	100
			Picea obovata L.	2	100
Np10	50.1784 87.8013	1584	*Picea obovata* L.	8	160–200
			Larix sibirica L.	2	
Np11	50.2097 87.8480	1490	*Larix sibirica* L.	10	50–100
Np12	50.0837 87.7813	2120	*Larix sibirica* L.	20	50–150
Np13	50.0958 87.7925	2080	*Larix sibirica* L.	14	50–150
			Picea obovata L.	4	
			Basin of the Tyurgun stream		
Np14	50.2509 87.8935	1560	*Picea obovata* L.	10	35–45

To assess the growth of trees in icing areas, the icing index was also used (Tsvid, Khomichuk 1981). It was calculated using the Ust-Ulagan weather station using the formula:

$$In = \frac{QVIII{-}IX \times \sum TX{-}IV}{1+5h},$$

where h is the maximum thickness of snow cover for the winter period in meters, $QVIII\text{-}IX$ is the sum precipitation for August–September in meters, and $\sum TX - IV$ is the sum of average monthly air temperatures for October–April in °C. The relationship between tree-ring chronologies and icing indicators was determined by calculating Pearson correlation coefficients.

Result

Analysis of the resulting tree-ring chronologies made it possible to establish that the age and width of tree rings vary widely in the studied icing areas (Table 2). The average age of trees on the sites varies from 55 (*Picea obovata* L., site Np9) to 217 years (*Larix sibirica* L., site Np2), and the average width of annual rings ranges from 0.43 mm (*Larix sibirica* L., site Np13) to 2.71 mm (*Picea obovata* L., site Np14). In general, there is a stable dependence of the average width of tree rings on the age of trees, which indicates the presence of an age-related trend of a decrease in the width of tree rings.

Table 2. Average characteristics of the age and width of tree rings in areas covered with icing

Site number	*Larix sibirica* L.		*Picea obovata* L.		*Pinus sibirica* Du Tour	
	Age	Width of annual ring, mm	Age	Width of annual ring, mm	Age	Width of annual ring, mm
Np1	74	1.9	87	1.82	-	-
Np2	217	0.86	177	0.89	88	0.81
Np3	179	0.80	-	-	-	-
Np4	67	1.47	-	-	-	-
Np5	106	1.07	-	-	-	-
Np6	111	1.01	-	-	-	-
Np7	99	1.68	-	-	-	-
Np8	132	1.28	107	1.07	-	-
Np9	63	1.33	55	1.64	-	-
Np10	154	0.62	93	1.31	-	-
Np11	84	1.70	-	-	-	-

Site number	***Larix sibirica* L.**		***Picea obovata* L.**		***Pinus sibirica* Du Tour**	
	Age	**Width of annual ring, mm**	**Age**	**Width of annual ring, mm**	**Age**	**Width of annual ring, mm**
Np12	93	0.92	-	-	-	-
Np13	177	0.43	61	0.691	-	-
Np14	-	-	58	2.71	-	-

Analysis of the growth at different heights within the tree trunk in icing areas did not show an unambiguous trend: there was a decrease in the width of the annual ring with trunk height (Table 3). In 28 out of 53 trees examined in the icing areas of the Kubadru River basin, the width of the annual ring at a height of 30 cm was greater than at a height of 130 cm. A similar situation is observed in trees in the Aktru River basin.

Table 3. Average width of growth rings (mm) at different trunk heights for the same periods in the ice-covered areas of the Kubadru river basin

