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MIXED RESPONSE OF DECADAL VARIABILITY IN LARCH TREE-RING CHRONOLOGIES FROM UPPER TREE-LINES OF THE RUSSIAN ALTAI

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ABSTRACT

We developed a network of tree-ring width chronologies of larch (*Larix sibirica* Led.*)* from upper tree-lines of the southeast Altai Mountains, South Siberia. Annual tree-ring variability of chronologies since A.D. 1710 was compared using factor analysis. The factor analysis clustered eight tree-ring chronologies into two groups that were used for compositing chronologies. One resulting composite chronology (A.D. 1582–1994) averaged sites from upper tree-lines in glacier-free areas and another chronology (A.D. 1090–1999) captured the sites at upper tree-lines in valleys of the Korumdu, Aktru, Yan-Karasu and Kizil-Tash Glaciers (North-Chuya Range). There is no significant difference in the estimated strength of temperature signals (June and July) of the composite chronologies. However, we observed a remarkable contrast in the decadal variability of larch growth between upper tree-lines of glacier-free areas and glacier valleys. The tree-ring growth of larch was coherent among the chronologies for the period A.D. 1582–1725. Suddenly, low-frequency similarity declined around A.D. 1730. The magnitude of differences became more pronounced after A.D. 1775 indicating three periods with opposite growth tendency (1775–1850, 1900–1915 and 1960–1994) that alternated with short periods of coherent growth. We assume that the low-frequency signal in the glacier valley larch chronology accommodates oscillations of both summer temperature and glacier dynamics. The periods of low-frequency departures are consistent with the 19th Century advance and tremendous 20th Century retreat of the glaciers. We argue that expanded glaciers enhance harmful impacts of katabatic wind on larch growth. It appears that employing tree rings from upper tree-lines of glaciated areas for estimation of decadal and centennial variability climatic proxies should be selected with great caution.

Keywords: Dendrochronology, larch tree-ring chronology, Altai Mountains, Central Asia.

INTRODUCTION

Recent multidisciplinary efforts to estimate global climate variability over past millennia indicate tree rings are the most reliable annual climatic proxy (Jones and Mann 2004; Jones *et al.* 1998). In Eurasia, climatic proxies developed from long tree-ring chronologies are restricted mostly to arctic regions (Fennoscandia, Polar Ural, Yamal,

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Taymir, Yakutia) and highlands of Central Asia (Tibet, Tian-Shan, Pamir), where subfossil wood is well preserved in the cold environment (Hantemirov 1999; D'Arrigo *et al.* 2001; Bräuning 2001; Esper *et al.* 2002; Gunnarson and Linderholm 2002; Naurzbaev *et al.* 2002). Expanding the aerial coverage of long climate change records requires extensive expansion of tree-ring networks to Asian temperate latitudes (Mann *et al.* 1998).

Developing millennium-scale tree-ring chronologies is challenged by the well-recognized statistical problem of underestimation or overestimation of low-frequency signals in tree-ring variability. There are several sources that can weaken the low-frequency signal in tree-ring variability. The standardization method applied to tree-ring series is considered to be the most crucial factor to preserving low-frequency variability in tree rings (Briffa and Osborn 2002; Esper *et al.* 2002). Another important aspect of developing a long proxy record from tree rings is maintaining climatic signal at a regional scale (Briffa *et al.* 2002). It seems that assessment of the regional climatic signal in mountain areas demands a wider network of tree-ring chronologies because of a higher variety of growth conditions caused by topography (Watson and Luckman 2002). Furthermore, growth conditions in highlands might be amplified by the impact on tree-ring growth of glacier behavior, ice fields, avalanches, debris flows, landslides, etc. (Schweingruber 1987). We assume that, although some of those geomorphological phenomena might enhance a climatic signal in tree-ring growth, the low-frequency oscillations of tree-ring chronologies are likely to be non-coherent because of the non-climatic nature of internal dynamics of those phenomena. In this paper, we demonstrate a conspicuous distortion of low-frequency signals in regional long tree-ring chronologies from Central Asia caused by dynamics of adjacent glaciers.

We designed a tree-ring network of larch from upper tree-lines of the Altai Mountains, Central Asia, to build a long-term temperature proxy record. The tree-ring sites clustered in southeastern Russian Altai where mountain glaciation is widespread. Because of that, we raised the question about the degree to which glaciation impacts low-frequency variability of larch growth at the upper tree-lines. The experiment took place in two distinctive areas: 1) upper-tree lines on mountain ranges without glaciers and 2) upper tree-lines near glaciers and in glacier valleys where ice fronts were in recent contact with larch stands. This strategy of tree-ring sampling should reveal (i) spatial patterns in climatic signals of the local (site) tree-ring chronologies, and (ii) their low-frequency variability. It should indicate the validity of low-frequency signals in the regional reconstruction of temperature from the larch tree-ring network.

