

# Dynamics of moisture regime in the Selenga River downstream basin and its reconstruction from *Pinus sylvestris* tree-ring width chronology

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**Abstract:** Regional tree-ring width chronology of the Scots pine (*Pinus sylvestris*) was developed from 8 sites in the forest-steppe belt situated in the foothills of the Selenga midlands. Moisture signal contained in this chronology allowed to receive tree-ring based linear regression reconstruction models for 1767-2015 of annual August-July regional precipitation sum and of mean annual water discharge of the Selenga River playing an important role in the water balance of the Baikal Lake. Comparison of the smoothed series allowed to estimate long-term variation component of these moisture regime parameters with high precision. At the same time, regional drought indices are less correlated with pine radial growth, because they have contribution of the other environmental variables, which are much less reflected in the tree rings of the investigated pine forest stands. Reconstructed dynamic of the moisture regime parameters is supported by documental evident of many socially significant events in the regional history, such as crop failures caused by both droughts and floods, and catastrophic fire in the Irkutsk city in 1879. Also, dependence of the amount of precipitation in the study area on the atmospheric circulation in Central Asia was revealed to have common pattern with other regions: negative relationship of precipitation with the development of large high atmospheric pressure area with its center in the Altai and Tien Shan mountains.

**Keywords:** tree-ring width; Scots pine (*Pinus sylvestris*); climate; hydrology; reconstruction model

## 1 Introduction

Recent substantial climatic changes support great scientific interest in the analysis of past climate dynamics. However, main climatic variables have distinct characteristics. Indeed, numerous studies have shown that temperature variation has high spatial coherence up to the global level (Easterling et al., 2000; IPCC, 2014 Wu X et al., 2014). In contrast, precipitation dynamics under influence of relief irregularities and atmospheric masses circulation has a significant spatial heterogeneity, especially in mountain systems and adjacent to them regions; thus analysis of its dynamics is more expedient on the regional level (Pederson et al., 2001; Batima et al., 2005; Dulamsuren et al., 2010).

High latitudes and altitudes are usually characterized by sufficient humidity, and spring-summer temperatures are the main limiting factor for vegetation growth. Therefore, contemporary warming trends lead to the positive response of ecosystems there (Wieser and Tausz, 2007; Bellard et al., 2012; Huhtamaa, Helama, 2017). On the other hand, there is a wide belt of semiarid and arid regions in the temperate latitudes, where vegetation productivity is limited by amount of available water (Sun, Liu, 2014; Yadav et al., 2015). Moisture regime there stems from interaction of temperature as the main evapotranspiration regulator with precipitation and hydrological network as sources of water (De Girolamo et al., 2011; Wang et al., 2016). An example of such a region is the downstream basin of the Selenga River, located in the Western Transbaikalia (Siberia, Russia). It is of great research and practical interest, because Selenga River provides more than half of the inflow in the Baikal Lake – one of the greatest freshwater lakes and a UNESCO World Heritage Site (Berezhenykh et al., 2012; Törnqvist et al., 2014). It has lead to the scientific attention to the Selenga River basin hydrological and climatic regime (Törnqvist et al., 2014; Frolova et al., 2017a, 2017b; Kasimov et al., 2017). Their current change is evident, and its consequences are substantial not only in aquatic ecosystems (Khazheeva, Plyusnin, 2016; Moreido, Kalugin, 2017),

but also in terrestrial ones, particularly forests (Mikhailova et al., 2013; Puntsukova et al., 2015). In consequence of the limited availability and time span of instrumental climatic and hydrological data series, analysis of their past dynamics often includes various natural proxy records (Leclercq, Oerlemans, 2012; IPCC, 2014; Bradley, 2015). Tree rings have some advantages, such as annual temporal resolution, precise dating and widespread distribution of woody plants (Cook, Kairiukstis, 1990). Besides that, trees as the basement of many terrestrial ecosystems reflect the dynamics of their status and productivity (Babst et al., 2014; Klesse et al., 2016).

In the Selenga River downstream basin, dendroecological studies carried out by Andreev S.G. (1999, 2001a, 2001b) were continued recently by our group (Demina et al., 2017). Also tree-ring based analysis of climate dynamics was performed in the river upstream basin, e.g. by Davi et al. (2015). Vegetation of the Selenga River downstream basin is represented by steppes and forests depending on the elevation. Trees growing on the border between these ecosystems (i.e. forest-steppe ecotone) are the most promising indicators of the moisture supply. It was of interest to analyze regional moisture regime dynamics using instrumental series of climatic and hydrological variables, as well as their reconstruction models based on tree-ring chronologies.

## 2 Materials and methods

### 2.1 Study area

The study was performed in the Selenga midlands, south-east from the Baikal Lake (Fig. 1). Its valleys are covered by steppes and surrounded by the mountains up to 1300-1800 m asl covered by Scots pine (*Pinus sylvestris* L.) and Siberian larch (*Larix sibirica* Ledeb.) forests. Soils are represented by mountain chernozems and mountain permafrost taiga turf soils. There are also aeolian sand deposits along the valleys.

