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Climate-growth relationships of Schrenk spruce and precipitation variability at the high-mountain areas of the northern Tien Shan

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ABSTRACT

This article presents a new tree-ring chronology of Schrenk spruce (Picea schrenkiana Fisch. et Mey.) developed based on the samples collected at the upper tree limit of the northern Tien Shan (southeastern part of Kazakhstan). The correlation analysis with daily climate data revealed that precipitation in the period from the previous July 8th to November 5th is the main limiting factor of tree-growth $r = 0.648$ ($p<0.05$). The obtained chronology was used to reconstruct precipitation in the period from 1829 to 2016. The reconstruction explains 41% of the variance in instrumental precipitation records during the calibration period 1948-1987. The reconstruction revealed six extreme years (± 2σ). Extreme drought years were detected in 1846, 1886, and 1912, and extreme wet years were detected in 1879, 1917, and 1920. Both the occurrence of extreme years and variation of increase/decrease of the amount of precipitation changed significantly during the last 70 years. The amount of precipitation increased in the periods 1829-1843, 1856-1869, 1880-1905, 1920-1935, 1946-1955 and 1978-1993 and decreased in 1843-1856, 1869-1880, 1905-1920, 1935-1946, 1955-1978 and 1993-2016. The Morlet wavelet analysis revealed ~2-4, ~5-7, and ~10-16 year cycles, indicating a possibility to connect the precipitation variability in the study area with the oscillations of certain atmospheric circulation indices. The study provides new information for understanding high-mountain environmental changes in the northern Tien Shan.

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1. Introduction

Adaptation to climate change, water security, protection of the environment, and many other issues remain on the agenda because they strongly affect peoples' life in different regions of the world (Garcia et al., 2014). The high-mountainous territories of Central Asia are one of the most vulnerable regions of the world in terms of climate change. (Mountain Research Initiative EDW Working Group, 2015). Many actions have already been taken to improve the situation, and different organizations and institutions in Kazakhstan are still working on the implementation of projects launched as a part of the commitments undertaken by the government after the ratification of the United Nations Framework Conventions on Climate Change, Aarhus Convention and Convention on Biological Diversity. However, a noticeable obstacle arises here, which is associated with the lack of hydroclimatic data because of the suspension of instrumental observations in the period after the collapse of the Soviet Union. Additionally, the period of observations itself is relatively short, the data often have significant gaps, and only a few stations have sufficiently long data series necessary for conducting qualitative studies (Williams and Konovalov, 2008; Menne et al., 2012).

In this context, increases the role of climatic proxy data such as tree rings, used in the dendrochronological analysis. Dendrochronological analyses have proved their effectiveness and great potential, especially in regions with a temperate climate, where trees form clearly visible annual rings (Esper et al., 2002; Cook et al., 2010; Büntgen et al., 2011). In recent years, work in this direction in Kazakhstan has markedly advanced, especially in the southeastern part of the country, in forests of the northern Tien Shan mountains, where the dominant tree species is Schrenk spruce (Picea schrenkiana Fisch. et Mey.). Dendrochronological analysis based on this tree species has already provided a lot of exciting information about environmental changes in the region. For example, several works on the reconstruction of drought, vegetation index, precipitation, and temperature were published (Chen et al., 2017; Zhang et al., 2017; Zubairov et al., 2018a). Thus, using dendrochronological analysis, we can significantly improve our understanding of the spatial and temporal patterns of the development of various natural processes. Dendrochronological research can bring undoubted benefits however, we should remember that the key elements of this analysis are quality, span, and spatial coverage. Unfortunately, most of the recent studies were conducted in the lower forest belt (from the lower tree limit to 2100-2200 m a.s.l.). In contrast, climate-growth relationships near the upper tree limit are still relatively poorly understood (Zubairov et al., 2019; Zubairov, 2020). Meanwhile, this information could be essential for our understanding of environmental changes in high mountain areas especially taking into consideration projected climate change impacts.