DATA AND METHODS

The Altai Mountains are the northwestern part of the South Siberian mountainous belt that blocks Central Asian landscapes from the impact of the prevailing westerly winds. Temperate and extremely continental climate is characterized by large gradients in precipitation and temperature variability throughout the region. Average winter temperature varies from −27.1°C to −17.6°C, and summer temperature from +11.8°C to +14.1°C. Total annual precipitation ranges from 1300 mm on northwest slopes to 150 mm in southeastern inner lowlands. Altitudinal position of modern upper tree-line runs from 1900 m a.s.l. in northwestern Altai to 2350 m a.s.l. in southeastern Altai. *Larix sibirica* Led. and *Pinus sibirica* Led. are dominant species in upper tree-line stands that are sometimes mixed with *Picea abies.* The upper tree-line (UTL) is defined here as a location of open canopy forest stands in the forest-tundra ecotone. The tree-ring sites were not established at the highest elevation of larch distribution because we looked for the oldest trees.

The tree-ring network lies between 50°10′ and 50°30′N latitude and 87°35′ and 87°45′E longitude with elevations from 1950 to 2350 m a.s.l. All ten sites are located in southeastern Altai near the Russian State Border with Kazakhstan, China and Mongolia (Figure 1). The sites are distributed unevenly along upper tree-lines of the Severo-Chuyskiy, Kurayskiy and Aygulakskiy Ranges (Figure 1) as we endeavored to find the oldest stands of living larch and locations with highest accumulation of well-preserved dead larch *in situ.* Mountain glaciers cover the top of the Sev-

Figure 1. Location of the meteorological stations (x), and tree-ring sites at the climatic upper tree-line (■) and in valleys of the Aktru, Korumdu, Kizil-Tash and Yan-Karasu glaciers (●) in the Altai Mountains, South Siberia: 1—KOR, 2—YAN, 3—KZT, 4—AKTR, 5—ALTB, 6—UGBO, 7—ALTA, 8—UGLA, 9—AKTA, 10—ALTC.

ero-Chuyskiy range close to the studied locations. Some mountain glaciers advanced into valleys and destroyed UTL forest stands during Late Holocene climatic events. In the case of the Korumdu (KOR) and Aktru (AKTR) tree-ring sites, named after glaciers of the same names, the UTL is still recovering and elevation of modern UTL in the valleys is slightly lower than thermal UTL in the region (Adamenko 1978). Forest in valleys of the Korumdu Glacier, B. Aktru and M. Aktru Glaciers shows clear signs of recently overrun larch-pine stands, providing plentiful remains of dead *in situ* larch trees and logs in stream outwash nearby. The B. Aktru Glacier and M. Aktru Glacier are two parts of one large glacier that were separated recently during the 20th Century retreat (Ivanovskiy *et al.* 1982). Another two tree-ring sites are in valleys of the Yan-Karasu Glacier (YAN) and the Kizil-Tash Glacier (KIZ) that have not interacted with the UTL recently. Their ice fronts are about 300 m above the modern UTL elevation. We found larch logs and trunks between 2 km and 3 km down the valleys below the glacier terminus. The other six tree-ring sites are approximately 40–120 km away from the glacier valley sites (Table 1).

The field collection was done in summer seasons of 1978, 1983, 1994 and 1999. Wood discs from dead trees in the glacier valley sites were cut with a hand saw. We tried to make the cuts in the lower part of tree trunks and to sample at breast height when it was possible to identify tree base. For living trees, two cores from opposite radii were taken with an increment borer at breast

Table 1. Tree-ring width chronologies of larch from upper tree-lines of southeast Altai Mountains.

Site	Location/Range	Elevation m a.s.l	Sample Size	Period	Mean Sensitivity	Autocorrelation	
						Lag1	Lag2
	Severo-Chuyskiy:						
KOR	Korumdu GV*	2,220–2,300	27	818–1999	0.30	0.30	0.17
KZT	Kizil-Tash GV	2,240	13	1336–1999	0.30	0.81	0.42
YAN	Yan-Karasu GV	2,300	8	1389–1979	0.33	0.51	0.27
AKTR	Aktu GV	2,320–2,400	53	895–1999	0.31	0.40	0.15
	Kurayskiy:						
ALTA	NE slope, 12°	2,150	16	1550–1995	0.24	0.59	0.22
UGLA	”	2,150	22	1581–1994	0.24	0.69	0.16
UGBO	NW slope, 3°	1,950	19	1698–1994	0.20	0.49	0.22
ALTB	”	1,950	17	1699–1994	0.20	0.48	0.23
	Aygulakskiy:						
AKTA	SW slope, 15°	2,000	19	1601–1994	0.20	0.50	0.20
ALTC	”	2,010	15	1604–1994	0.20	0.50	0.20