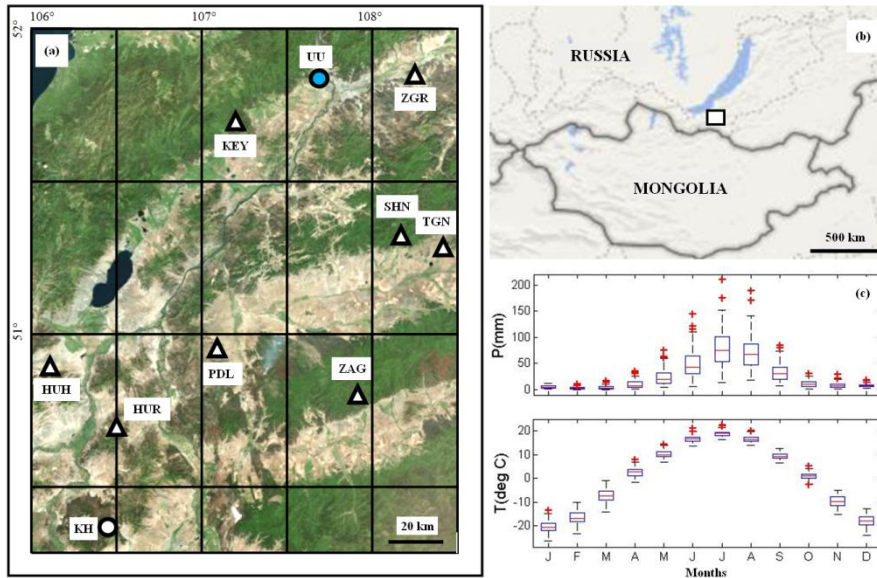
The climate is temperate sharply continental (Alisov, 1956). It is characterized by large daily and annual temperature variation amplitudes with a long low-snow winter and relatively hot summer. January temperature is  $-26$ - $20^{\circ}\text{C}$ ; winter (November-March period of negative temperatures) precipitation is 20-35 mm. July temperature is  $+16$ - $20^{\circ}\text{C}$ ; summer (June-August period of temperatures above  $+15^{\circ}\text{C}$ ) precipitation is 170-230 mm with the maximum in July (66-90 mm). The annual mean temperature is  $-3$ - $0^{\circ}\text{C}$ , and the annual precipitation is 240-380 mm.

### 2.2 Data sources

Monthly data series on precipitation (P) and mean temperatures (T) were obtained from Kyakhta (KH, #30925,  $50.4^{\circ}\text{N}$   $106.4^{\circ}\text{E}$ , 791 m asl, 1940-2015) and Ulan-Ude (UU, #30823,  $51.8^{\circ}\text{N}$   $107.6^{\circ}\text{E}$ , 514 m asl, 1921-2015) state weather stations in the study area; daily P and T series (1921-2015) were obtained from Ulan-Ude station. These stations are situated in forest-steppe zone and have the longest monthly series in the study area, which are sufficiently correlated between each other. Regional monthly P and T series for 1921-2015 (Fig. 1b) were computed from the stations data by the method of averaged standardized anomalies (Jones and Hulme, 1996). For comparison monthly series of P, Palmer Drought Severity Index PDSI and Standardised Precipitation-Evapotranspiration Index SPEI for 1901-2015 were obtained from Climate Research Unit Time-Series (CRU TS 4.01) database (<http://climexp.knmi.nl>) for area of  $50$ - $52^{\circ}\text{N}$   $106$ - $109^{\circ}\text{E}$ . Other two drought indices were calculated from regional monthly P and T series for May-September: Selyaninov hydrothermal coefficient (HTC) and wetness index (WI) (Selyaninov, 1937; Lei et al., 2014). As a main hydrological characteristic of the Selenga River, its mean annual discharge (Q) from the Mostovoy state hydrological station (Ulan-Ude city) for 1934-2015 was used.

Wood samples of pine were collected from 8 sites (Fig. 1a, Table 1) in the forest-steppe zone of basin, where trees are expected to be moisture-sensitive. The forest-steppe is characterized by low-productive open pine dry stands on sandy soils. The sparse underbrush is represented by *Dasiphora fruticosa* L., *Rosa acicularis* Lindl., *Spiraea trilobata* L., *Cotoneaster melanocarpus* Fisch. ex Blytt. The grass cover has total coverage of 5-15% and predominantly consists of steppe species: *Stipa krylovii* Roshev., *Koeleria macrantha* (Ledeb.) Schult., *Scabiosa comosa* Fisch. ex Roem. & Schult., *Thymus serpyllum* L. The first sample collection was carried out in 1999 by

Andreev S.G. (Andreev, 1999). To prolong series, the additional sample collection was performed in 2015, but not at all sampling sites (Demina et al., 2017). Both times, not suppressed healthy living trees were selected, and cores were sampled with 5-mm-diameter increment borers at breast height (~1.3 m).



**Fig. 1.** The study area: satellite map (a) with marked sampling sites (triangles), weather stations (circles) and hydro station (shaded circle); location of the study area in Siberia (b); climatic diagram (c) of 1921–2015 regional monthly P and T. Horizontal lines are medians, boxes are lower and upper quartiles, whiskers represent dataset without outliers, markers are outliers.