Specific differences between Schrenk spruce growth at the upper and the lower elevations we already know, thank a comparative analysis of publications presented in Zubairov et al. (2019). These differences include the stretching of the ontogenesis and the offset of the growing season of trees at the upper tree limit, associated with variations of hydrothermal conditions with altitude. And also, a strong influence on climate-growth relationships is caused by the presence of permafrost. However, we should remember that these results were obtained around 40 years ago, and therefore, they do not reflect the current state and more recent changes in climate-growth relationships. At the same time, we can expect to see such or similar changes, taking into consideration the results that have been published during the last five years (Zubairov et al., 2018b).

Therefore, to address this issue, I decided to conduct a dendrochronological study based on the samples collected at the upper tree limit to find out what tree rings can tell us about environmental changes in high mountain areas.

2. Methods and Materials

2.1 Study area and meteorological data

Schrenk spruce samples from the three sites at the upper tree line of the Ile Alatau Range were collected (Fig. 1). The Schrenk spruce (Picea schrenkiana Fisch. et Mey) which covers the slopes of the Ile Alatau Range is the dominant tree species here. Schrenk spruce forests of the Ile Alatau belong to the Dzungar-North Tien Shan group of vegetation altitudinal zonality types, which consist of five belts and sub-belts of vegetation types, including steppes, dark coniferous forests and meadows, subalpine-like meadows and juniper elfin woods, cryophytic (alpine-like) meadows and communities of Kobresia and the subnival belt (Akzhygitova et al., 2003). For sampling, only healthy trees without signs of diseases and injuries were chosen. Sampling was conducted on a north-facing slope, characterized by a shallow soil layer and inclination from 15° to 25°. For sampling, a standard 400 mm increment borer with 3 blades was used. In general 2 cores from each tree were taken, from the opposite side from each other, parallel to the slope, at breast height, following standard dendrochronological procedures outlined in Speer (2010). In total, 82 samples from 42 trees were collected.

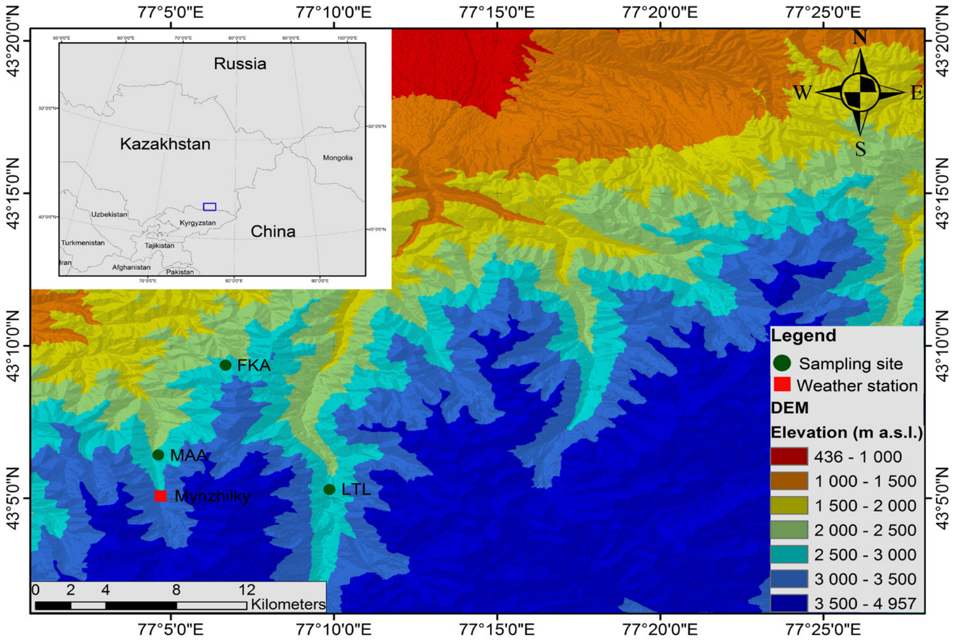

Figure 1. Study region.

