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Climatic signals in tree rings of *Juniperus turkestanica* in the Gulcha River Basin (Kyrgyzstan), reveals the recent wetting trend of high Asia

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Abstract: Drought variability of Kyrgyzstan is an important component of climate change of high Asia. Long-term information about the history of drought is, however, limited because the instrumental records are short. Here, we developed three chronologies for juniper trees (*Juniperus turkestanica*) under different microsite conditions in the Gulcha River Basin, Kyrgyzstan. The three chronologies (GUL, GUR and GUD) were compared with climate data which covered the study area. Growth of the GUL site correlates positively with May–June precipitation of the current growing season and September precipitation of the previous year, but negatively with temperatures of prior July, current May and July. Growth of the GUR site correlates positively with precipitation of current May and September, and negatively with temperature of current June and July. Ring width at GUD site is negatively correlated with temperature of the current May and July, and positively correlated with precipitation of prior December and current September. Response analysis shows that water availability is the main factor limiting the radial growth of juniper trees at the GUL and GUD sites. Based on the relationships derived from climate response analyses, the potential of tree-ring chronologies from this species to provide drought reconstructions in the Gulcha River Basin has been established. The GUL chronology and other moisture sensitive tree-ring series from high Asia capture the recent wetting trend. The records contribute to a growing tree-ring network for high Asia, including sites in China, Kyrgyzstan, Pakistan and Tajikistan.

Additional key words: *Juniperus turkestanica*, Kyrgyzstan, tree rings, climate response

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Introduction

The subalpine coniferous forest of high Asia, which is one of the largest terrestrial carbon pools in the Eurasia continent, has great effects on the global storage of carbon, and affected by hydroclimatic changes (Fang et al. 2001; Treydte et al. 2006; Esper et al. 2007). At the upper tree line of high Asia, the forests are often dominated by the evergreen juniper trees. Thus, the responses of radial growth of juniper trees to climate change can significantly influence the carbon pool and hydroclimatic cycle of high Asia. In recent years, a lot of research work about the responses of juniper trees to climate has been done. At the upper timberline in the Alai Range of the western Tian Shan in Kyrgyzstan, the tree-ring widths of the juniper trees are positively influenced by temperatures in June–September (Esper et al. 2003). Some dendroclimatic studies from the Qinghai-Tibet Plateau have also revealed an increase in tree growth rates and a rise in tree-line position in response to recent climate warming (Zhu et al. 2008; Liu et al. 2011). Other studies suggested that the abnormal increase in radial growth in the recent years was due to the recent wetting trend, and the situation was more complex (Treydte et al. 2006; Chen et al. 2013; Yang et al. 2014). Because of the vast area, more chronologies are needed to interpret this warming and wetting trend of high Asia.

The geographical features can play important roles in the radial growth of trees. Kirchhefer (2000) reported differences in the responses of tree-ring widths of *Pinus sylvestris* to temperature and precipitation between the north-facing and south-facing slopes in an area north of the Arctic Circle in Norway. Fang et al. (2009) reported differences in the responses of tree-ring widths of *Juniperus przewalskii* to temperature and precipitation among four tree-line sites in Qilian and Anyemaqen Mountains, northeastern Tibetan Plateau. Because of changes in growth environment that might be expected to occur as a result of possible future changes in climate, it is important to identify the responses of the radial growth of juniper trees to climate variables under different microsite conditions.

The purpose of the present study is to clarify the influence of temperature and precipitation on tree-ring widths of juniper trees (*Juniperus turkestanica*) growing in different environments in the Gulcha River Basin, Kyrgyzstan. A comparison of the climatic responses of tree-ring widths between different environments should help to clarify the impact of temperature and precipitation on the radial growth of juniper trees growing under specific conditions with microscale variations and to identify mechanisms that control radial growth. Furthermore, the tree-ring series developed for this study allows us to investigate the effects of drought on radial growth of juniper trees.