**Table 1.** Sampling sites and statistics of the residual TRW chronologies

Site	Coordinates			Sample			Chronology			EPS > 0.85 period	
	N	E	h, m asl	time span, years	length, years	No. of trees/cores	stdev	sens	r-bar	time span, years	min no. of trees
HUH	50.9°	106.1°	700	1768–2015	248	55/73	0.34	0.43	0.60	1770–2014	4
HUR	50.7°	106.5°	850	1751–2015	265	32/48	0.33	0.40	0.56	1777–2015	5
KEY	51.7°	107.2°	700	1807–2015	209	25/42	0.35	0.36	0.52	1818–2014	6
PDL	51.0°	107.1°	600	1760–2014	255	36/51	0.34	0.42	0.57	1817–2014	4
ZGR	51.8°	108.3°	600	1645–2014	370	27/42	0.27	0.32	0.58	1807–2014	7
SHN	52.1°	108.9°	571	1666–1998	333	11/11	0.26	0.30	0.49	1834–1998	7
TGN	51.5°	106.9°	747	1811–1998	188	13/13	0.40	0.46	0.62	1837–1998	4
ZAG	51.9°	108.2°	675	1719–1998	280	18/18	0.39	0.49	0.70	1726–1998	3
<b>Regional</b>	–	–	–	<b>1645–2015</b>	<b>371</b>	<b>217/298</b>	<b>0.47</b>	<b>0.29</b>	<b>0.39</b>	<b>1769–2015</b>	<b>22</b>

### 2.3 Processing of the tree-ring data

Wood samples processing were performed using standard dendrochronological methods (Cook, Kairiukstis, 1990). Tree-ring width (TRW) was measured to the nearest 0.01 mm using LINTAB and TSAP Win program (Rinntech, 2011). Cross-dating of the TRW series and measurement accuracy test were performed with COFECHA program (Grissino-Mayer, 2001; Holmes, 1983). Each individual series was detrended using a cubic smoothing spline with a frequency response of 0.50 at 67% of the series length as an estimation of the age trend (Cook, Kairiukstis, 1990). After that autocorrelation was removed from each series, because unlike TRW climatic and hydrological variables in the study area have not any significant autocorrelation component. Resulting residual individual series contain only interannual variability (Vaganov et al., 1996). On their base

local TRW chronologies were obtained for all sites as a bi-weighted mean (Cook, 1985). To analyze coherence among local chronologies in different frequency domains, they were decomposed into high- and low-frequency components using binomially weighted 5-years reciprocal filters (see examples of 5-, 8- and 13-year reciprocal filters using in LaMarche, Fritts, 1972; Schweingruber, 1988, p. 86; Yuan et al., 2013; Zhang et al., 2014) As correlations between local chronologies are significant in all frequency domains (Table 2), we were able to combined them in one regional chronology.

The following statistical characteristics of TRW chronologies were used: standard deviation (stdev) as estimation of general variability of TRW; mean coefficient of sensitivity (sens) to the environmental interannual variation; and mean inter-series correlation coefficient ( $\bar{r}$ ) as estimation of variation consistency between trees (Cook, 1985). The expressed population signal (EPS) was used to identify the period when chronology contain enough samples to capture sufficient percentage of the external signal common for the population on local or regional scales (Wigley et al., 1984).

**Table 2.** Correlation coefficients between unfiltered, high-, and low-pass filtered TRW chronologies over common period 1813-1996

	ZGR	SHN	ZAG	HUR	PDL	HUH	KEY	TGN
Unfiltered								
SHN	0.87							
ZAG	0.71	0.68						
HUR	0.49	0.46	0.49					
PDL	0.54	0.50	0.51	0.76				
HUH	0.45	0.41	0.45	0.79	0.66			
KEY	0.58	0.56	0.55	0.54	0.57	0.61		
TGN	0.39	0.35	0.53	0.63	0.56	0.63	0.64	
<b>Regional</b>	<b>0.67</b>	<b>0.63</b>	<b>0.69</b>	<b>0.88</b>	<b>0.81</b>	<b>0.88</b>	<b>0.73</b>	<b>0.74</b>
Low-pass filtered								
SHN	0.88							
ZAG	0.78	0.70						
HUR	0.47	0.42	0.47					
PDL	0.60	0.53	0.63	0.76				
HUH	0.47	0.34	0.48	0.78	0.73			
KEY	0.65	0.52	0.55	0.55	0.60	0.61		
TGN	0.38	0.25	0.47	0.60	0.59	0.61	0.54	
<b>Regional</b>	<b>0.69</b>	<b>0.59</b>	<b>0.70</b>	<b>0.86</b>	<b>0.85</b>	<b>0.86</b>	<b>0.71</b>	<b>0.71</b>
High-pass filtered								
SHN	0.89							
ZAG	0.70	0.70						
HUR	0.53	0.52	0.49					
PDL	0.51	0.50	0.42	0.75				
HUH	0.45	0.49	0.47	0.78	0.60			
KEY	0.57	0.62	0.58	0.54	0.54	0.61		
TGN	0.48	0.49	0.60	0.64	0.54	0.64	0.70	
<b>Regional</b>	<b>0.69</b>	<b>0.70</b>	<b>0.70</b>	<b>0.89</b>	<b>0.78</b>	<b>0.88</b>	<b>0.75</b>	<b>0.78</b>

All correlations are significant at  $p < 0.05$ .

## 2.4 Dendroecological analysis and reconstruction

During summer monthly P and T series in the study area are significantly negatively correlated ( $r = -0.38-0.17$ ). It is typical pattern for inter-mountain valleys of the South Siberia (Bazhenova, Tyumentseva, 2010). Therefore, to estimate climatic response of the tree growth, paired and partial correlations of TRW chronology with P and T respectively were calculated with Seascorr program (Meko et al., 2011). It also integrates climatic series for seasons of various lengths. In this study seasons of 1, 3, 6 and 12 months were chosen.