For the correlation analysis, monthly and daily climate data (the mean annual air temperature (MAAT) and precipitation) were used, including the following databases: the Global Historical Climatology Network (GHCN)-Daily v.2 (Menne et al., 2012), Climate Research Unit (CRU) TS 4.00 (Harris et al., 2014), and Central Asia temperature and precipitation data, 1879-2003 (Williams and Konovalov, 2008). Data from the Mynzhilky meteorological station (#36889, 43.05°N, 77.04°E, 3020 m a.s.l.) were used because it is the nearest station to the sampling sites). The climate in the region experiences strong seasonality in temperature. The mean July temperature is 7.9°C, the mean January temperature is -11.4°C, and MAAT is -1.89°C in the period from 1937 to 1997. The precipitation regime has just one peak in June-August, which is in contrast to lower elevations where we have two peaks, one in April-May and the second in October-November. The mean annual precipitation totals are about 870 mm/year, with strong fluctuation ranging from 577 to 1200 mm/year in the period from 1937 to 2008. The precipitation doesn't show a clear trend, whereas temperature exhibits warming around 0.16°C $10a^{-1}$. The total June-August precipitation accounts for around 50% of annual total precipitation (Fig. 2).

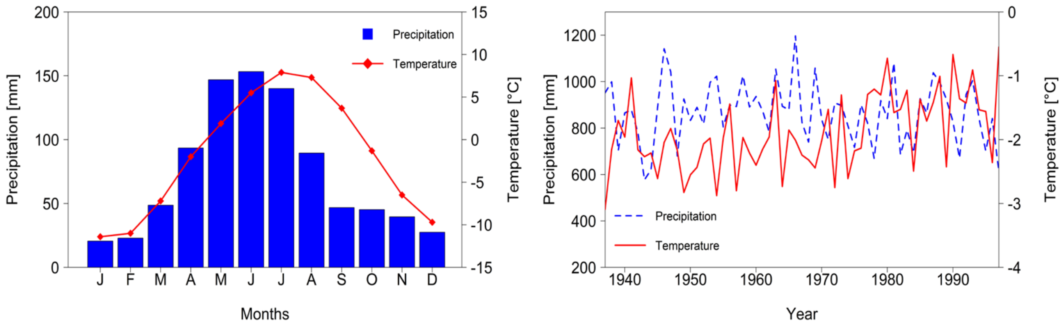

Figure 2. Precipitation and temperature graphs, left – monthly average, right – MAAT and annual precipitation totals, based on the Mynzhilky meteorological station.

2.2 Chronologies development and data analysis

Collected cores were dried, mounted, polished with sandpaper, and scanned at 1200 dpi. For tree-ring width measurements, the WinDENDRO (Regent Instruments Canada Inc., 2009) semi-automatic system was applied. In this system, tree rings on the image are detected based on light intensity differences and, after that, we also visually check the presence of missing or false rings as well as misclassifications. All series were visually cross-dated using the TSAPWin program (Time Series Analysis and Presentation for Dendrochronology and Related Applications; version 4.67c © 2002-2011 Rinntech). Results were checked using the COFECHA program (Version 6.06P © 1997-2004 Absoft Corporation) and corrected whenever it was necessary (Holmes, 1983). Tree-ring index chronologies were developed by using the standardization technique in the ARSTAN program (AutoRegressive STANdardization; MRWE Application Framework © 1997-2004 Absoft Corporation) (Cook and Holmes, 1986). The standardization removed non-climatic signals and reduced noise from individual series. A cubic smoothing spline at a wavelength of two-thirds the sample series length (Cook and Peters, 1981) was applied for detrending. The variance was stabilized using the adaptive power transformation method, and a bi-weight mean was applied for the development of final indexed chronologies (Cook, 1985). These procedures reduce the noise caused by individual trees and remove non-climatic variability such as age-related growth trends. The mean inter-series correlation (Rbar), the Expressed Population Signal (EPS), and other statistics were calculated for the assessment of the quality of the developed chronologies. The minimum sample depth of 10 samples (5 trees) and EPS of 0.85 was used as the appropriate criterion for the reliability of developed chronologies. To maximize the high-frequency signal, the residual chronologies were chosen for correlation analysis. Due to the close location of sampling sites and similar growth conditions, tree-ring series with high inter-series correlation were combined to form a composite chronology to increase sample size and extend the length of chronologies.