*GV = Glacial Valley.

height. At least 12 living trees were cored per site. Tree-ring widths were measured on a LINTAB measuring system with an accuracy of 0.01 mm in the V.N. Sukachev Institute of Forest—Siberian Branch of the Russian Academy of Science (Russia) and the Swiss Federal Institute of Forest, Snow and Landscape Research (Switzerland). We crossdated tree-ring width series visually with help of time-series plots. Crossdating control was evaluated by interserial correlation using the COFECHA program (Holmes, 1983). Age-growth-related trends in tree-ring series were estimated by either negative exponential, linear regression or straight line through a mean. Tree-ring width indices were calculated as the ratio between actual ring width and fitted growth-model width and later averaged into a site chronology. Factor analysis of site chronologies was done by extracting varimax normalized principal components through a Pearson's correlation matrix. Grouping of site chronologies in the factor analysis provided the basis for averaging site chronologies into a composite chronology. Climatic relationships of the two composite chronologies were estimated by calculating response functions based on bootstrap regression (Fritts 1991). We ran monthly temperature of the Ak-Kem meteorological station (observation period 1950–1996), and summer (May–September) and winter (prior year October-current April) precipitation of the Kara-Tureg station (period 1940–1996) as independent variables for calibration of the tree-ring data. The regressions were calculated for a 12-month period from October of the previous year to September of the current year.

RESULTS AND DISCUSSION

Site Tree-Ring Chronologies

Tree-ring sampling at upper tree-line revealed unusually old ages of *Larix sibirica* in the Altai Mountains. The longest life of one dead larch tree was 813 years with pith dating back to the beginning of the 9th Century A.D. We found two dead stands with vertical *in situ* larch trunks excellently preserved on a plateau below the Kizil-Tash Glacier and on a lateral moraine terrace of the Korumdu Glacier. Individual upstanding tree trunks have been seen at terraces of the Aktru Glaciers as well. All branches were gone from the trunks but bark patches still survived on some trees. Tree-ring width series from those trees and trees recovered from moraines or found in outwash streams were considered directly affected by glacier front changes. Later we used them to compare variation of thermal conditions at UTL in currently glaciated and glacier-free areas.

Tree-ring width chronologies were built for all 10 sites of the network (Table 1). The average coefficients of correlation between site trees are 0.6 and higher. The age curve of most larch trees expressed a common shape in their tree-ring width variability that could be modeled with a negative exponential curve. Tree-ring growth for the first 80–120 years is unusually high, after which growth slowly declines. Only a few tree-ring series did not show clearly the early period of enhanced growth, but had a very slow rate of growth through the whole life span. We purposely applied the conservative standardization (see methods above) to all time series to emphasize unusual intra-decadal-scale variations (growth releases or declines) in tree rings from glacier valleys. Length of the site chronologies ranges from 296 to 1,182 years. Two chronologies (KAZ and KRSU) have a gap in the crossdated series because of lack of trees at the sites for certain time intervals. The KAZ chronology from A.D. 1343–1999 has no overlapped tree-ring series for period 1712–1842. The KRSU chronology begins at A.D. 1390 but has only one tree for period 1710–1979, which is the result of a big fire in the late 1980 that consumed almost all trees. Thus, only the period A.D. 1390–1709 was analyzed. We did not use these two chronologies in factor analysis to avoid a reduction of correlation period, but later we compared them with composite tree-ring chronologies.

Composite Tree-Ring Chronologies

The factor analysis correlation matrix from the eight site chronologies for the common period A.D. 1710–1994 (283 years) extracted two principal components. The explained variance of the first eigenvector is 4.2 representing 69.3% of total variance. The first factor unites six site chronologies from glacier-free upper tree-lines (Table 2).

Table 2. Factor loadings for principle component #1 and #2 given by varimax normalized correlation matrix of the site tree-ring chronologies from the Altai tree-ring network (bold scores at R > 0.7). Note that YAN and KZT site chronologies are absent in the factor analysis because they have short overlap with the analyzed period 1710–1994 (see details in Site Tree-Ring Chronologies section).