In correlation analysis of environmental and tree growth variables, cross-correlation with time shifts (lags) was used to take into account possible temporal differences between variables. To obtain tree-ring based reconstructions the moisture regime parameters, linear regression models were used. The model fitting to instrumental data was estimated with coefficient of determination ( $R^2$ ), adjusted coefficient of determination ( $R^2_{adj}$ ) and F-test. The stability of model was analyzed using split-sample procedure (Meko and Graibill, 1995). The total length of instrumental series

was divided into two sub-periods. The model was calibrated on one of sub-periods with accuracy measurement with  $R^2_{\text{adj}}$ , validation skill was estimated with correlation coefficient (R) between model and instrumental data for other sub-period, reduction of error (RE), and coefficient of efficiency (CE) statistics (Cook et al., 1994). To analyze frequency domains of variation for instrumental and reconstructed series, they were deconstructed with aforementioned 5-year reciprocal filters. Then sign test (ST) was performed for full series and their high- and low-frequency components. It is a ratio of agreements to disagreements between instrumental and reconstructed series in signs of departures from their mean values over considered period (Cook, Kairiukstis, 1990; Buckley, 2009).

The influence of the atmosphere circulation on the regional moisture regime and on TRW was investigated using composite map of the 500 mb geopotential height anomalies. It was calculated as field of differences between extremely dry and extremely wet years in the 1948-2015 (period of the reanalysis database NCEP/NCAR) with online mapping tool from the NOAA Earth System Research Laboratory (<https://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl>).

### 3 Results

#### 3.1 TRW chronology development

The length of local *Pinus sylvestris* TRW chronologies ranges from 188 (TGN) to 370 years (ZGR). Statistical characteristics of local chronologies (Table 1) are acceptable for the dendroecological research. All chronologies are significantly positively correlated (Table 2) and well cross-dated, which justifies possibility of their generalization into one regional chronology. Regional chronology has lower values of sensitivity (sens = 0.29) and inter-series correlation ( $\bar{r} = 0.39$ ) than local ones (sens = 0.32-0.49,  $\bar{r} = 0.49$ -0.70). On the other hand, standard deviation value is higher for regional chronology than for local ones (stdev = 0.47 and stdev = 0.26-0.40 respectively). However, all regional chronology characteristics are acceptable as well.

#### 3.2 Climatic response of TRW and reconstruction of annual precipitation

Seascorr analysis showed that regional TRW chronology has positive response to P. It is maximal in June of current year and previous August-September (Fig. 2a). Partial correlations showed that T influences pine growth independently from P only in winter (October-February); this impact is positive. Generalization for longer seasons revealed maximal correlations of TRW with P for July-June and August-July annual periods. To clarify reason behind approximate equality of these periods and to chose one of them for the following analysis, annual P series were calculated from daily data for periods ending on June 30 - July 31 with 1-day step of moving. Correlations of these series with TRW have maximum for periods ending on July 18-21 (Fig.2b), so actual influence of precipitation on the development of single tree ring of pine in the study area does not coincide with the calendar months but lasts approximately from the third decade of previous July to the second decade of current July. Therefore, P reconstruction was performed for August-July. Linear regression reconstruction function is  $P(\text{TRW}) = 142.5 + 164.3 \cdot \text{TRW}$  (Fig. 3a). Its statistical characteristics and results of split-sample validation procedure are shown in Table 3. Sign test shows that reconstruction model captures precipitation variation in both high- and low-frequency domains.

Grid series of August-July P for 50-52°N, 106-109°E area have correlations with reconstructed series  $r = 0.59$ -0.69, with instrumental series  $r = 0.70$ -0.85.

**Table 3** Statistical parameters of split-sample calibration–verification for tree-ring based reconstruction of August-July precipitation

Calibration				Verification									
Period	$R^2$	$R^2_{\text{adj}}$	$F^*$	ST			Period	R	RE	CE	ST		
				full	high	low					full	high	low
1922-1968	0.30	0.28	19.1	36/11	28/17	38/7	1969-2015	0.79	0.64	0.60	34/13	34/11	38/7
1969-2015	0.63	0.62	75.5	34/13	26/19	38/7	1922-1968	0.55	0.35	0.27	34/13	35/10	38/7
1922-2015	0.44	0.44	72.9	71/23	65/25	76/14							

$R^2$  – coefficient of determination (explained variance);  $R^2_{adj}$  – adjusted coefficient of determination; F – Fisher test statistics; ST – sign test, calculated for unfiltered (full), high-, and low-pass filtered series; R – Pearson correlation coefficient; RE – reduction of error; CE – coefficient of efficiency.

