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Climatic Response of Conifer Radial Growth in Forest-Steppes of South Siberia: Comparison of Three Approaches[1]

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Abstract—We compared three approaches to study climatic signals of *Pinus sylvestris* and *Larix sibirica* tree-ring width chronologies from the forest-steppe zone of South Siberia, where both temperature and precipitation limit the conifer tree growth: 1—paired correlation of chronologies with monthly climatic variables; 2—paired and partial correlations with monthly and seasonal series of primary and secondary climatic factors, calculated in the Seascorr program; 3—paired correlation with a 15-day moving average series of climatic variables. The comparison showed that simple paired correlation with monthly series as the simplest approach could be used for a wide range of dendroclimatic studies, both as a main procedure and for preliminary analysis. The Seascorr analysis is the most suitable for assessing climate-growth relationship in extreme growth conditions and for reconstructions of extremes, e.g. droughts, and of their impact periods. The application of the 15-day moving average series is limited by availability of daily climatic data, but it describes the seasonal window of climatic response with high precision. Altogether, the combination of three approaches allowed to explore the spatial-temporal pattern of the conifers radial growth climatic response in South Siberia.

Keywords: radial growth, *Pinus sylvestris*, *Larix sibirica*, climatic response, forest-steppe

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INTRODUCTION

Variability of tree growth is determined by a complex of environmental factors, among which climatic variables play an important role, especially in high and moderate latitudes. As a result, radial growth of trees is an important source of proxy records about the environment, including climate (Fritts, 1976; Vaganov et al., 2006). Long-term tree-ring chronologies are especially recognized for reconstructing past climate variability outside of intervals covered by instrumental and historical data (Cook et al., 2007; Touchan et al., 2007; Yang et al., 2014; De Rose et al., 2015); modeling of woody plants growth and development processes (Fule, 2010; Vaganov et al., 2011); estimating health conditions of vegetation (Cortina et al., 2006; Laughlin and Grace, 2006); forecasting future dynamics of climatic factors and forest ecosystems (Pan and Raynal, 1995; Tessier et al., 1998; Goldblum and Rigg, 2005).

Presently, climate–growth relationships have been studied most comprehensively in forests from the high altitudes and high latitudes (i.e. upper and northern tree-lines) due to predominant influence of a single limiting climatic factor – temperature of the first half of vegetative season, which determines radial growth up to 60–80% (Shiyatov, 1986; Vaganov et al., 2000; Shishov et al., 2007; etc.). In less extreme conditions, tree growth is limited by more than one factor, including not only climate but also local conditions (Fritts, 1976; Schweingruber, 1996; Panyushkina et al., 2005; Moser et al., 2010; Seim et al., 2016). Moreover, even when growth is limited by a single factor, the analysis of its influence could be complicated by lack of instrumental measurements for that factor. This pattern is typical for arid regions, where plant growth is limited by soil moisture. However, when there is no long series of soil moisture measurements, growth response to it is analyzed through feedbacks of environmental factors driving its variability that have instrumental observations. These factors include temperature, precipitation, snow depth, drought indices, etc. (Pederson et al., 2001; Meko et al., 2013; Belmecheri et al.,

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2015; Hou et al., 2016). In addition, the response of tree growth to environmental conditions is more dependent on species-specific adaptation mechanisms when limitation is complex (Vaganov and Shashkin, 2000; Wilson and Elling, 2003; Friedrichs et al., 2009).

The methodological apparatus of dendroclimatic analysis has undergone significant development during its history. The most conventional and widely used analysis tool is Pearson paired correlation coefficients between tree-ring indexed chronologies and monthly series of climatic factors during all period of instrumental data (Pederson et al., 2011; Slimani et al., 2014; Maxwell, 2016; Opała et al., 2016; Restaino et al., 2016; Cavin and Jump, 2017; Rozas and Olano, 2017). To take into account the impact of several factors on the tree growth, various changes and additions were made in this method over time. For example, the averaged or summed series over longer periods (season, year, etc.) are calculated from monthly climate data. Most often, only some specific periods are chosen on the basis of monthly series analysis (Wang et al., 2016, Cai and Liu, 2017; Opała et al., 2017). However, this selection is not always obvious, in this case more complete and accurate picture can be obtained with exhaustive search for periods with length from one month to a year or even more (Kurz-Besson et al., 2016; Tejedor et al., 2017).

Research in regions where tree growth is limited by two interrelated factors (e.g., temperature and precipitation) often includes ranking of these factors on the strength of their impact. For the growth response to the primary factor, simple paired correlation coefficients are used. At the same time, response to the secondary factor is calculated by partial correlation coefficients, i.e. taking into account the effect of its relationship with the primary factor (Meko et al., 2013; Touchan et al., 2014; Lavergne et al., 2015; Shah et al., 2015; Coulthard and Smith, 2016). There are specialized computer programs that allow automation of dendroclimatic analysis algorithms, for example the Seascorr module for MATLAB developed at the Laboratory of Tree-Ring Research, the University of Arizona (Meko et al., 2011).