The CLIMTREG_V4 program was applied for the analysis of climate-growth relationships (Beck et al., 2013). This program calculates correlations between the chronology and daily climate data, from July of the previous year to the end of October of the current year, starting with a 21 days window shifting every time by one day. After finishing the first calculations, the program starts calculation again but now with 22 days window, and this process repeats until reaching 121 days. In the end, the program presents the best correlation results. Correlation analysis using daily climate data provides a more precise time interval and higher correlation values. Calculation of correlations with the previous year is necessary because the growth of trees in the current year can be affected by the temperature and precipitation conditions of the prior year (Schweingruber, 1996). Both, the length of chronologies and climate datasets were limited to the span of the minimal available period, from 1948 to 1987, to exclude the influence of different lengths of climate datasets on correlation results. The composite chronology was used as a predictor for precipitation reconstruction using a linear regression model. The reliability of the reconstruction was checked using a split calibration-verification scheme (Cook and Kairiukstis, 1990). The predictive ability of the model was tested by the coefficient of efficiency (CE) and reduction of error (RE) statistics. The geographic representation of our reconstruction was shown by applying the spatial correlation analysis, performed for the territory (35°N–55°N, 50°E–90°E), which covers Central Asia and adjacent regions of Russia, Mongolia, and China. Low-frequency variation of precipitation was summarized by annual precipitation smoothed with a 15-year low-pass filter. Obtained reconstruction was also compared with other nearby climatic reconstructions to confirm its reliability. Finally, the Morlet wavelet analysis was applied to investigate the variations of reconstructed precipitation in the frequency domain (Torrence and Compo, 1998). This analysis is one of the most commonly used methods in the analysis of climate reconstructions in dendrochronological studies, which proved its reliability.

3. Results

3.1 Tree-ring chronologies and climatic signal

In total, 77 series from all three locations were used to develop a composite residual ring-width chronology "west" (Tab. 1). Inter-series correlations, EPS, SNR, and other statistics of obtained chronology demonstrated sufficient quality and applicability for further climate correlation analysis for the period 1948-1987 and a potential to build a 188-year climatic reconstruction spanning from 1829 to 2016.

Table I. Statistics for the residual chronologies.

Site ID	Coordinates	Elevation m a.s.l.	Number of trees and radii	SDa	SNRb	EPSc	1EVd (%)	Mean correlation between all series	Chronology span
LTL	43.04°N-77.10°E	2700	14 trees 24 radii	0.19	15.22	1855	63.29	0.72	1751-2016
MAA	43.06°N-77.04°E	2600	21 trees 39 radii	0.17	22.19	1909	53.47	0.61	1743-2016
FKA	43.09°N-77.06°E	2650	7 trees 14 radii	0.17	10.18	1907	42.16	0.74	1865-2016
west	43.04°-43.09°N, 77.04°-77.10°E	2600-2700	42 trees 77 radii	0.18	24.52	1829	55.34	0.63	1743-2016