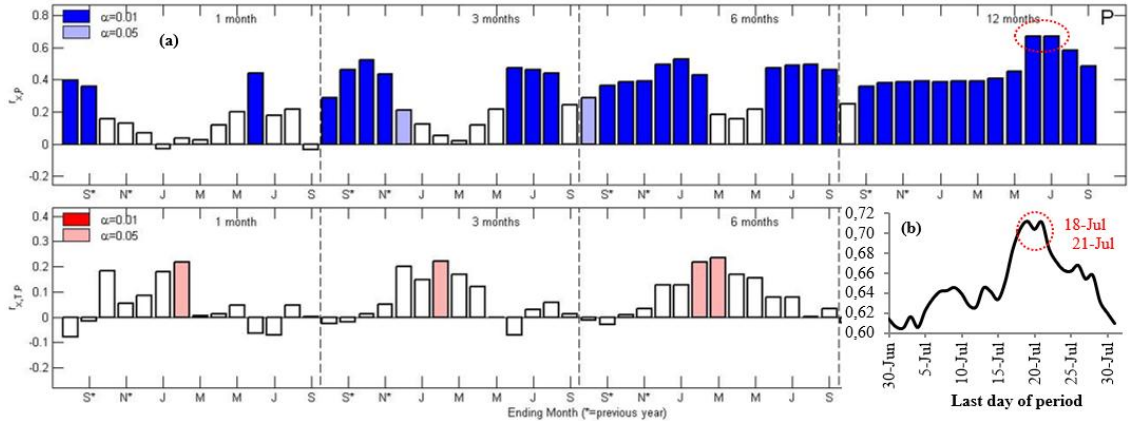
\*All F-test values are significant at  $p < 0.05$ .

### 3.3 Historical documentation of extreme years

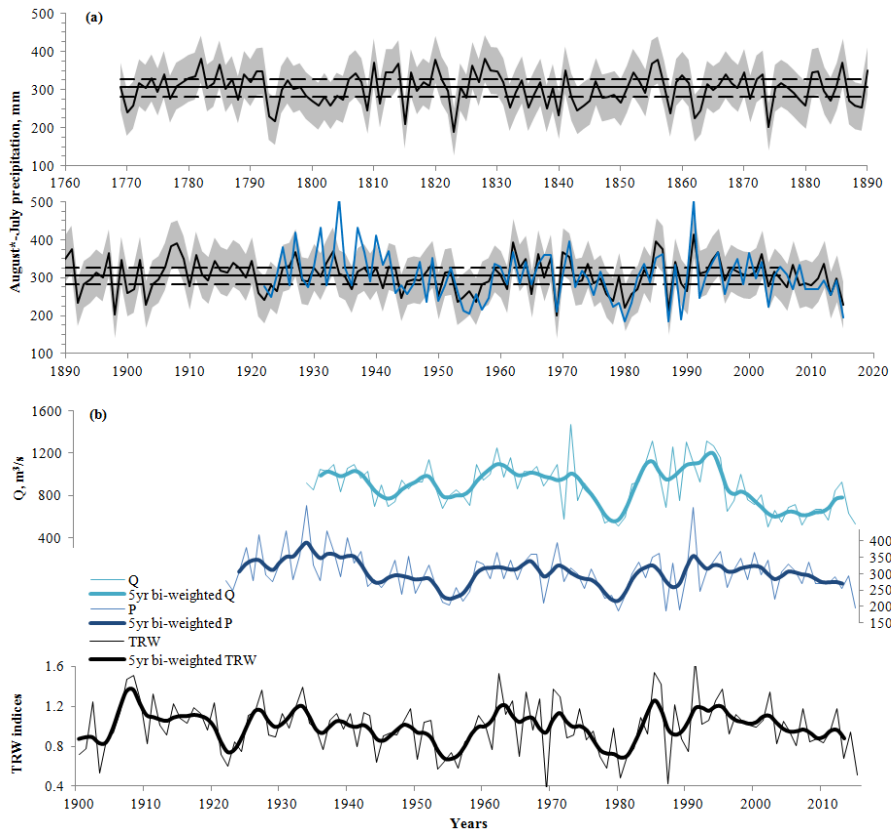
Many extremes of both signs of the reconstructed P outside the instrumental data period are confirmed by historical sources (Table 4). E.g. some maxima are consistent with the reports on floods from high water or heavy rains in Transbaikalia and Irkutsk province. Kozhuhov Y.V. (1967) mentioned that "1801, 1811, 1820, 1830, 1840 and 1848 were the most severe years for agriculture". There is also stated that in 1802, in Transbaikalia "due to lack of bread in the summer time, people were fed with a quinoa and other grasses"; in 1809 "the settlers suffered a calamity of bad harvest" which lasted several years; "crop failure continued for several years and almost all Transbaikalia suffered from it in 1811, and 1813-1816"; "from the bad harvest of grass and the lack of a forage feed in September 1838, cattle began to die...". Poor harvests of 1811-1816 were also mentioned by Shcheglov I.V. (1884). As reconstructed P showed, bad harvest could have been caused by drought), as well as by heavy spring-summer rains. Besides that, catastrophic fire of 1879 in Irkutsk also was drought-related (Kudryavtsev, Vendrih, 1971). May and June of that year were extremely hot and dry, and when fire ignited (June 22 and 24) the weather also was very hot, which made fire-fighting difficult. As a result, the fires produced a huge devastation, more than half of the city was destroyed (Antonov, 1996).