Tree-ring Chronology	Factor 1	Factor 2
KOR	0.25	**0.89**
AKTR	0.24	**0.89**
ALTA	**0.74**	0.55
UGLA	**0.73**	0.52
UGBO	**0.90**	0.20
ALTB	**0.88**	0.19
ALTC	**0.86**	0.27
AKTA	**0.83**	0.30
Eigenvalue variance	4.2	2.4
% Total Variance	69.3	13.3

The explained variance of the second eigenvector is 2.4, which covers 13.3% of total variance. It brings the explained cumulative variance up to 83.6%. The second factor groups two site chronologies from the Korumdu and Aktru Glacier valleys. Distance between chronologies united by the first factor ranges from 40 to 140 km, and distance between the second factor chronologies is about 50 km. Based on distribution of the factor loadings we developed two composite tree-ring chronologies of larch averaging tree-ring index series from site chronologies related by factor 1 (composite chronology #1) and factor 2 (composite chronology #2). The total number of individual time series averaged in composite chronology #1 is 108 and in composite chronology #2 it is 80.

Statistical properties of the tree-ring chronologies demonstrate a strong common signal in their variability and response to environmental changes. Between the two groups, tree-ring chronologies from glacier valley sites (factor 2) have much higher mean coefficient of sensitivity than chronologies from the factor 1 group, *i.e.* >0.3 and 0.2–0.24, respectively (Table 1 and 2). The obvious reason for the higher variance of those chronologies is the site locations, which are adjacent to glacier fronts. First-order autocorrelation exceeds 0.5 and the second-order autocorrelation is *ca.* 0.2 in most cases. Subsample signal strength (SSS) requires a minimum sample depth at 5–7 trees for all site chronologies and composite chronologies to maintain chronology variance at a confidence level of 0.85. By the 85% SSS criteria, the length of site chronologies varies from 279 to 921 years, which shorten the full-length chronologies from 3 years to 162 years. Likewise, the time-span of the composite chronology #1 suggested by the 85% SSS statistic is A.D. 1582–1994 and the composite chronology #2 is A.D. 1070–1999. Thus, the period A.D. 1582–1994 (412 years) is suitable for comparison of tree-ring variability in glacier valleys and glacier-free upper tree-lines. Generally speaking, the statistical properties of *Larix sibirica* tree rings from the Altai UTL are similar to those for alpine larches (*Larix sibirica* Led., *Larix dahurica* Gmel., *Larix cajenderi* Mayr. and *Larix lyallii* Parl.) in the Ural Mountains, Taymir, Yakutia and Canadian Rockies (Shiyatov 1986; Colenutt and Luckman 1995; Vaganov *et al.* 1998). It suggests once again that alpine larch is very suitable for dendroclimatic studies in the Northern Hemisphere.

Climatic Data

Weather data in the high Altai Mountains are extremely sparse, short and often with 1–2 years of consecutive missing monthly observations. Usually, length of temperature observations exceeds precipitation observations from the same weather station. Moreover, a number of weather stations were terminated since 1991, which limited comparison for the last decade. One of the oldest weather stations in Siberia is the Barnaul station located in the steppe foothills of the Altai Mountains (53°40′N, 83°70′E), which has observations since 1838. However, the Barnaul station is only 158 m a.s.l. and lies far northwest of the tree-ring network. Among the few weather stations above 1,800 m a.s.l. in the Altai Mountains, we found three stations appropriate for the study: Aktru, Ak-Kem and Kara-Tureg. The location of the Aktru station is well-positioned to the tree-ring sites. The station was established near the Aktru Glacier (50°05′N, 87°45′E) at an elevation of 2,150 m a.s.l. in the Severo-Chuyskiy Range and surrounded by an open mixed stand of larch and pine. Unfortunately, the Aktru continuous monthly observations are only from 1972 to 1994 (23 years). Two other stations are south of the network in Kazakhstan's Altai. The Ak-Kem station is 90 km away from the Aktru station (49°58′N, 86°42′E; Katunskiy Range; 2,050 m a.s.l.) with relatively long temperature observations starting in 1949. Temperature data of the Ak-Kem station are most suitable because observations are available from 1950 to 1991 (42 years) and few years are missing. The Kara-Tureg station is above the upper treeline and 110 km from the Aktru station (49°98′N, 86°42′E; Katunskiy Range; 2,600 m a.s.l.). The station has reliable precipitation data from 1941 to 1986 (45 years). We compared correlation relationships of temperature and precipitation data among those weather stations. The strongest significant correlation was found for mean summer and mean winter temperatures of the Aktru and Ak-Kem stations. Correlation coefficients vary from 0.8 to 0.72 at $p < 0.05$. Summer and winter precipitation are well-correlated between all stations ($R > 0.5$ at $p < 0.05$). Total precipitation amount for the hydrological year (October through September) of the Kara-Tureg station is similar to the Ak-Kem and Aktru data (535 mm, 567 mm and 541 mm for total precipitation, respectively). In the end, we chose the Ak-Kem temperature for the period 1950–1996 (two years missing data, 1975 and 1993, were estimated by linear regression) and the Kara-Tureg precipitation over the period 1941–1991 for climatic response-function analysis of the composite chronologies.