Data and Methods

Sampling sites

Dry soil site (GUL). At this site (Fig. 1), tree-ring cores were collected from juniper trees from 2850 to 3000 m a.s.l. in September 2013. GUL is located on a southeast facing slope (slope inclination ranges from 20 to 30°) with thin and rocky soils, surrounded by the subalpine meadows. The biophysical environment implies that tree growth is limited by moisture

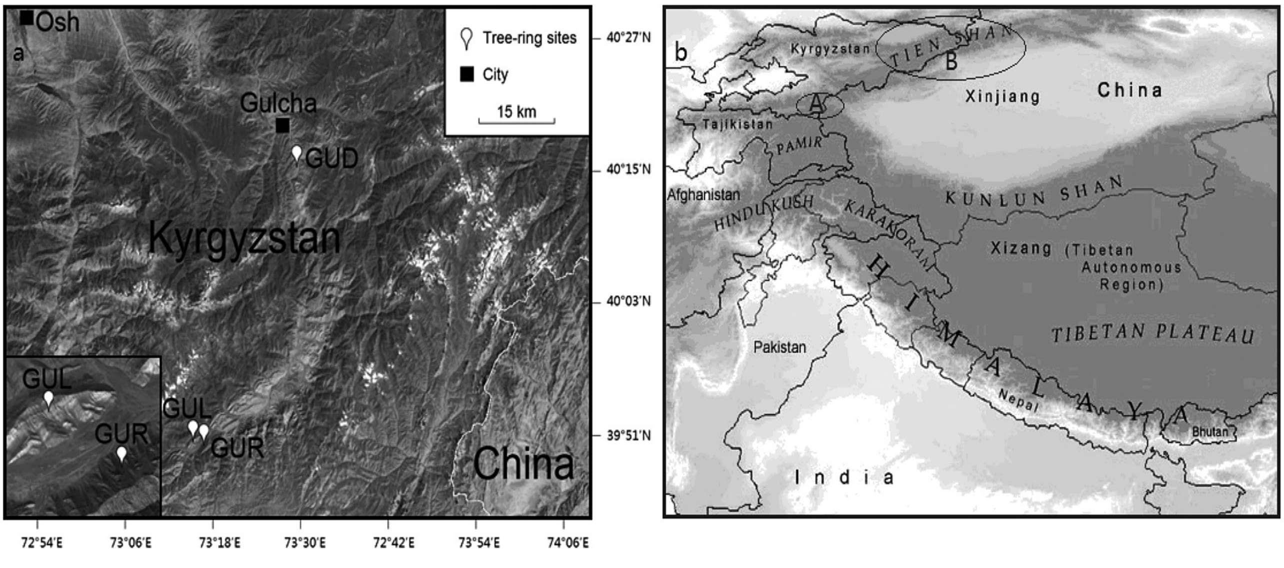

Fig. 1. Location map of sampling sites and towns (a). The ellipses in (b) denote the Gulcha River basin (A) and western Tien Shan (B)

Table 1. Information about the sampling sites in the Gulcha River basin

Site code	Latitude (N)	Longitude (E)	Elevation (m)	Slope	Aspect	Species
GUL	39°50'05"	73°15'09"	2850–3000	20–30°	SE	*J. turkestanica*
GUR	39°49'45"	73°16'38"	2800–2980	0–20°	NW	*J. turkestanica*
GUD	40°14'53"	73°29'08"	1660–1700	5–30°	W	*J. turkestanica*

availability. In total 20 cores from 20 trees were collected.

Wet soil site (GUR). The GUL site and the GUR site are divided by the Gulcha River. Elevation of this sampling site ranges from 2850 m in the riverbed of the Gulcha River Basin up to 2980 m a.s.l. on the mountain tops. Geologically, the mountains mainly consist of Proterozoic and Paleozoic rocks. Presently, this sampling site is covered by widespread forests dominated by juniper and birch owing to location (the shady side of the mountain) and relatively wet soil. 20 samples were taken from 20 trees.

Low altitude site (GUD). This site (1660–1670 m a.s.l.) was located in the Gulcha River valley near Gulcha town. Forest canopy closure of this site ranged from 0.2–0.5, and slopes ranged from 5° to 30°. This area is also a humid area in the Gulcha River basin, and bryophytes are present under the dominant juniper forests. Soils are mainly brown forest soil. In total 20 cores from 20 trees were collected. Site information, including latitude and longitude and slope, is listed for each of the three sites in Table 1.