**Table 4** Comparison of reconstructed precipitation extremes with data on historical events

Year	P extremes	Historical event	Reference
1785	+	heavy rains, flood	Pezhensky, Krotov, 1911
1801	-	severe year for agriculture	Kozhuhov, 1967
1802	-	food deficit	Kozhuhov, 1967
1806	+	heavy rains, flood	Pezhensky, Krotov, 1911
1809	-	bad harvest	Kozhuhov, 1967
1810	+	bad harvest	Kozhuhov, 1967
1811	-	severe year for agriculture	Kozhuhov, 1967; Shcheglov, 1884
1812	+	bad harvest	Kozhuhov, 1967; Shcheglov, 1884
1813	+	bad harvest	Kozhuhov, 1967; Shcheglov, 1884
1814	+	bad harvest	Kozhuhov, 1967; Shcheglov, 1884
1815	-	bad harvest	Kozhuhov, 1967; Shcheglov, 1884
1816	+	bad harvest	Kozhuhov, 1967; Shcheglov, 1884
		heavy rains, flood	Kozhuhov, 1967
		heavy rains, flood	Shcheglov, 1884
1820	+	severe year for agriculture	Kozhuhov, 1967
1827	+	heavy rains, flood	Pezhensky, Krotov, 1911
1828	+	heavy rains, flood	Pezhensky, Krotov, 1911
1829	+	heavy rains, flood	Pezhensky, Krotov, 1911
		heavy rains, flood	Pezhensky, Krotov, 1911
1830	+	severe year for agriculture	Kozhuhov, 1967
1838	-	bad harvest	Kozhuhov, 1967
1840	-	severe year for agriculture	Kozhuhov, 1967
1841	+	flood	Kozhuhov, 1967
1848	-	severe year for agriculture	Kozhuhov, 1967
1879	-	catastrophic fire in Irkutsk	Kudryavtsev, Vendrih, 1971; Antonov, 1996
1897	+	heavy rains, flood	Voznesensky, Shostakovich, 1913

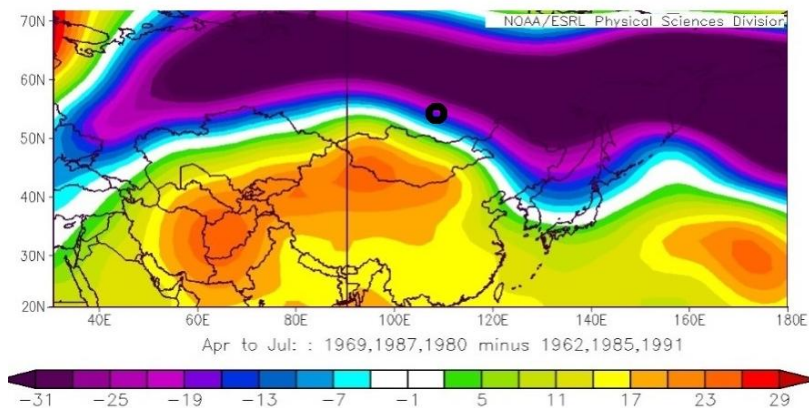


**Fig. 2.** Climatic signal in regional TRW chronology: Seacorr summary (a); correlation between regional chronology and P summarized for moving annual periods from (1 Jul\* - 30 Jun) to (1 Aug\* - 31 Jul) with 1-day step. Periods with maximal correlations are marked.



**Fig. 3.** Dynamics of the regional moisture regime: regional August-July P instrumental series and TRW-based reconstruction model (a); low-frequency components of the Selenga River mean annual Q, August-July P and regional TRW chronology, estimated with 5-year bi-weighted low-pass filter (b). On the panel (a) horizontal solid line is the mean, and dashed lines are the 25th and 75th percentiles of the regional instrumental P for 1922-2015. Uncertainty in reconstructed values is shown by an 80% confidence interval (shade).





**Fig. 4.** Composite map of April-July 500-mb geopotential height difference between dry and wet years. Color bar represents departures (m) from 1981–2010 climatology. Circle indicates study area location.

### 3.4 Anomaly of atmospheric circulations in extreme years

To analyze the effect of atmospheric circulation on the regional moisture regime, extremely dry 1969, 1987, 1980 and extremely wet 1962, 1985, 1991 were chosen. These years have extremal amount of precipitation in April-July, as well as extremes of the same sign in the regional TRW chronology (values outside the range of mean  $\pm$  stdev). As it is shown on the composite 500 mb geopotential height anomaly map for the same months (Fig. 4), drought is associated with high atmospheric pressure area with center in the Altai and Tien Shan mountains.

### 3.5 Relationships of precipitation and its reconstruction model with drought indices

Four indexes describing the moisture availability on the territory were considered. HTC and WI can be calculated only for a period of temperature above  $+10^{\circ}\text{C}$ , therefore in the study area they were obtained for May-September. HTC is persistently more closely related to August-July P than WI. The correlations of these indices with instrumental P series are  $r = 0.61-0.78$  in current May-July,  $r = 0.54-0.65$  in previous August-September, and the best convergence with the annual precipitation is shown by the indices combined for both these periods ( $r = 0.79-0.96$ ). Comparison of these drought indices with the regional TRW chronology showed that relationships have the same temporal pattern during season, but they are weaker, and difference between indices is much smaller:  $r = 0.43-0.45$  in May-July,  $r = 0.40-0.47$  in previous August-September, and  $r = 0.57-0.61$  in the combined period.