[a]*SD* Standard deviation,

[b]*SNR* Signal-to-noise ratio,

[c]*EPS* first year Expressed population signal > 0.85, 5-6 trees

[d]*1EV* Variance in first eigenvector

Correlations between the composite chronology and daily climate data revealed that the strongest effect on tree growth is caused by precipitation of the previous year in the period from July 8th – to November 5th, r = 0.648 (p<0.05). Additionally, positive correlations with precipitations were revealed for the current year, including the following periods, January 30th – February 26th r = 0.485 (p<0.05) and June 8th – July 8th r = 0.460 (p<0.05). Two periods in the current year, from the beginning of July until the end of September, showed negative correlations with precipitation August 29th – September 26th r = -0.451 (p<0.05) and July 9th – August 2nd r = -0.373 (p<0.05). Significant correlations with temperature were revealed in current and previous years. For the current year correlation results are positive in periods August 21st – September 28th r = 0.493 (p<0.05) and February 5th – February 25th r = 0.370 (p<0.05). Whereas correlations for the previous year are negative, July 10th – July 30th r = -0.440 (p<0.05) and August 4th – August 26th r = -0.378 (p<0.05) (Fig. 3).

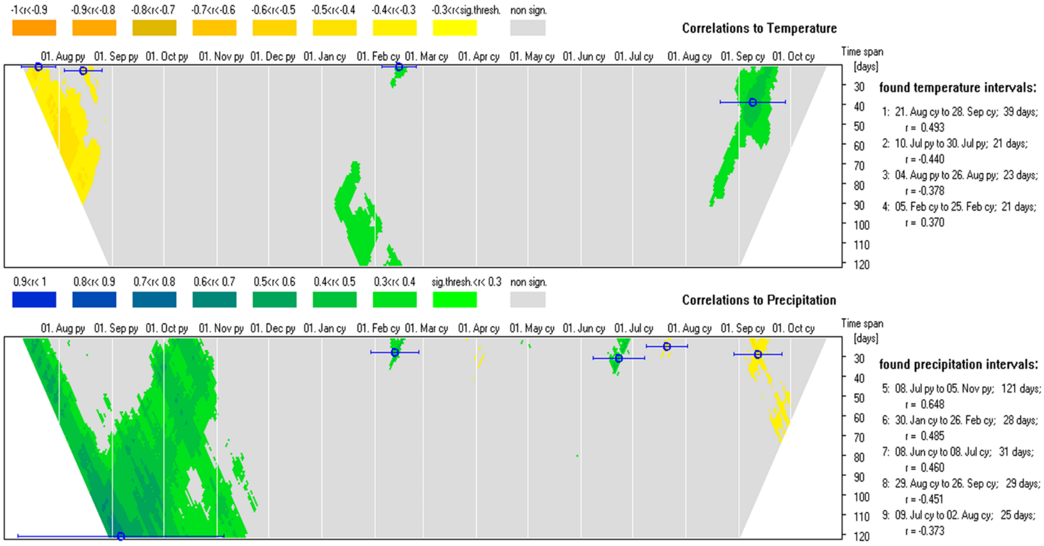

Figure 3. Correlations between the composite chronology and daily climate data (1948-1987) from previous July to current October.

3.2 Reconstruction of precipitation

The strongest correlation results were used to develop a regression model for further precipitation reconstruction. This model had the following form

$$y = 371.9x - 92.713 \quad (1)$$

During the calibration period (1948-1987) the statistics of developed regression model demonstrated its reliability, RE = 0.17, CE = 0.16, $R^2 = 0.41$, $R^2adj = 0.4$ ($p<0.001$) and therefore obtained model could be used for the reconstruction of precipitation over 1829-2016 from the July 8th to November 5th. To verify the reliability of reconstruction results, reconstructed precipitation series were compared with the precipitation data observed at the Mynzhilky meteorological station (Fig. 4).