Recently, series of climatic factors generalized from daily data for moving short periods (5–15 days) have also been used in dendroclimatic analysis, most often for parameters of the anatomical tree-ring structure (Panyushkina et al., 2003; Babushkina et al., 2010; Liang et al., 2013; Carrer et al., 2017).

Selection of suitable approach from the variety of dendroclimatic procedures and algorithms to identify climatic signal in tree-ring series depends on the specific purpose of research and on environmental conditions of the study area. South Siberia is one of the interesting but understudied dendroclimatically regions, where complex terrain creates a wide range of growth conditions and highly diverse vegetation (Chytry et al., 2008; Makunina, 2016; Polyakova et al., 2016). Particularly, complex limitation of tree growth by temperatures and precipitation of both the current and the previous season is observed in the forest-steppe zone of the region. Therefore, it was of interest to apply and compare several different algorithms of dendroclimatic analysis, as well as to estimate the possibility of their joint use for revealing spatio-temporal and species-specific patterns in the trees climate–growth response on the example of this region.

MATERIALS AND METHODS

Study Area

The material was collected at two sites in the forest-steppe zone on the boundary between Khakass-Minusinsk depression and Kuznetsk Alatau mountain system. The KAZ site (53°23′ N, 90°05′ E, 685 m a.s.l.) is located in the vicinity of Kazanovka vilage in the Askiz district of Khakassia, in the foothills of the Abakan ridge, basin of the Askiz river. The BID site (54°00′ N, 91°01′ E, 660 m a.s.l.) is located in the vicinity of Vershino-Bidja vilage near the upper reaches of the Bidja river, on the southern macroslope of the Batenevsky ridge. Both sites were selected on the southern 15°–20° slopes covered with open-canopy larch-pine forest on mountain gray forest soils.

We used two weather stations with 1936–2012 period of observation: Tashtyp (WMO #29956, 52°48′ N, 89°53′ E, 655 m a.s.l.) and Minusinsk (WMO #29866, 53°41′ N, 91°40′ E, 251 m a.s.l.) for the KAZ and BID sites, respectively (Fig. 1). The climate of the study area is extremely continental with a relatively short and hot summer, a long and cold winter and low snow pack. The average annual sum of precipitation ranges between 340 mm on the plains and 450 mm in the foothills, with most part of it falling from April to October with the maximum in July. From June to September, temperature and precipitation correlate negatively ($r = -0.23...-0.41$, $p < 0.05$) as expected in Southern Siberia (Bazhenova and Tyumentseva, 2010). Monthly observations and moving 15-day with 1-day step series calculated from daily observations for temperature and precipitation were used in the study.

Chronologies of Radial Growth

At each site, we sampled 15–20 living trees of Scots pine (*Pinus sylvestris* L.—PS) and Siberian larch (*Larix sibirica* Ledeb.—LS). Tree selection, collection and processing of wood samples, measurement of radial growth, cross-dating and standardization of chronologies were carried out using standard dendrochronological methods (*Methods*..., 1990) with the help of LINTAB 5 measuring system, TSAPWin, COFECHA and ARSTAN programs (Holmes, 1998; Cook and Krusic, 2005; Rinn, 2011). We used in this study the residual local chronologies (Fig. 2), i.e. chronologies obtained after removing the age trend, represented as a negative exponential function, removing the autocorrelation dependence and averag-