Tree number	**Np1**				**Np2**						**Np3**	
	***Picea obovata* L.**		***Larix sibirica* L.**		***Picea obovata* L.**		***Pinus sibirica* Du Tour**		***Larix sibirica* L.**		***Larix sibirica* L.**	
	Sampling height											
	30 cm	**130 cm**	**30 cm**	**130 cm**	**30 cm**	**130 cm**	**30 cm**	**130 cm**	**30 cm**	**130 cm**	**30 cm**	**130 cm**
L1	3.19	2.81	1.32	1.38	0.89	1.33	0.66	0.94	0.37	0.63	0.51	0.32
L2	1.74	2.6	2.74	3.36	0.35	0.47	-	-	1.17	0.78	0.87	0.71
L3	2.98	2.45	1.82	1.8	0.75	0.87	-	-	1.62	1.18	0.98	0.78
L4	2.22	1.77	-	-	2.01	1.26	-	-	0.6	0.63	1.19	0.64
L5	1.71	3.31	-	-	0.6	0.95	-	-	0.48	0.67	1.01	0.82
L6	1.81	1.23	-	-	0.64	0.78	-	-	-	-	-	-
L7	0.92	1.11	-	-	-	-	-	-	-	-	-	-
L8	2.35	2.88	-	-	-	-	-	-	-	-	-	-
L9	1.53	1.04	-	-	-	-	-	-	-	-	-	-
L10	3.08	1.31	-	-	-	-	-	-	-	-	-	-
L11	2.21	2.16	-	-	-	-	-	-	-	-	-	-
L12	1.94	1.44	-	-	-	-	-	-	-	-	-	-
L13	0.72	0.89	-	-	-	-	-	-	-	-	-	-
L14	1.64	1.94	-	-	-	-	-	-	-	-	-	-
L15	1.63	1.1	-	-	-	-	-	-	-	-	-	-

Tree number	**Np4**		**Np5**					**Np6**				
	***Larix sibirica* L.**		***Larix sibirica* L.**					***Larix sibirica* L.**				
	Sampling height											
	30 cm	**130 cm**	**30 cm**	**40 cm**	**80 cm**	**120 cm**	**130 cm**	**20 cm**	**30 cm**	**100 cm**	**130 cm**	**200 cm**
L1	1.21	1	1.51	-	-	-	1.86	-	1.69	-	1.31	-
L2	2.41	2.43	0.73	-	-	-	0.9	-	1.47	-	1.44	-
L3	1.33	1.52	0.84	-	-	-	0.79	-	0.63	-	0.57	-
L4	1.58	1.3	0.66	-	-	-	0.74	-	0.6	-	0.57	-
L5	1.78	1.46	1.5	-	-	-	1.23	0.87	-	0.8	-	-
L6	0.89	1	-	1.8	1.61	1.67	-	2.16	-	2.07	-	1.98

The similarity of tree-ring chronologies within one icing area turned out to be significantly lower than those in adjacent forest stands. So, if in non-frozen areas near plots Np1–Np6 the population signal (EPS) for larch was 0.97, then in icing areas it varied from 0.54 to 0.91 (Table 4). At many sites (Np1, Np2, Np7–9, Np12–14), the EPS value was below the critical value of 0.85 required for constructing a generalized chronology. At the same time, the sensitivity of generalized tree-ring chronologies remained high (Table 4).

Table 4. Population signal (EPS) and sensitivity coefficient (r) of generalized tree-ring chronologies in icing areas of Altai

Site number	***Larix sibirica* L.**		***Picea obovata* L.**		***Pinus sibirica* Du Tour**	
	EPS	**r**	**EPS**	**r**	**EPS**	**r**
Np1	0.78	0.33	0.92	0.24	-	-
Np2	0.62	0.30	0.12	0.24	0.79	0.31
Np3	0.85	0.31	-	-	-	-
Np4	0.87	0.31	-	-	-	-
Np5	0.88	0.36	-	-	-	-
Np6	0.88	0.37	-	-	-	-
Np7	0.82	0.28	-	-	-	-
Np8	0.60	0.32	0.77	0.24	-	-
Np9	0.54	0.28	0.72	0.38	-	-
Np10	0.86	0.40	0.86	0.29	-	-
Np11	0.91	0.30	-	-	-	-
Np12	0.84	0.34	-	-	-	-
Np13	0.79	0.35	0.84	0.24	-	-
Np14	-	-	0.65	0.33	-	-