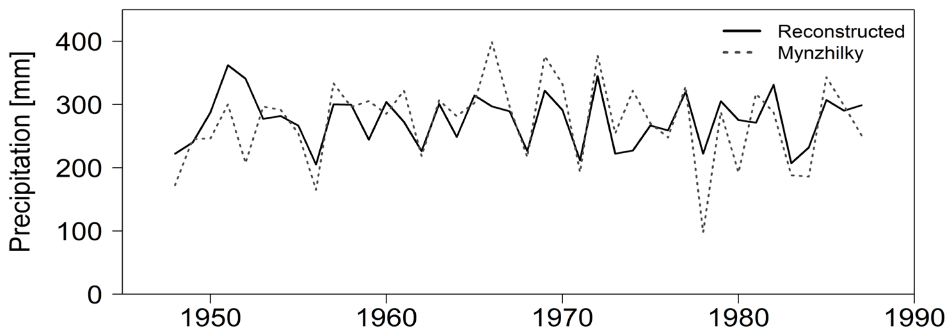

Figure 4. Comparison between observed (gray line) and estimated (black line) precipitation from July 8th to November 5th in the period 1948-1987.

The reconstruction revealed six extreme years when the amount of precipitation was lower or exceeded the mean of 2σ. Extreme drought years occurred in 1846, 1886, and 1912, whereas extreme wet years occurred in 1879, 1917, and 1920 (Fig 5A). All extreme years occurred before 1950, which is consistent with other dendroclimatic studies conducted in the region (Zubairov et al., 2018a). Good consistency with other dendroclimatic reconstructions for the territory of southeastern Kazakhstan is also demonstrated by the comparison graph (Fig. 5B). In particular, we can see the coincidence of certain peaks of extreme years, for example, in 1879 and 1917. The 15-year low-pass filtering revealed 12 periods of precipitation variation. The amount of precipitation from the July 8th to November 5th at the upper tree limit was growing in the following periods 1829-1843, 1856-1869, 1880-1905, 1920-1935, 1946-1955, and 1978-1993 and decreased in 1843-1856, 1869-1880, 1905-1920, 1935-1946, 1955-1978 and 1993-2016 (Fig. 5C). There was also a significantly stronger variation in the amount of precipitation before 1925, which is shown by both 5A and 5C graphs. Variations of precipitation in the frequency domain indicated higher precipitation variability until the 1960s, compared to the last decades. The ~5-7 year cycle was detected in the period 1850-1960, ~10-16 in the period 1865-1950, and ~2-4 year high-frequency cycles in the whole precipitation reconstruction (Fig. 5D).

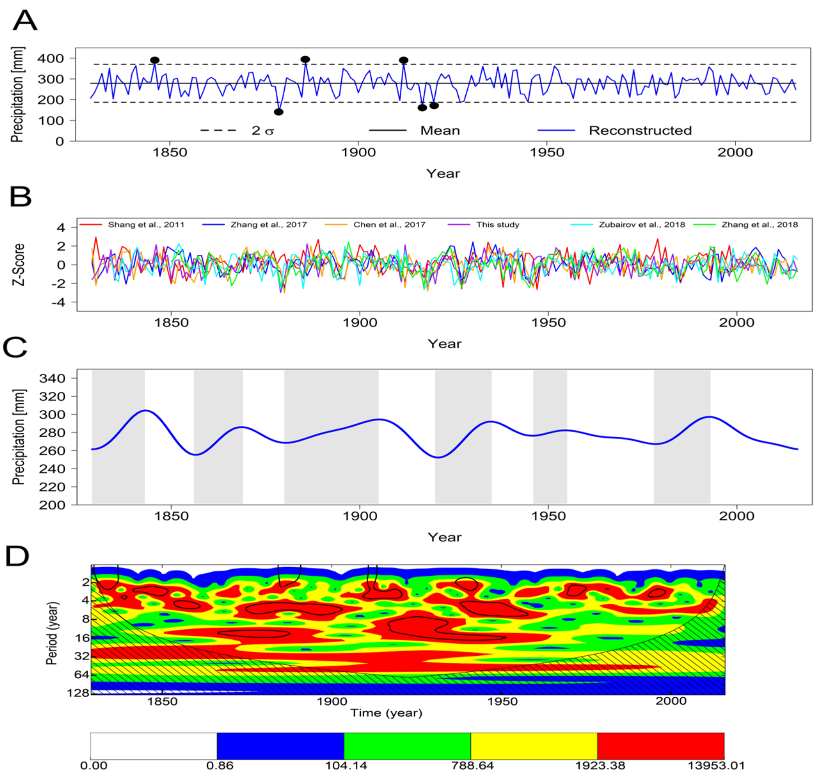

Figure 5. (A) Reconstructed precipitation for the period 1829-2016, from July 8th to November 5th.