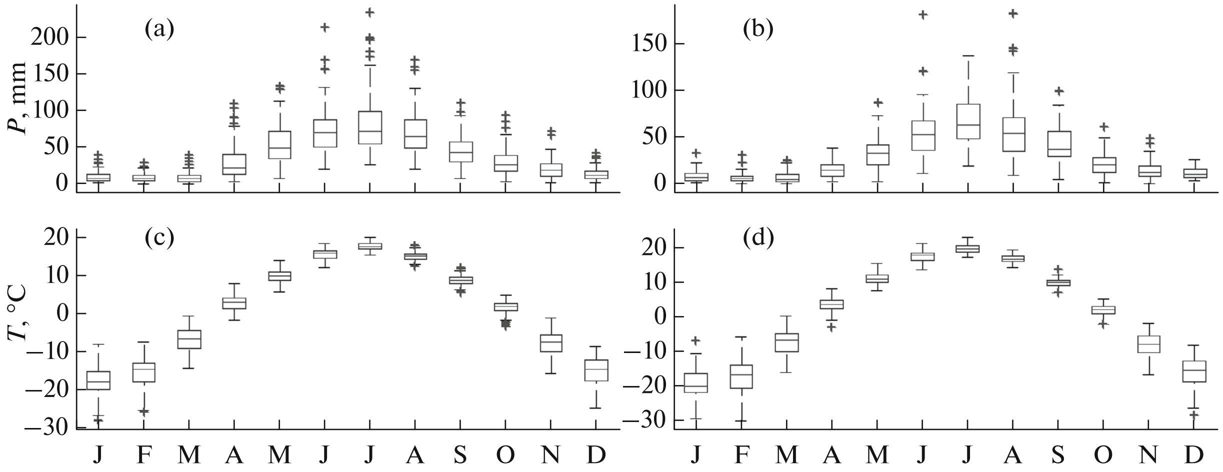

Fig. 1. Climograms calculated from monthly observations of the Tashtyp (a) and Minusinks (b) weather stations for 1936–2012. Distributions for individual months are displayed as box plots with a horizontal (a, c) line at the median (b, d), a box over the interquartile range, plus signs marking outliers, i.e. values more than 1.5 times the interquartile range above or below the box, and whiskers marking data extremes without outliers.

ing series over the site and the species. For every developed chronology over 1936–2012 period the following statistical characteristics were calculated: mean value of tree-ring width (*mean*), standard deviation of raw and residual chronologies (*stdev*), first-order autocorrelation of raw chronology (*ar*-1), mean sensitivity coefficient (*sens*), mean inter-series correlation coefficient (*r-bar*), and expressed population signal (*EPS*) of the residual chronology (*Methods*..., 1990).

The third approach applied in this work is an analysis of radial growth response to the 15-day moving with 1-day step series of climatic variables, using paired Pearson correlation coefficients for the entire instrumental coverage period (Liang et al., 2013; Carrer et al., 2017).

Dendroclimatic Analysis

Dendroclimatic analysis of pine and larch radial growth was carried out using three approaches. In the first, classical approach, climate – growth relationship was estimated with simple Pearson correlation coefficients (Pearson, 1895) between the residual chronologies and monthly climatic series from July of a previous year to August of a current year in relation to the tree-ring development. Then, exhaustive search was carried out for all period lengths from 2 to 12 months (Kurz-Besson et al., 2016; Tejedor et al., 2017).

In the second approach that accounts for interactions between climatic variables, response to the primary limiting factor was calculated with paired correlations, and response to the secondary factor was calculated with partial correlations, i.e. correlations after removing the influence of the primary factor for the corresponding interval. In practice, to calculate the partial correlation coefficient $r_{x_2,x_3|x_1}$ between the variables x_2 and x_3, taking into account the influence of the variable x_1, simple linear regressions $x_2(x_1)$ and $x_3(x_1)$ are calculated, and then paired correlations of their residuals, i.e. the results of subtracting the regression function from the original variable. In dendroclimatic analysis, the variable x_1 is the primary climatic factor, x_2 is the secondary climatic factor, and x_3 is the chronology of radial growth. These calculations were done in the Seascorr program (Meko et al., 2011). The algorithm of this program also includes analysis of longer periods.

RESULTS

Statistical characteristics of raw and res chronologies for the period of instrumental climatic data (Table 1) are high enough for use in dendroclimatic analysis. The mean tree-ring width varies between 1 and 1.7 mm. KAZ PS has the slowest growth rate, as well as the smallest standard deviation and autocorrelation. Chronologies at the KAZ site are more sensitive than at the BID site. Correlations between chronologies of different tree species within one site are $r = 0.66–0.67$, and correlations of the same species between sites are $r = 0.28–0.45$ ($p < 0.01$). The weakest correlation ($r = 0.17$, $p = 0.096$) is observed between BID PS and KAZ LS.

Classical approach to dendroclimatic analysis showed the following results (Fig. 3). Typical for semi-arid regions combination of a positive response to precipitation and a negative response to temperature is observed for previous July-September and current April–June at the KAZ site, for previous July–September and current April-July at the BID site. For the month when a stable snow cover is formed (November), there is a weak positive effect of both temperatures and precipitation on the larch growth with the