Climatic Response of Composite Chronologies

Climatic response functions estimated a strong relationship of larch tree-ring widths with June and July temperature for both composite chronologies. R^2 adjusted for degrees of freedom is 0.52 for composite chronology #1 and 0.56 for composite chronology #2. The regression results are slightly better for the UTL chronology near glaciers. The response function analysis did not show any significant correlations of the tree-ring growth with precipitation. Variance of tree-ring width indices positively corresponds with June temperature (Figure 3a). There are a few years of disagreement between tree-ring index and temperature that are different for each chronology. Composite chronology #1 has indices with opposite sign to temperature changes in years 1971 and 1990 and composite chronology #2 in years 1963, 1964 and 1965. Most of those years occurred for the period 1963–1975 when variability of June temperature notably decreased. Amplitude and sign of June temperature changes coincide particularly closely with tree-ring index for periods 1950–1961 and 1980–1996 (Figure 3a). Correlation of tree-ring indices with July temperature is almost half that with June temperature but is still significant. The disagreement between July temperature and tree-ring index comes for periods 1956–1965 (10 years) and 1976–1985 (15 years) and year 1972, which are *ca.* 55% of total number of analyzed years (Figure 3b). It is notable that the highest positive peaks of July temperature correlate well with highest tree-ring indices of composite chronology #2 but not as well with tree-ring indices of composite chronology #1 (for example, in 1974, 1966 and 1992). It is possible that commonly warm July mitigates growth conditions of larch and tree-ring width becomes less sensitive to the July temperature variability. But in years when June is cold and July temperature is remarkably high, larch from stands near the glacier fronts responds well to the additional heating and produces wider rings than larch from other upper tree-line sites (Figure 3a, b).

Although, June temperature contributes most to the statistical relationship between *summer* temperature and larch tree-ring width growth, July temperature might more precisely estimate the highest peaks in a reconstructed temperature curve. We assume that 1) mean or sum of June–July temperature will be the best parameter for summer temperature reconstruction from the tree-ring records, and 2) tree-ring chronologies from sites near glaciers should show better verification statistics in a reconstruction model than upper tree-line chronologies from glacier-free sites.

Long-Term Variability of Composite Chronologies

Because of relative shortness of UTL chronology #1, the overlapping chronology period begins

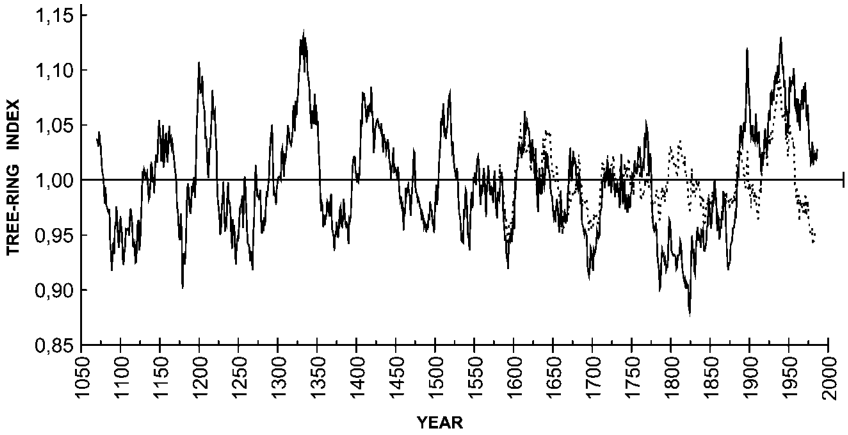

Figure 2. Twenty-five-year moving-average curves of composite tree-ring width chronologies for *Larix sibirica* at upper tree-lines of glacier-free area (chronology #1, dashed line) and in currently glaciated valleys (chronology #2, solid line) of southeastern Altai.

at A.D. 1582. Before 1582, composite chronology #2 displays generally sustained positive growth interrupted by 30–50 year periods of reduced growth conditions. The highest growth peak appears between A.D. 1325 and 1350. The 25-year moving average curve of composite chronology #2 shows extreme larch growth suppression in the Korumdu and Aktru glacier valleys from 1784 to 1885 and extraordinary growth release from 1890 until 1980 (Figure 2). It is interesting that both growth periods lasted about 100 years. Composite chronology #1 has the highest larch growth in the 20th Century, which occurred in the 30-year period 1925–1955, but tree-ring growth has remained low since 1960. Moreover, the magnitude of low growth in 1964–1984 is similar to the lowest growth periods of 1587–1601 and 1687–1709 (Figure 2). The longest low-growth period occurred from 1837 to 1875 and lasted only 39 years.