The black dots represent extreme moist and dry years. The dashed lines represent the mean value of ±2 standard deviations, and the solid line represents reconstructed precipitation. (B) Graphical comparison with other tree-ring reconstructions for the territory of southeastern Kazakhstan. (C) 15-year low-pass filter graph of the reconstructed precipitation (D) The wavelet power spectrum. The contour levels were chosen so that 5, 25, 50, and 75% of the wavelet is above each level, respectively. The black contour is the 10% significance level, using a red-noise (autoregressive lag-1) background spectrum.

The spatial correlation analysis, as expected, revealed the strongest correlations with the territory of southeastern Kazakhstan. However, some significant correlations are also associated with the adjacent regions of northern Kyrgyzstan (Fig. 6).

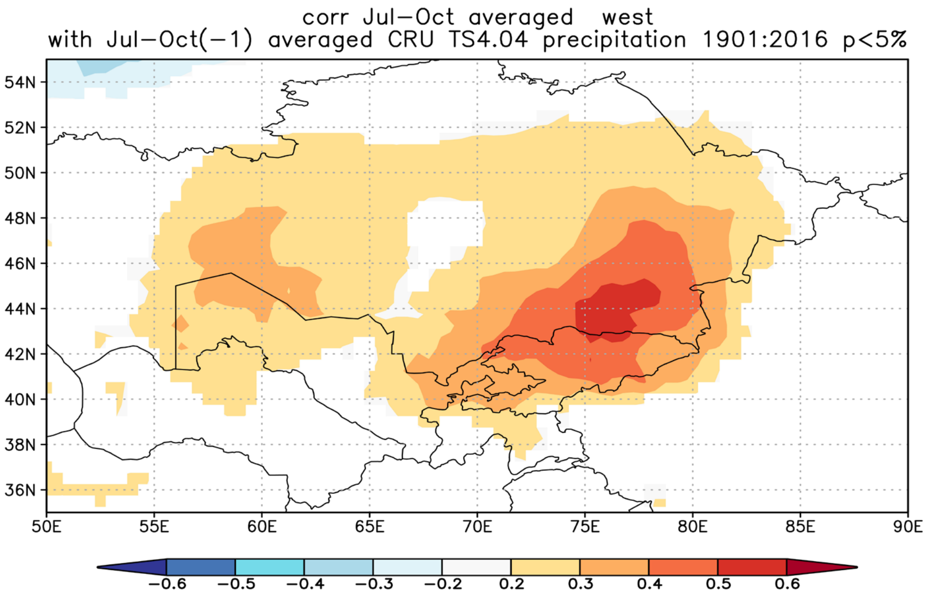

Figure 6. The spatial correlation analysis with CRU TS 4.04 precipitation data (1901-2016, $p<0.05$).