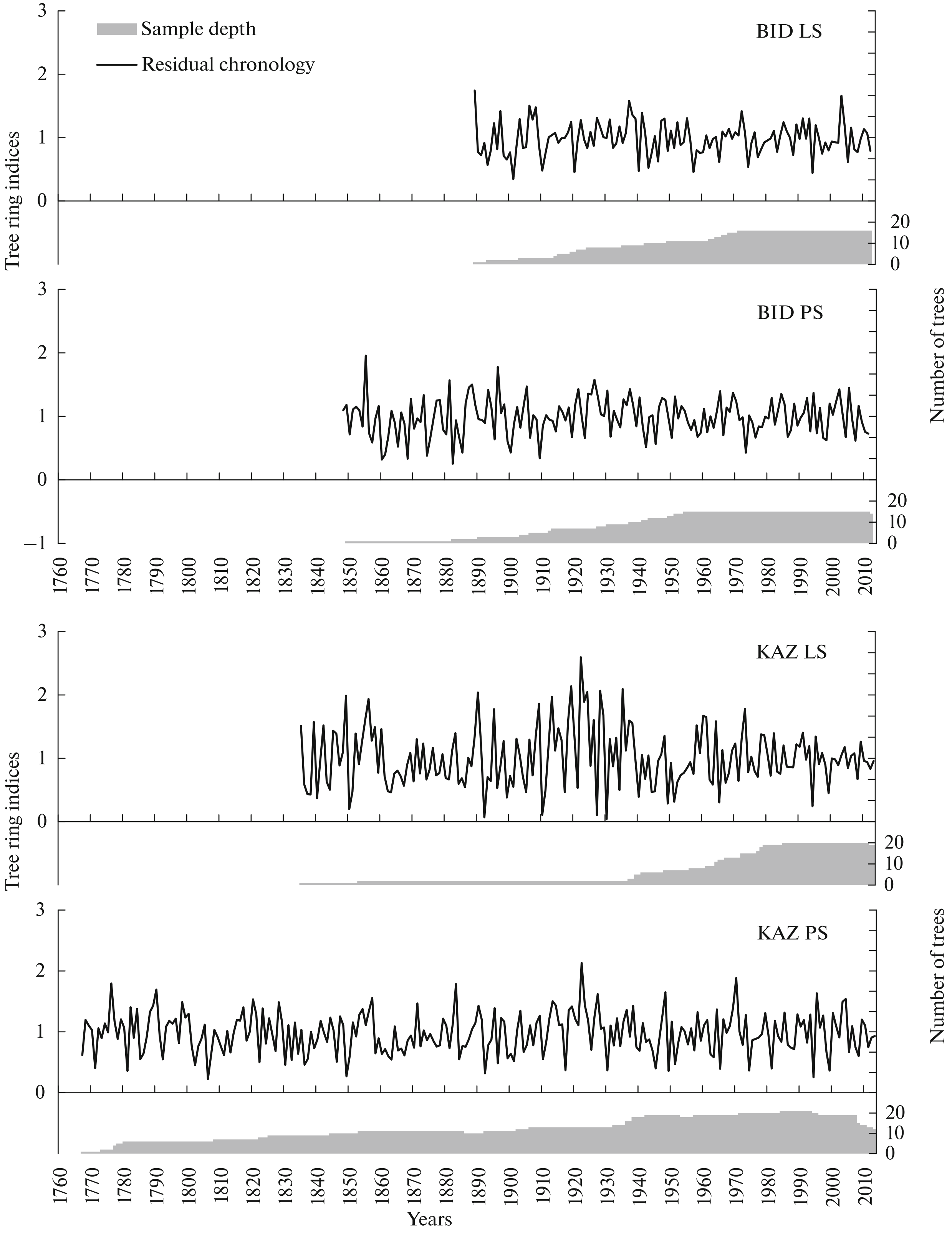

Fig. 2. The residual chronologies of radial growth with indication of the number of trees (sample depth) for each year.