Comparison of the composite chronologies indicates that magnitude of decadal tree-ring variability at the UTL is distinct from variability in the glacier valleys but only in certain time intervals. Variability of both chronologies coincides well between A.D. 1582 and 1725 but suddenly the low-frequency oscillation correspondence falls apart after A.D. 1775. Changes in decadal variability show opposite sign and duration of low/high growth periods are distinctively different between the composite chronologies. The most notable periods of opposite growth tendencies were 1775–1850, 1900–1915 and 1960–1994 (Fig. 2). Composite chronology #2 exhibits the longest period of low larch growth in A.D. 1776–1883, which surprisingly lasted over 100 years. At the same time, the chronology shows unprecedented high larch growth through all of the 20th Century. It suggests that composite chronology #2 enhanced its low frequency variability after A.D. 1775. It also means that the tree-ring variability of chronology #2 was under the influence of another environmental factor besides the limiting influence of summer temperature.

Thus, the major disagreements in low-frequency variability of those chronologies were for the last 200 years according to the 412-year comparison. This is problematic because those incongruous periods of larch growth might cause misinterpretation of regional summer temperature trends inferred from the tree-ring records. The number of periods of possible low-frequency distortions present in the long tree-ring chronology #2 before A.D. 1582 is unknown. We believe that glacier dynamics likely strongly impact the low-frequency variability of tree rings if glacier fronts were positioned near upper tree-lines. A glacier advance at upper tree-line elevation could cause an underestimation of tree-ring variability, and subsequent glacier retreat could result in overestimation. Further, evidence exists that glacier-front dynamics in the Korumdu and Aktru Valleys could surely change larch growth conditions at upper tree-line,

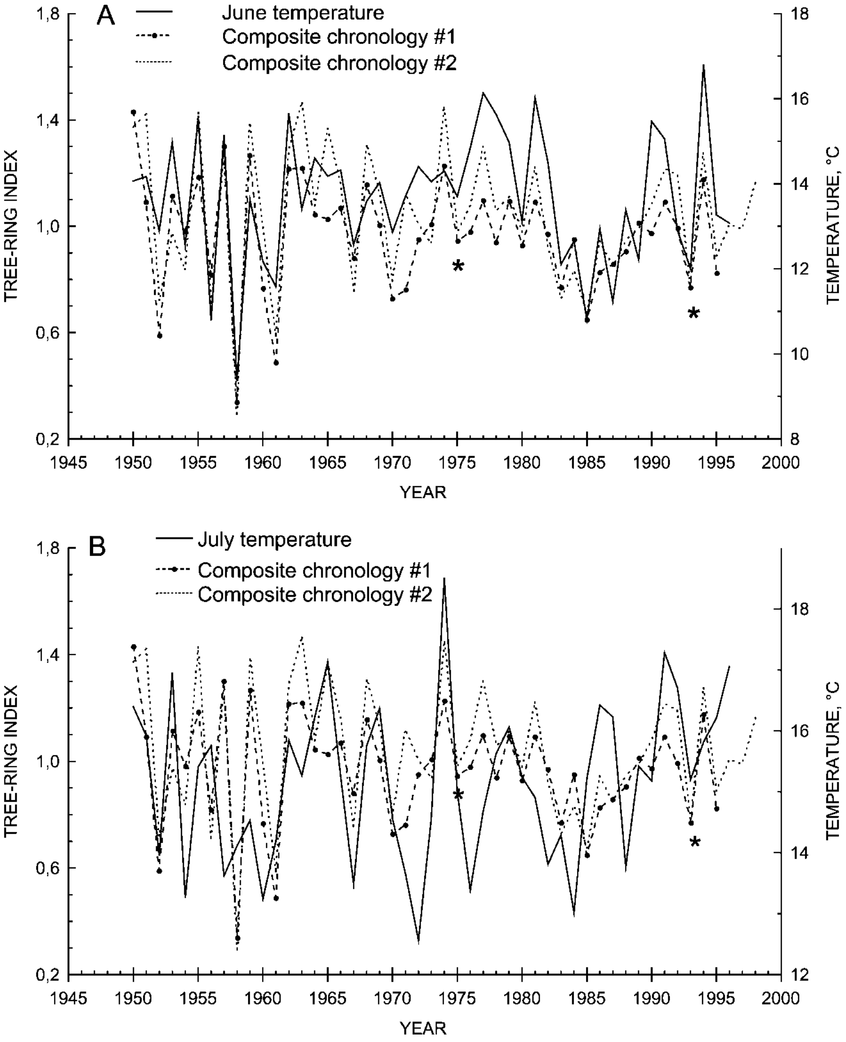

Figure 3. The UTL composite chronologies plotted against June (A) and July (B) temperature observed on the Ak-Kem station for the calibration period 1950–1996. Correlation coefficients are 0.71 and 0.36, respectively.

mainly through the impacts of katabatic winds and ice fields.