A published 12-year series of observations on the icings of the Aktru Valley (Narozhny 1997) showed that in half of the observed years the icings of the "GMS" and "Maly Aktru" developed in antiphase (Fig. 2a), which is due to their different origins. The "GMS" icing develops due to the freezing of bed sediments of the Aktru River. The "Maly Aktru" icing dam is periglacial. Its size increases with a decrease in the continentality of winter, when the discharge of firn zone waters occurs more intensively (Narozhny 1997). On the "GMS" icing, two dendrochronological sites were laid out – 12Np and 13Np; on the "Maly Aktru" icing there are no trees. Generalized chronologies for these sites demonstrate a similar response to an increase in the areas and volumes of icings, with the best similarity noted with indicators of periglacial icings. At the same time, the response of individual trees to icing indicators varies from positive to negative, which indicates that the trees are in different environmental conditions (Fig. 2d). The response of the generalized chronologies of all studied icing sites is also different (Fig. 2c). Almost all generalized chronologies, with the exception of the spruce chronology at site 10Np, react positively to the "HMS" icing indicators. The generalized chronologies of sites 2Np–5Np, 10Np, 14Np react negatively to the increase in icing indicators of the "Maly Aktru" icings. Generalized chronologies of sites 2Np, 5Np, 11Np, 14Np have statistically significant negative correlation coefficients with the icing volume of the "Maly Aktru" ice, and positive ones Np6, Np8, Np12, Np13.

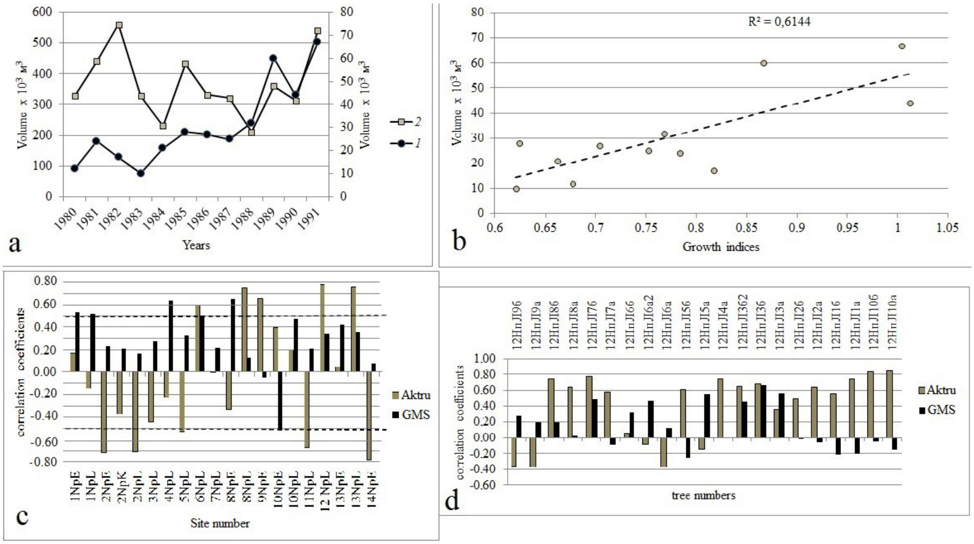

Figure 2. Long-term dynamics of icing in the Aktru Valley (**a**) and the response to them indices of generalized (**b**, **c**) and individual (**d**) tree-ring chronologies. Legend: **a** – Volume of icing at maximum development in winter (**1** – Maly Aktru ice; **2** – GMS ice); **b** – Dependence of the growth indices of the generalized tree-ring chronology for site 12Np on the ice volumes of the Maly Aktru icing; **c** – correlation of growth indices of generalized chronologies with ice volumes of the "Maly Aktru" (**1**) and GMS (**2**) icing; correlation of growth indices of individual chronologies on site 12Np with ice volumes of the Maly Aktru icing (**1**) and GMS icing (**2**). Dotted line are 95% confidence intervals for Pearson correlation coefficients.