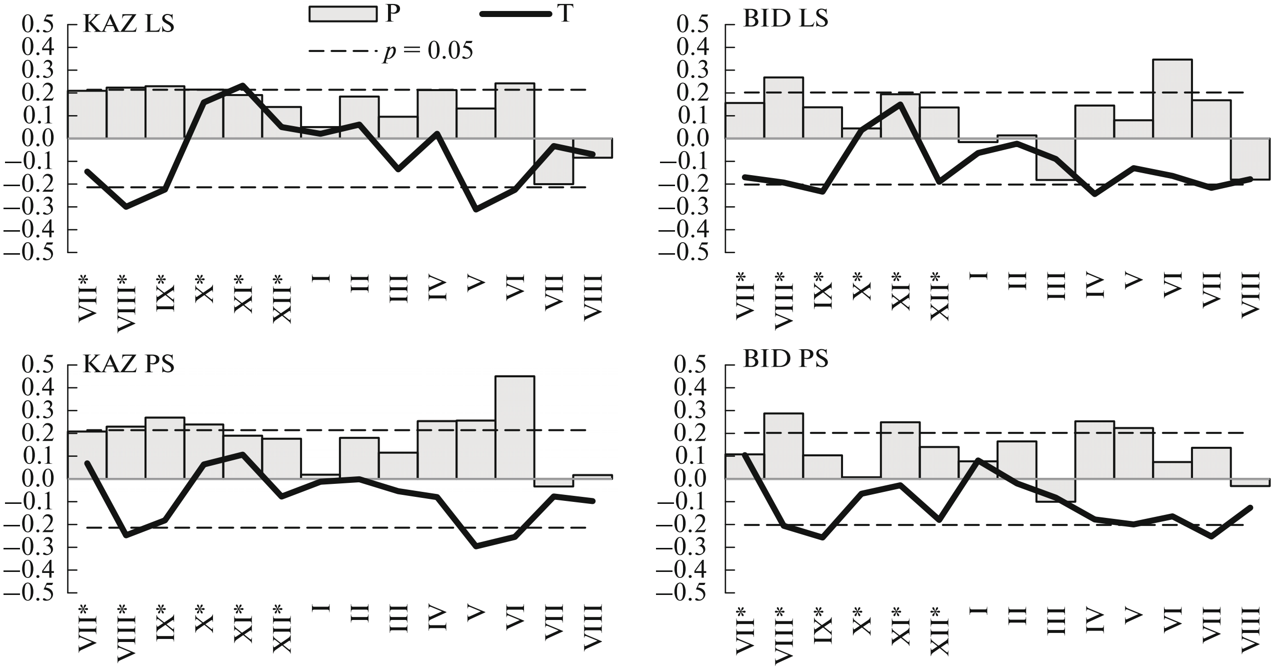

Fig. 3. Paired correlations of tree-ring chronologies with monthly climatic series. Asterisks (*) mark months of the previous year.

level of significance near the limit $p \approx 0.05$. However, only precipitation of this period is significant for the pine growth.

When using 2–12 months of climatic generalization in the classical approach (Fig. 4), very similar patterns are noticeable for both species, but differences between the sites are significant. The BID site shows negative growth response to temperature with the most pronounced correlations in April–July or April–August of the current year, August–September and August–December of the previous year. The response to precipitation has a pronounced maximum for the annual period August–July. But adjacent period July–June has almost the same intensity, i.e. we can speak about period of the precipitation influence from previous July to current July. At the KAZ site, the reaction to temperature is weaker, the maxima are observed in previous August–September and current May–June or May–July. On the contrary, the response on precipitation is more pronounced with maxima for the July–June and February–June periods.

In Seascorr analysis, taking into account possible temperature–precipitation interactions (Meko et al. 2011), precipitation has been selected as a primary climatic factor, since in the study area it has more pronounced and persistent effect on the growth of conifers. Calculations of the climatic response for periods of different lengths have shown that the best seasonal window of temperature signal is 4 months, and the precipitation signal—12 months in all chronologies (Fig. 5). The Seascorr pattern for the precipitation response matches with the results of the classical approach, since the Seascorr calculates simple correlation coefficients for the primary factor. The use of partial correlation coefficients for temperature response leads to much weaker estimation of these relationships.

The third approach that used correlation with 15-day moving climatic series provides a more accurate determination of the temporal windows of temperature and precipitation effects on the conifers radial growth (Fig. 6). For example, the KAZ larch chronology shows the positive impact of precipitation from the start of April almost until the end of June. The negative impact of high temperature on the growth lasts from the end of April to the end of June. The maximum of this impact appears in May and the first half

Table 1. Statistics of the raw and residual (*res*) local chronologies of the radial growth

Statistics	KAZ LS	KAZ PS	BID LS	BID PS
N	20	21	16	15
		raw chronologies		
mean, mm	1.632	1.061	1.593	1.696
stdev, mm	0.809	0.418	0.678	0.598
ar-1	0.531	0.295	0.722	0.685
		res chronologies		
stdev	0.467	0.353	0.239	0.252
r-bar	0.712	0.589	0.526	0.606
EPS	0.948	0.959	0.918	0.946
sens	0.514	0.447	0.295	0.308