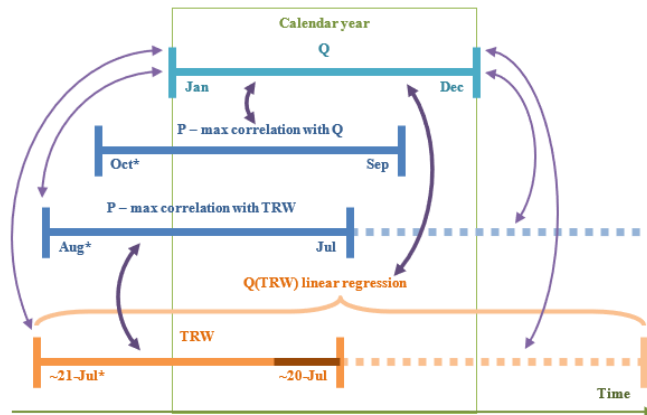
Spatially distributed PDSI and SPEI can be calculated throughout all the year, so for this study they were generalized for August-July. Nevertheless, despite more temporal accordance correlations of their averaged series for  $50-52^{\circ}\text{N}$ ,  $106-109^{\circ}\text{E}$  area with instrumental P series are noticeably lower than correlations of the indices above:  $r = 0.41$  for PDSI and  $r = 0.40$  for SPEI. The TRW chronology correlate with these indices even less:  $r = 0.35$  and  $r = 0.27$ , respectively. However, it should be noted that all listed relationships are statistically significant at  $p < 0.05$ .

### 3.6 Relationships of precipitation and its reconstruction model with the Selenga River discharge

The only available series of the Selenga River mean Q were for calendar years, i.e. from January to December. Therefore, it makes sense to consider Q relationship not only with annual P from previous August to current July, but also with P from current August to next July (i.e. the same series with lag of +1 year), and to P of other annual periods in-between (Fig. 5). The correlations between Q and August-July P are  $r = 0.48$  without lag and  $r = 0.29$  with +1-year lag, both of them are significant at  $p < 0.05$ . The maximal correlation between Q and annual P is observed for October-September:  $r = 0.65$ . The similar pattern is observed between Q and TRW:  $r = 0.44$  without lag and  $r = 0.32$  with +1-year lag. Thus, we can describe it quantitatively as two-factor linear regression with the following equation:  $Q(\text{TRW}) = 229 + 382 \cdot \text{TRW} + 292 \cdot \text{TRW}_{+1}$ . This regression



model has  $R_{\text{adj}}^2 = 0.28$  and correlation with instrumental series  $r = 0.54$ .



**Fig. 5.** Relationships between mean annual Q of the Selenga river, regional TRW chronology, and regional P calculated for annual periods of maximal correlation with Q and with TRW. Asterisks (\*) mark previous year. For TRW chronology approximate period of maximal precipitation impact is shown according to daily climatic data (see Fig. S2), approximate period of TRW development is marked with dark shade (from  $T > +10^\circ$  to the end of maximal P impact period). Dashed lines represent P and TRW with +1-year lag. Arrows represent significant at  $p < 0.05$  positive correlations. Correlation values  $r > 0.5$  are marked with bold arrows.

Comparing low-frequent components of P, Q, and TRW series (Fig. 3b), they have sufficiently higher correlations between each other:  $r = 0.59$  between precipitation and discharge smoothed series,  $r = 0.61$  between discharge and TRW ones, and  $r = 0.79$  between precipitation and TRW ones. Smoothed reconstructed and instrumental discharge series have correlation  $r = 0.63$  between each other. Also, comparison of smoothed series shows that they all have the same in-phase quasi-cyclic oscillation with period length of  $\sim 25$ – $35$  years (Balybina, 2006; Demina et al., 2017).

## 4 Discussion

The development of the regional TRW chronology made it possible to integrate the variation of pine growth from the entire area from which the material was collected, since the sites were selected in relatively close natural conditions and distributed throughout the study area (Fig. 1a). However, some differences between sites both in regards to habitat conditions and to local climate (because of uneven precipitation) lead to a decrease in the statistical characteristics of regional chronology relative to local ones. As a consequence, the period of its suitability for reconstruction also does not reach the maximum observed for ZAG local chronology. Despite that, in the investigation of the regional climate and the hydrological regime of territory, it is more expedient to use regional chronology and not local one.

The positive reaction of chronologies on precipitation as a source of moisture is typical for the forest-steppe zone of South Siberia (as it was shown in Andreev et al., 1999; Demina et al., 2017). However, unlike other territories (e.g. Shah et al., 2015; Babushkina et al., 2017), in the study area the temperature of the warm period affects the growth only indirectly, through the regulation of water loss. This is indicated by the absence of significant partial correlations, while paired temperature–growth correlations in the study area are significant (Demina et al., 2017). A positive response of growth to the temperature of the late autumn and most part of the winter is due to the fact that in conditions of low snow cover thickness soil freezing in extremely cold winters can cause damage to the most active part of the fine roots of trees (Tierney et al., 2001; Schaberg et al., 2008). Such damage can occur since October when temperature decreases sharply before establishment of stable snow cover, and continue until March, when severe frosts are unlikely.