A comparative analysis of generalized chronologies with the ice formation intensity index showed that they react in different directions to indicators of ice formation intensity (Fig. 3c). Not a single generalized chronology has negative correlations (statistically insignificant) with the ice formation intensity index (Fig. 3c). Statistically significant positive relationships were noted for generalized larch chronologies at sites Np8, Np10 and 11, as well as for spruce chronologies at sites Np10, Np13 and Np14. At the same time, individual tree-ring chronologies on aufeis areas located in the mountain-forest-steppe belt demonstrate multidirectional responses to the aufeis formation intensity index (Fig. 3b). The same differentiation of the response is also observed in trees of the forest belt, where the relationship between the growth indices of generalized chronologies and the index of ice formation intensity is negative (Fig. 3d).

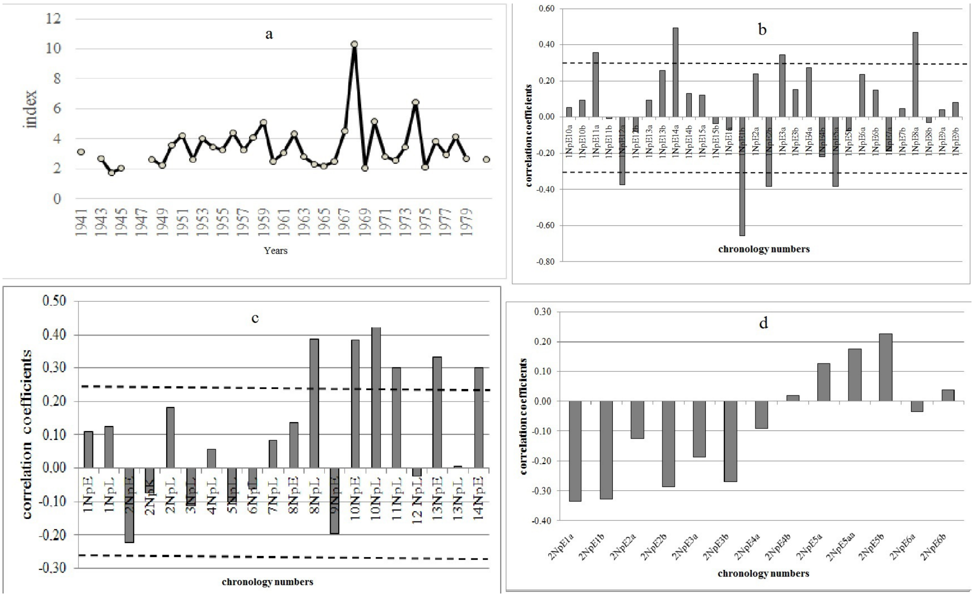

Figure 3. Icing formation intensity index at the Ust-Ulagan weather station for 1941–1986. (**a**) and its correlation with generalized (**c**) and individual chronologies (**b**, **d**). Dotted line indicate 95% confidence intervals for Pearson correlation coefficients.

An analysis of the dates of complete gathering of icing in icing areas showed that synchrony is not always observed between icing areas, which is due to both the difference in the altitude position of the areas and the origin of the icings (Fig. 4). For example, icing dams in areas Np10 and Np11 often develop in antiphase. This phenomenon is often observed on mountain rivers, since depending on winter conditions, interception of water for icing formation can occur in different parts of the river basin. During a frosty and low-snow winter, the waters of surface and under-channel runoff are spent on icing formation in the upper parts of the basin, and during a frosty and heavy-snow winter, in the lower parts.