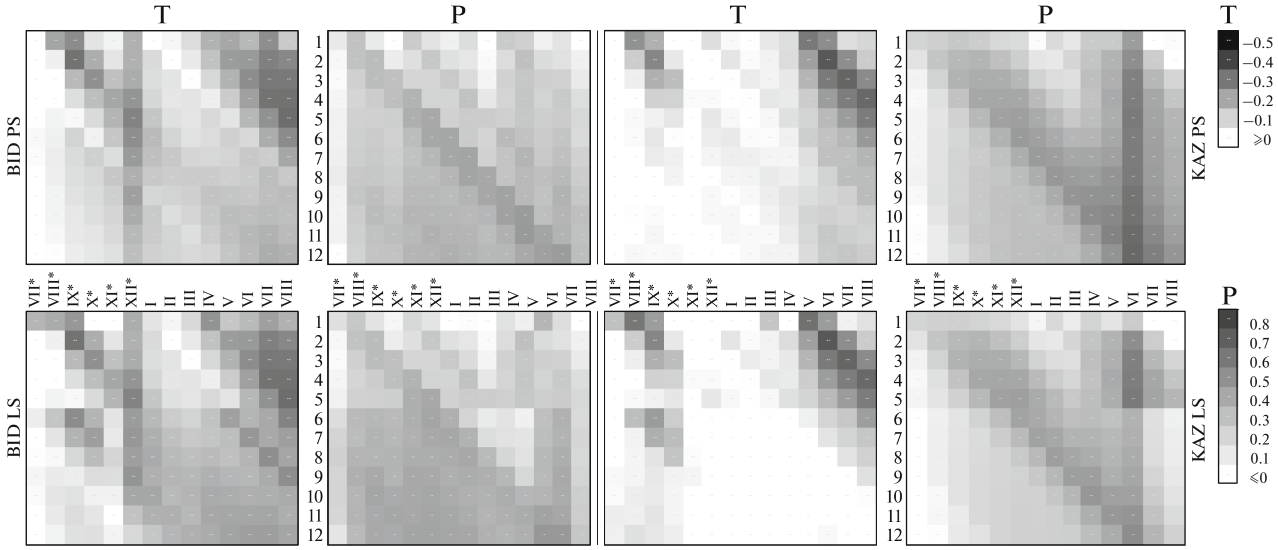

Fig. 4. Paired correlations of tree-ring chronologies with generalized climatic series for periods up to 12 months length (vertical axis). Last month of each considered period is labeled on the horizontal axis. For temperatures only negative correlations are shown, for precipitation only positive ones are shown. Absolute values of correlation coefficients exceeding 0.214 are significant on level $p < 0.05$.

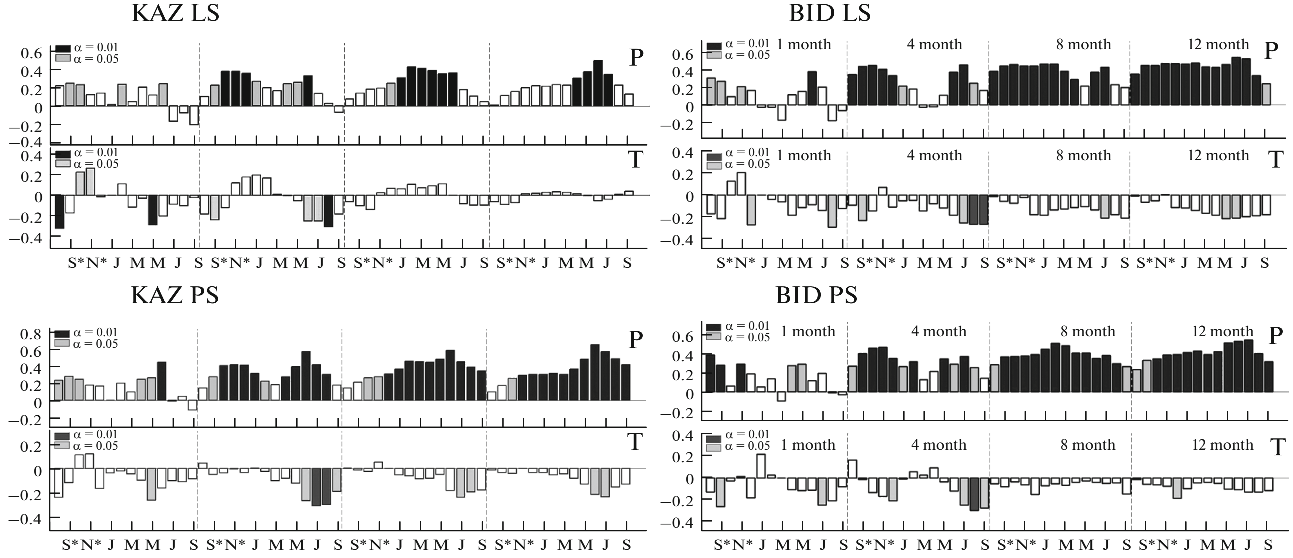

Fig. 5. Climatic response of tree-ring chronologies calculated in the Seascorr program for seasons of 1, 4, 8, and 12 months. The primary limiting factor is precipitation, and the secondary limiting factor is temperature. Last month of period is labeled on the horizontal axis.

of June. For the growth of pine at the same site precipitation effect is the most significant from mid-May to the end of June, in April and the first half of May it is less pronounced. The negative impact of temperature on the pine growth transpires mainly during two short intervals: the first decade of May and the first decade of June.

For larch at the BID site, the highest temperature influence is in the middle of April and the end of June, and the positive influence of precipitation is evident from mid-May to mid-July. For pine at this site three separate intervals are distinguished when the positive influence of precipitation and the negative influence of temperature are most pronounced (second half of April, third decade of May—first decade of June and the mid-July), while in the climatic response of larch these three intervals are observed only for the temperature influence. At both sites, termination of significant climatic influence on growth occurs earlier on about 5–10 days for larch than for pine. At the same