Evidence of Glacier Impact on the Larch Growth Variability

Glaciers of southeastern Altai belong to summer-accumulation-type glaciers that have both summer accumulation and ablation. Variation of summer temperature is an important component of mass balance for glaciers under such arid conditions. Simulations of ice dynamics and historical glacier-front variations based on climatic response for the M. Aktru Glacier and the Sofiyskiy Glacier (South-Chuya Range, 30 km south from M. Aktru Glacier) since A.D. 1800 showed the following important changes in surface mass-balance conditions: 1) distinct decline in the second half of the 19th Century, 2) slight increase at the beginning of the 20th Century (about 1900–1940), and 3) steady reduction toward the present (De Smedt and Pattyn 2003). The negative mass balance resulted in massive glacier retreat between 1898 and 2000. The most rapid retreat of the Maliy Aktru Glacier occurred between 1900 and 1940 (Pattyn *et al.* 2003). Coincidently, composite chronology #2 exhibits rapid release in tree-ring growth around 1900 that continues to the present (Figure 2).

Glaciological studies that include results on patterns of tree mortality and establishment on recent moraine complexes, and radiocarbon dating of those moraines in the Akturu and Korumdu Valleys, indicate three phases of glacier advance for the last millennium with lowest positions of glacier fronts dated around A.D. 1240, 1630 and 1850 (Ivanovskiy *et al.* 1982; Adamenko 1985). Our dates for most outer rings from dead trees found on upper terraces of glacier valley or in front of terminal moraines in the Yan-Kurasu, Aktru and Kizil-Tash Valleys (34 samples) suggest a common period of larch mortality in 1683–1726. Dead trees from similar locations in the Korumdu Valley (7 samples) show the peak of mortality in 1784–1798. These trees were slowly dried by katabatic wind from ice fronts approaching upper tree-line. Some of them were still in standing positions when we sampled the tree rings. Tree-ring dating of pith from dead and living trees from chronology #2 showed a common period of larch establishment at upper tree-line from 1350 to 1560 in all four glacial valleys. Another period of larch establishment was found in 1880–1940 only for the Korumdu and Aktru Valleys.

Thus, the deepest decline of tree-ring growth in 19th Century can be associated with the glacier's advance. Oscillations of low-frequency variability between 1200 and 1300 in chronology #2 could be affected by low terminus of glacier fronts around A.D. 1250. Periods of massive tree mortality at the upper tree-line coincide with periods of very low tree-ring growth in composite chronology #2. Massive larch recruitment at the upper tree-line agrees with periods of highest tree-ring growth for the last millennium. This means that the glacier impact can even be seen in sample depth and segment length of the long tree-ring chronology.

CONCLUSIONS

The developed network of larch tree-ring sites along upper tree-lines of the southeastern Altai Mountains resulted in two composite chronologies for glacier-free and glacier-occupied valleys. Estimated summer temperature signal in the tree-ring width chronologies is strong. June temperature contributes most to the statistical relationship between summer temperature and tree-ring growth. July temperature better estimates the highest values of tree-ring indices for the years with cold June. Patterns of low-frequency variability of the tree-ring chronologies change with geography because of the remarkable impact of glacier dynamics on tree growth at upper tree-line. Chronology comparison showed two distinct periods of low-frequency variability: 1) good agreement between chronologies from the two types of upper tree-lines in 1582–1750, and 2) profound discrepancy for the last 225 years. Composite chronology #2 (glacier-occupied valleys) reveals several periods of large-magnitude high and low tree-ring growth of unprecedented length (about 100 years) that are associated with impact of katabatic wind on larch stands adjacent to ice fronts. The most unusual release in tree-ring growth occurred in the 20th Century (1890–1980) after glacier retreated. Tree-ring growth in glacier-free upper tree-lines (composite chronology #1) tended to decline after A.D. 1950. Larch growth suppressions caused by glacier advances lasted about 100 years in the 13th and 19th Centuries.

The estimated distortion of low-frequency variability was observed in tree growth from several glacier valleys in southeastern Altai that provide tree-ring samples for a millennium-scale regional record of tree rings. Low-frequency variability of temperature reconstructed from the tree rings might maintain periods of temperature overestimation or underestimation caused by glacier behavior at upper tree-line. It is necessary to apply a selective approach to tree-ring series standardization from such locations. Standardization techniques that might strip down tree-ring variability related not only to tree age but to katabatic wind impact need to be investigated as well. Moreover, we need to find millennium-scale tree-ring chronologies in glacier-free locations of upper tree-line to use them as a scaling standard of decadal variability in tree rings from the region.