Clarification of the most significant climate influence period on tree growth using daily climatic series and the moving periods of their generalization was carried out in the previous research. E.g. in the previous study (Belokopytova et al., In print) it was demonstrated that climate influence

period can vary significantly between remote sites within the region due to climatic gradients even when their habitat conditions are homogeneous. Elevation and landscape features also can shift timing of cambial phenology and consequently tree ring development in general (Prislan et al., 2013; Jiang et al., 2015; Kraus et al., 2016). Therefore, taking into account the horizontal distance between the sites up to 170 km and the vertical difference up to 280 m, TRW series integrated into the regional chronology react to the climate during different periods even within one year. On the other hand, climatic variations lead to a change in the timing of the beginning and end of the tree ring development (Prislan et al., 2013; Gricar et al., 2014; Swidrak et al., 2014; Yang et al., 2017). Thus, the end of the maximum annual period of precipitation influence (July 18-21) revealed in this study gives us the estimation of spatio-temporal mean or most probable moment of the cambial activity ending for pine trees growing in the forest-steppes of the study area.

For the selected August-July period, the precipitation contribution in the tree rings development of pine in the forest-steppe zone is significant and sufficient to use the TRW chronology for precipitation reconstruction. The quality and accuracy of the reconstruction model is confirmed not only by its statistical characteristics, but also by convergence of reconstructed precipitation dynamics with other data sources: spatially distributed precipitation series and historical evidence of extremal events that are significant for the society and the national economy of the region.

Analysis of the atmospheric masses circulation revealed pattern in the spring-summer drought development, typical not only for the study area. Despite the choice of different dry and wet years, the composite map of the geopotential height has a high similarity with maps constructed for for Khakassia (Kostyakova et al., 2017) and Kashmir, India (Shah et al., 2018). Moreover, negative correlations between precipitation amount and geopotential height were reported in Mongolia and Northern China (Hu, 1997; Wang et al., 2017). Consequently, the formation of anticyclones in the Altai and Tien Shan mountains in the spring-summer season reduces the amount of precipitation not only on the spot, but also spreads its influence to other regions of Central Asia from Northern India to South Siberia, due to the flow of dry atmospheric masses there.

It is understandable that more closely related to the regional precipitation series amongst drought indices are ones calculated on the basis of the same series, i.e. HTC and WI. When calculating WI (Lei et al., 2014), the precipitation variable is used as an argument of the logarithm function. This non-linearity of the relationship reduces the correlations in comparison with the HTC, which is proportional to the sum of precipitation. The less pronounced difference between HTC and WI correlations with TRW chronology indicates that during extreme droughts precipitation has stronger influence on the pine growth, i.e. this influence is nonlinear. The possible reason of this nonlinearity is that drought not only depresses radial increment rate, but also reduces duration of cambial activity (Rossi et al., 2014). Weaker relationships of PDSI and SPEI with precipitation are explained partially by their calculation on the basis of another data set, and partially by a greater contribution of other climatic variables to these indices, including temperature (Vicente-Serrano et al., 2010; Osborn et al., 2017). And since in the study area the temperature does not exert an independent influence on the tree growth, all four considered drought indices correlate with regional TRW chronology (and P reconstruction based on it) weaker to the certain degree than with instrumental precipitation series.

Similarly to the drought indices, the water balance of hydrological objects depends not only on the amount of precipitation, but also on evaporation, i.e. it is connected with temperature (e.g. water balance equations in Shanahan et al., 2007; Giadrossich et al., 2015). Another factor lessening the correlations of the Selenga River with regional precipitation series is that the study region represents only part of the Selenga basin. Therefore, discharge measured at the Mostovoy station integrated precipitation amount from much larger area. As it is shown on Fig. 5, the inflow of water from precipitation into the riverbed occurs with a certain lag, which can be due to two main reasons: 1) low speed of surface and underground runoff (e.g. Gillies et al. 2011, 2015; Babushkina et al., 2017), and 2) solid form of winter precipitation falling which leads to delay of the water flow until the spring snowmelt. In connection with this lag, the average annual discharge of the Selenga River have significant correlations with both the August-July precipitation and the TRW chronology with the 1-year lag. This allowed us to develop much more accurate two-factor

regression model of discharge reconstruction based on the tree rings variability with zero and 1-year lag than simple regression would be.

A higher similarity between the low-frequency dynamics components of the precipitation, Selenga discharge and tree growth indicates the possibility of using the obtained reconstruction models to assess decadal to centennial fluctuations in the moisture regime of the territory with high accuracy. Such assessments are important for forecasting economic activity within the Selenga River basin, as well as for assessing the risks of long-term extremal variations of the Baikal Lake under conditions of its regulation (Törnqvist et al., 2014).

## 5 Conclusions

Radial growth of *Pinus sylvestris* in the forest-steppe zone of the downstream basin of the Selenga River is closely related to the amount of precipitation during the year, while the independent effect of temperature is expressed only in the winter months. Based on the regional TRW chronology, the August-July precipitation was reconstructed for the period 1769-2015. The quality and accuracy of the reconstruction model are confirmed statistically, by other sources of instrumental data and by documentary evidence. The historical significance for the region is shown not only for droughts, but also for extremely high precipitation. TRW response to other indicators of moisture regime, namely drought indices and Selenga discharge, is less pronounced than to precipitation. The relationships of the mean annual discharge with precipitation and TRW were described quantitatively, resulting in a model of its reconstruction, but it has less accuracy than precipitation one. However, tree growth registers long-term fluctuations of both parameters of the moisture regime with very high accuracy. The patterns of atmospheric circulation in Altai and Tyan Shan were revealed to impact development of droughts in South Siberia among other regions of Central Asia.

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