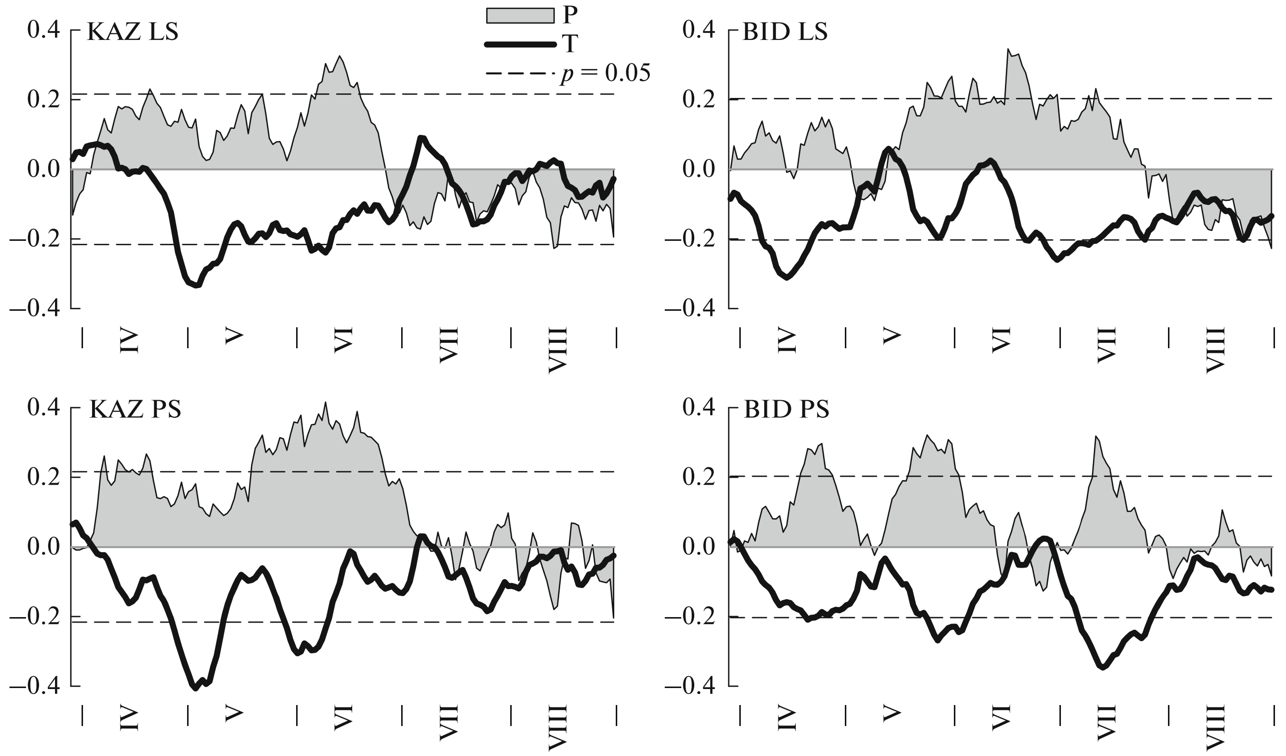

Fig. 6. Paired correlations of tree-ring chronologies with moving series of temperatures and precipitation (15-day window, 1-day step) for the current vegetative period.

time, it occurs more than two decades earlier at the KAZ site than at the BID site.

DISCUSSION

In the forest-steppe, the main limiting tree growth factor is soil moisture (Fritts, 1976). However, the lack of long instrumental observations leads to assessing the moisture impact indirectly through environmental factors that regulate moisture variability in the soil. Frequently, to approximate the soil moisture impact on tree growth in the studied region, tree-ring studies use a combination of average air temperature and sum of precipitation. The joint application of the three discussed approaches to dendroclimatic analysis allowed us to explain how larch and pine growth in the forest-steppes of South Siberia is regulated by temperature and precipitation variation throughout different seasons (Andreev et al., 2001; Agafonov and Kukarskih, 2008; Magda et al., 2011).

The soil moisture deficit results in a positive response of ring growth to precipitation, as the main source of water, during the entire growing season. After the end of vegetation as the temperature decreases, the precipitation accumulates in the soil. Later it forms a snow cover that protects the soil from freezing and slows soil drying in spring as additional moisture accumulator (Vaganov et al., 1999). The impact of precipitation occurs in the second half of the cold season, when the snowpack has been formed already and precipitation is at the minimum: in the study area an average amount of precipitation during January–March is less than 10 mm per month.

The negative impact of temperature throughout growing season is determined by changes in potential evapotranspiration, which expresses the rate of moisture loss by soil and plants (Fritts, 1976, Rossi et al., 2008, Bjorklund et al., 2017). During the hottest time of year (June–July) the temperature impact is accelerated by potential heat stress on trees. In March–April, air temperature can increase enough to terminate the dormancy and resume tree growth, occurring after that spring frosts damage tissues, thus restraining tree growth (Schulze et al., 2005).

The result of comparison of different approaches applied to the dendroclimatic diagnosis of the tree-ring chronologies suggests that the classical correlation with monthly climatic variables detects the significant input of key months for the climate–growth response. It can be used for a preliminary assessment of climatic factors limiting the tree growth. However, the complex structure of the climatic response leads to the fact that each individual factor determines a small fraction of the growth variability, which often reduces the correlation coefficients. Therefore, the next step is generalizing the climatic series over time intervals when their influence is homogenous. This generalization integrates the climatic influence throughout all season or even year, which leads to the identification of the most pronounced relationships and to the lessening of inter-species differences in the climatic response caused by the discrepancy in the phenology of pine and larch. On the other hand, distinctions in climatic response between sites do exist since the ecological-climatic conditions differ between sites. For example, shift in the seasonal peak of annual precipitation and spring-summer temperature impacts propagates a delay of growing season and ring formation at the BID site, where extremely high temperature is commonly observed in summer.