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REFERENCES CITED

Adamenko, M. F.
1978 Glaciation of the Bie-Katunskiy watershed. In *Glaciology of Altai Mountains* 12:45–58. Tomsk: TGU (in Russian).

Adamenko, M. F.
1985 *Reconstruction of Summer Temperature Variability and Glacier Dynamics in the Gorniy Altai for Period 14th–20th Centuries.* Ph.D. thesis, Press of SBRAS Institute of Geology and Geophysics, Novosibirsk, USSR (in Russian).

Bräuning, A.
2001 Climate history of the Tibetan Plateau during the last 1000 years derived from a network of juniper chronologies. *Dendrochronologia* 19:127–137.

Briffa, K. R., and T. J. Osborn
2002 Blowing hot and cold. *Science* 295:2227–2228.

Briffa, K. R., T. J. Osborn, F. H. Schweingruber, P. D. Jones, S. G. Shiyatov, and E. A. Vaganov
2002 Tree-ring width and density around the Northern Hemisphere: Part 1, local and regional climate signals. *The Holocene* 12:737–757.

Colenutt, M. E., and B. H. Luckman
1995 The dendrochronological characteristics of alpine larch. *Canadian Journal of Forest Research* 25:777–789.

D'Arrigo, R., G. Jacoby, D. Frank, N. Pederson, E. Cook, B. Buckley, Baatarbileg Nachin, R. Mijiddorj, and C. Dugarjav
2001 1738 years of Mongolian temperature variability inferred from a tree-ring record of Siberian pine. *Geophysical Research Letters* 28:543–546.

De Smedt, B., and F. Pattyn
2003 Numerical modeling of historical front variations and dynamic response of Sofiyskiy glacier, Altai Mountains, Russia. *Annals of Glaciology* 37(1): 143–149.

Esper, J., E. R. Cook, and F. H. Schweingruber
2002 Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* 295: 2250–2253.

Fritts, H. C.
1991 *Reconstructing Large-scale Climatic Patterns from Tree-ring Data: Diagnostic Analysis.* U. of Arizona Press, Tucson-London.

Gunnarson, B. E., and H. W. Linderholm.
2002 Low-frequency summer temperature variation in central Sweden since the Tenth Century inferred from tree rings. *The Holocene* 12(6):667–671.

Hantemirov, R. M.
1999 Tree-ring reconstruction of summer temperature in the north of Western Siberia for the last 3,248 years. *Siberian Journal of Ecology* 2:185–191.

Holmes, R. L.
1983 Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin* 43:68–75.

Ivanovskiy, L. N., V. A. Panichev, and L. A. Orlova
1982 Age of terminal moraines for ''Aktru'' and ''historical'' phases in the Altai Mountains. In *Late Pleistocene and Holocene in South of the Western Siberia.* NAUKA, Novosibirsk; 57–64 (in Russian).

Jones, P. D., K. R. Briffa, T. P. Barnett, and S. F. B. Tett
1998 High-resolution palaeoclimatic records for the last millennium: Interpretation, integration and comparison with control-run temperatures. *The Holocene* 8: 455–471.

Jones, P. D., and M. E. Mann
2004 Climate over past millennia. *Review of Geophysics* 42:RG2002, doi: 10.1029/2003 RG000143.

Mann, M. E., R. S. Bradley, and M. K. Hughes
1998 Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* 396:779–787.

Naurzbaev, M. M., E. A. Vaganov, O. V. Sidorova, and F. H. Schweingruber.
2002 Summer temperatures in eastern Taimyr inferred from a 2427-year late-Holocene tree-ring chronology and earlier floating series. *The Holocene* 12(6):727–736.

Pattyn, F., B. DeSmedt, S. DeBrabander, W. VanHuele, A. Agatova, A. Mistrukov, and H. Decleir
2003 Ice dynamics and basal properties of Sofiyskiy glacier, Altai Mountains, Russia, based on DGPS and radio-echo sounding surveys. *Annals of Glaciology* 37(1):286–292.

Shiyatov, S. G.
1986 *Dendrochronology of Upper Tree-Line in the Ural Mountains.* NAUKA, Moscow (in Russian).

Schweingruber, F. H.
1987 *Tree Rings: Basics and Applications of Dendrochronology.* D. Reidel Publishing Company. Dordrecht, The Netherlands.

Vaganov, E. A., S. G. Shiyatov, and V. S. Mazepa
1998 *The Dendroclimatic Study of Siberian Subarctic.* NAUKA, Novosibirsk (in Russian).

Watson E., and B. H. Luckman
2002 The dendroclimatic signal in Douglas-fir and ponderosa pine tree-ring chronologies from the Southern Canadian Cordillera. *Canadian Journal of Forest Research* 32:1858–1874.

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