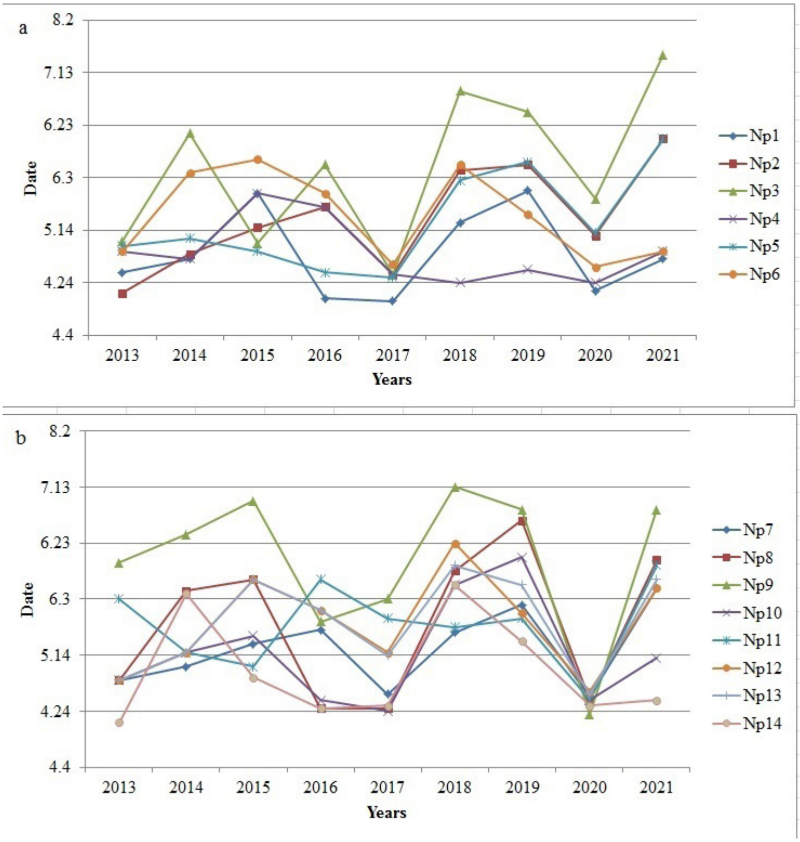

Figure 4. Dates of complete melting of icing in the Kubadru (**a**) and Aktru (**b**) river basins in 2013–2021.

Despite the short series of dates for the gathering of icings, a statistical analysis of their relationships with series of generalized chronologies of the width of tree rings was performed. It was found that the response of the radial growth of trees in icing areas to the dates of gathering of icing is also different. Larch generalized chronologies react negatively to the dates of icing gathering in areas Np1, Np4, Np6, Np11 and positively in areas Np2, Np3, Np5, Np10, Np12, Np13 (Fig. 5a). Spruce generalized chronologies react negatively at sites Np9 and Np14 and positively at sites Np8 and Np13. The cedar chronology in the Np2 area responds positively to the dates of gathering of icing, that is, the earlier the icing gathers, the greater the growth of the cedar in the subsequent growing season. A statistically significant negative correlation is observed only for the larch chronology at site 4Np and for the spruce chronology at site 9Np, and a statistically significant positive correlation is observed for the larch chronology at site 5Np, spruce chronology at site 8Np and cedar chronology at site 2Np.

At the same time, the response of individual chronologies to the dates of gathering of icing in the same icing area can also vary from negative to positive (Fig. 5b), which indicates the diversity of ecological niches within one icing area.