The rationale for employing the second approach (partial correlation coefficients) is a significant negative correlation between temperature and precipitation in the region, as well as their divergent influence on the soil moisture dynamics. The results of Seascorr analysis show that the effect of temperature and precipitation on conifer growth is indeed interrelated, since the partial correlations of temperature with growth are lower than the paired ones. Nevertheless, the significant partial temperature–growth correlations indicates that the climatic response of trees in the Siberian forest-steppe zone cannot be described solely by the influence of precipitation, in contrast with extremely dry regions such as the U.S. Southwest (Meko et al., 2013). In this respect, the tree-ring response to climate in the South Siberia forest-steppes is comparable to the semiarid environments of Mediterranean region, where tree-ring signal of conifer trees is driven by the divergent influence of precipitation and temperatures, although within other seasonal intervals (e.g., Touchan et al., 2016). The main advantage of this approach is the assessment of the most critical limiting factor and the interval of its greatest impact. As appears, it is the annual July–June (KAZ) or August–July (BID) precipitation. Thereby, Seascorr analysis can be especially useful in such a direction as the long-term reconstruction of climatic and other environmental variables (e.g., Meko et al., 2013; Touchan et al., 2014, 2016; Shah et al., 2015; Coulthard and Smith, 2016). However, this approach does not provide details of the climate response with high temporal resolution.

The third approach employing climatic series calculated for moving 15-day periods with 1-day step yields more detailed results (Vaganov et al., 1999, Panyushkina et al., 2003, Babushkina et al., 2010; Carrer et al., 2017). It is commonly used to analyze the climatic response of the tree-ring structure, e.g., of the cell dimensions or maximal density, because such parameters are formed in a relatively short period of time. Nevertheless, this approach is also applicable to dendroclimatic analysis of radial growth. There is no doubt that the seasonal growth of trees is not confined to the calendar boundaries, and monthly climate data may not correspond exactly to the actual moments of start or termination of the growth season. Likewise, the climatic response depends on tree species, local growth conditions, and climatic gradients (Friedrichs et al., 2009; Velisevich and Khutorornoy, 2009; Kuznetsova and Kozlov, 2011). Our results demonstrate that while higher summer temperature and lower precipitation at the BID site caused the significant difference in growth responses between the sites (Fig. 1), the details of climatic response assessed with the third approach characterize the inter-species differences related to the tree physiology of evergreen pine and deciduous larch. Therefore, the third approach helps to identify the periods of significant climatic influence. That is, its use allows to specify more accurately those critical periods of the season, when the limiting impact of climatic variables is most prominent in the tree rings.

Thus, the third approach, in spite of restriction to the availability of daily climatic data, can be useful for tree physiology and development studies. Especially, it is important for regions with a high diversity of terrain, climate and growth conditions, where local differences lead to a significant spatial variation in the climatic response of plants. This approach is also very promising in the analysis of the shifts in dates and rate of seasonal tree growth under the regional climate changes. This is confirmed by a number of studies in which such directed changes in the vegetation season onset are revealed from tree-rings, other tree phonological data or in remote data (Bunn et al., 2013; Yang et al., 2017). There is no doubt that in the framework of this paper, it is not possible to investigate in more details the application of the moving averaged or summed climatic series with a certain window and step as a tool for detecting trends in the climate–growth response, but this task seems to be very interesting for further research.

CONCLUSIONS

In forest-steppe environments of the South Siberia, where the moisture regime plays a primary role in tree growth, the comparison of three statistical approaches to the analysis of climate-growth response concludes the following:

(1) The classical dendroclimatic analysis estimates the significance of monthly mean temperatures and precipitation amounts for the radial growth, thereby highlighting the positive or negative effects of conditions during individual months. This analysis shows significant differences between both tree species, and habitat conditions (sites).

(2) Integration of climate variables over several months explains better common patterns of the climate–growth response for different species in the same conditions.

(3) The Seascorr analysis effectively ranks used in the analysis climatic factors upon their significance in the radial growth variation under specific growth conditions, and identifies well the seasonal window of response to the primary factor. The results of Seascorr

analysis are potentially most suitable for reconstructing the primary climatic factor from the past variability of radial growth.

(4) Application of correlation between the tree-ring series and climatic series for short moving windows makes it possible to indicate precisely the seasonal intervals critical to tree growth when the limiting impact of climate is most profound. These intervals boundaries do not coincide with the calendar months; therefore it explains the weak correlation between the growth and monthly climatic series.

(5) In forecast of climatic changes and their impact on tree growth, the third approach is the most effective, since it assesses the climate–growth response taking into account the current duration of the growth season and possible changes in the timing of growth inception or termination.

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