4. Discussion

The climate-growth correlation analysis indicated that the most substantial effect on Schrenk spruce growth was caused by the previous year's precipitation. On the one hand, it was expected, because humidification conditions from last autumn to current spring have a direct influence on the soil moisture storage and evapotranspiration in the upcoming vegetation period, which was also demonstrated by the previous studies (Borscheva, 1983; Zhang et al., 2017; Zubairov et al., 2018b). On the other hand, you would expect to see a stronger influence of temperature conditions at the upper tree limit, especially considering higher mean annual precipitation totals and lower MAAT compared to the climatic conditions at lower elevations. Such discrepancies can appear due to non-climatic growth-controlling factors, for example, the presence of permafrost, soil characteristics, and orography which can increase or reduce the influence of climatic factors or also be a result of the direct impact of temperature increase during the last decades. Contrary to precipitation, the temperature in the previous year has significantly less effect on tree growth compared to temperature conditions of the current year. Positive correlations with temperature in February probably reflect the beginning of a rapid temperature increase in this month, which influences the onset of the current year's vegetation period. The strong effect of winter temperatures was also revealed in other studies. For example, was shown that an increase in mean winter temperatures by one degree Celsius can drive an increase in biomass of different coniferous species (Usoltsev et al., 2020b). Correlations with temperature revealed in the period August-September and precipitation in periods June-July and August-September agree with Borscheva's results, who indicated that humidification and thermal conditions in these periods determine the formation of latewood of Schrenk spruce (Borscheva, 1983). However, this observation, as well as the dominant effect of the precipitation regime, is more common for the lower elevations. These uncertainties demonstrate the high importance of further studies for understanding the influence of climate warming on the high mountain ecosystems, especially on the response of physiological processes of trees, since it has direct effects on the regeneration and growth of forests (Dulamsuren et al., 2013; Usoltsev et al., 2020a).

Reconstruction of precipitation indicated significant changes in the occurrence of extreme wet/dry years during the last 70 years. Such changes in the variation of the amount of precipitation were also revealed at the lower elevations and in the other parts of the Tien Shan mountains, for example, in the Terskey Alatau (Zhang et al., 2017; Zubairov et al., 2018a). If we take a look at the low-pass filtering graph, we additionally could note that after the 1950s, periods of precipitation increase became shorter. In contrast, periods of decrease in the amount of precipitation became longer. Although there are no big changes in the total amount of precipitations in the period July 8th to November 5th we could assume that the rising of MAAT should markedly increase the importance of all sources of water resources for the sustainable functioning of forest ecosystems in the study area. All cycles detected in the reconstruction are also in good agreement with the results of previous studies. For example, high-frequency and ~5-7 year cycles fall within the ranges of values previously detected in the studies conducted by Borscheva (1981), Passmore et al. (2004), and Zhang et al. (2019). In turn, the ~10-16 year cycle falls within the ranges of values detected in the studies by Chen et al. (2017) and Panyushkina et al. (2018).

Revealed cycles are probably associated with variability of several atmospheric circulation indices, including the El Niño-Southern Oscillation (ENSO) (Allan et al., 1996), the Siberian High index (D'Arrigo et al., 2005), the North Atlantic Oscillation (NAO) (Telesca et al., 2013; Gerlitz et al., 2016) and East Asian Winter Monsoon (EAWM) (Jhun and Lee, 2004) as well as with the solar activity.

5. Conclusion

A new tree-ring chronology, based on samples collected at the upper tree limit was built. The application of daily climate data for the climate correlation analysis provided more precise time intervals and better correlation values, which provided additional information about the climate-growth relationships of Schrenk spruce in the high-mountain ecosystems of the northern Tien Shan.

The strongest correlations were revealed with precipitation of the previous year in the period from July 8th – to November 5th. This result was applied for the reconstruction of precipitation from 1829 to 2016. Significant changes were revealed during the past 70 years. In particular, these changes are reflected in the occurrence of extremely dry and wet years, and the duration of periods of increase and decrease in precipitation. Results indicate the existence of ~2-4, ~5-7, and ~10-16 year cycles in the climatic reconstruction, which supports the association of precipitation variability in the study area with the oscillations of certain atmospheric circulation indices.

The dominant effect of precipitations on the tree growth at the upper tree limit was an interesting result, which requires further investigations, because the increase of MAAT and variation of temperature signal in tree rings at the lower elevations may suggest that this result was not only due to a site-specific, non-climatic growth controlling factors. Additional studies in other fields like tree physiology may help to increase the reliability of already obtained information and to improve our understanding of high-mountain ecosystems functioning under the ongoing climate warming.

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