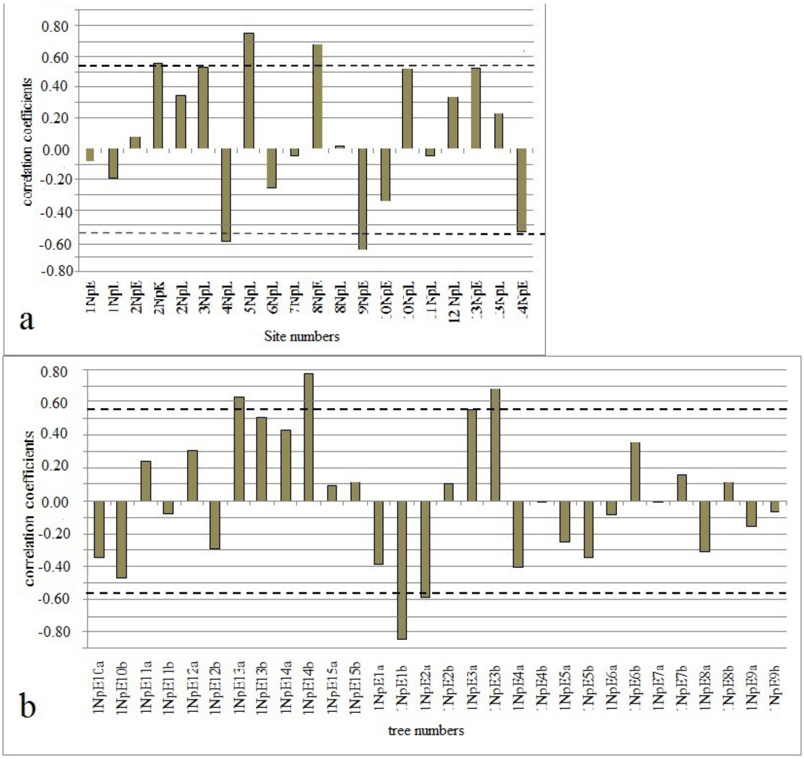

Figure 5. Correlation between the dates of icing disappearance and (**a**) the growth indices for generalized data and individual data on site 1Np (**b**) tree-ring chronologies of the studied icing.

Discussion

As shown above, the similarity of individual tree-ring chronologies on one icing site is low. This situation can be explained by a high variety of factors affecting trees in icing areas (soil heaving, thermal erosion subsidence, etc.) (Alekseev, Novitskaya 1985). Soil heaving and thermo-erosive subsidence cause trees to tilt. As a result, compression and tension wood is formed, which disrupts the synchronicity of chronologies obtained from one tree. In addition, icing areas are significantly differentiated by environmental conditions. In the transverse profile, they differ in the impact of icing dams, since the thickness and time of gathering of icing decrease from its center to the periphery. The peculiarities of the gathering of icings lead to the formation of multi-branch rivers and streams in icing areas, which leads to the emergence of many ecological niches, where the combination of factors affecting trees differs. At the same time, generalized chronologies obtained even at low EPS are characterized by a high sensitivity coefficient, which indicates that trees on icing areas grow in relatively harsh conditions and can be used for dendroclimatic studies (Table 4).

The positive response of the radial growth of trees in the Aktru valley (sites 12Np and 13Np) to the increase in ice volumes in the icings of this valley (especially in the "Maly Aktru" icings) can probably be explained by the fact that during a less continental winter, less significant freezing of soils and under-channel flow occurs of the Aktru River, which, in turn, causes less development of the "GMS" icing and, due to this, greater radial growth of trees in the subsequent growing season (Fig. 2b).

Differences in the response of generalized chronologies to the intensity of icing formation can be partly explained by different geographical locations (primarily altitudinal). For example, the positive reaction of the chronologies at sites Np8–11 and Np14 is most likely due to these sites being located in the mountain-forest-steppe altitudinal zone, where icings, especially on their periphery, often have a beneficial effect on tree growth.

The multidirectional responses of individual tree-ring chronologies to the icing formation intensity index (Fig. 3b) and the dates of icing gathering are likely determined by the position of trees within the site and the fact that environmental conditions within the icing areas are highly differentiated. This differentiation of the response is observed both in trees of the forest belt, where the relationship between the growth indices of generalized chronologies with the index of icing formation intensity is negative (Fig. 3d), and in trees of the mountain forest-steppe belt, whose generalized chronologies respond positively to an increase in the intensity of icing formation.

Conclusions

Based on the research performed, the following conclusions can be drawn:

1. Tree-ring chronologies are characterized by a low EPS value, which is due to a variety of factors affecting trees in icing-covered areas (soil heaving, thermal erosion processes, uneven distribution and gathering of icings both from place to place and from year to year, ice collapse, etc.).

2. The response of trees to icing indicators varies significantly depending on their local position of the tree in the icing area, especially in the mountain-forest-steppe altitudinal zone, where on the periphery of the icing area the formation of icings contributes to an increase in the growth rate of trees, while in its central part the growth rate of trees decreases.

3. The absence of long-term series of observations of icing dams in the study area makes the dates of icing gathering the most likely indicator that can be reconstructed using tree-ring indication. In the future, the dates of icing gathering can be used to calculate other characteristics of ice dams (thickness, area and volume of icing).

4. The results of the analysis of the relationship between icing indicators and the radial growth of trees can be considered as the initial stage of such research. As the range of observations of icing dams expands due to satellite and aerial studies, the reliability of correlations to such indicators will increase.

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