Tree-ring chronology building

After air-drying, the cores were mounted on the wooden mounts and a polished surface was prepared using fine sandpaper and a razor blade. The tree-ring widths were measured to 0.001 mm precision with a TA Unislide Measurement System (Velmex Inc., Bloomfield, New York). The tree-ring width series from the three sites were cross-dated visually by using skeleton plot procedures and confirmed by a statistical method to ensure that the correct date was assigned to each annual ring (Fritts 1976). Statistical cross-dating was performed with the COFECHA program (Holmes 1983). The cross-dated tree-ring width sequences were detrended by fitting either a negative exponential curve or negative slope or a straight line of horizontal using the computer program ARSTAN and to average the detrended tree-ring width sequences into the standard chronologies (STD) for the three sites (Cook and Kairiukstis 1990). Expressed population signal (EPS) analysis was used to assess the degree to which chronologies of each site portray the perfect hypothetical chronology (Wigley et al. 1984).

Climate data and statistical analysis

Since climate stations were not installed near the sampling sites, we ultimately, used gridded precipitation data for our final analyses because it showed higher correlations with the tree-ring data than the station records, and because it provides a more regional signal than the station records away from the study area. This gridded monthly instrumental climate data, including precipitation, temperature and Palmer Drought Severity Index (PDSI) was obtained from the Climatic Research Unit (CRU), East Anglia, UK (http://www.cru.uea.ac.uk; 0.5°×0.5°) for the Gulcha River Basin for 1901–2012 (averaged over 39.5–40.5°N, 73.0–74°E; Hulme and New 1997; Van der Schrier et al. 2011). We analyzed the responses of ring widths to climate variables by calculating the simple correlations between standard chronologies and climate variables. In the correlation analysis, the climate data series along with each tree-ring chronology were examined from July of the prior year to September of the current growth year. To assess the potential for climate reconstruction, the simple linear regression models were used to estimate the climate from tree-ring chronology. A split calibration-verification scheme was employed to test the reliability of the climate reconstruction (Cook and Kairiukstis 1990). Statistics used to test the reliability of the reconstruction models included the reduction of error and coefficient of efficiency statistics, sign test, first-order sign test and the Pearson's correlation coefficient (Fritts 1976; Cook and Kairiukstis 1990). The reduction of error and coefficient of efficiency examine the strength of the association between actual and estimated values. The sign test and first-order sign test shows whether or not sufficient similarity exist between the actual and estimated data sets. They account the number of times that the estimated and observed values are on the same side of the dependent data mean or they are on opposite side of the mean. The detailed explanation of these tests is given in Fritts (1976). We also compare the new tree-ring series from the Gulcha River Basin with the PDSI reconstruction for western Tien Shan (based on the tree-ring width data of Schrenk spruce) to assess the influences of the recent wetting trend of high Asia.

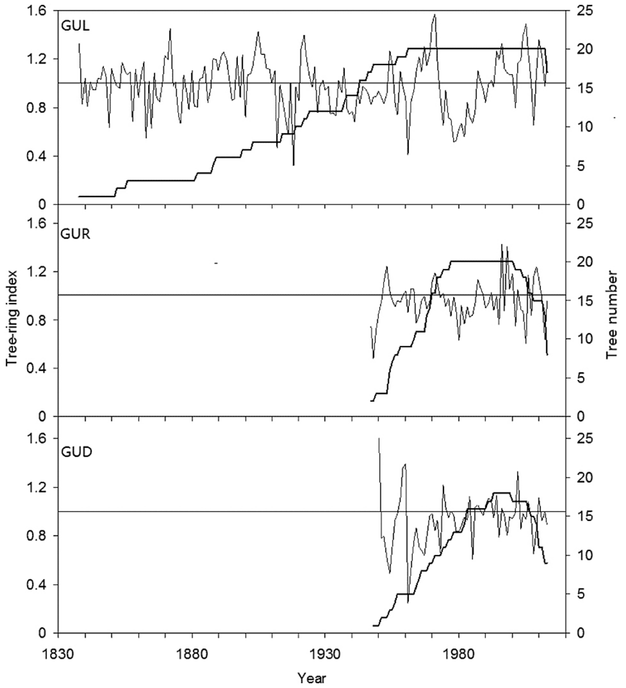

Fig. 2. Standardized ring-width chronologies with tree number for *J. turkestanica* at GUL, GUR, and GUD in the Gulcha River basin

Table 2. Summary of statistics for tree-ring width chronologies of *J. turkestanica*.

	Ring width		
	GUL	GUR	GUD
Mean sensitivity	0.20	0.19	0.21
Standard deviation	0.22	0.17	0.28
First order autocorrelation	0.42	0.14	0.41
Variance in first eigenvector (%)	30.5	29.9	43.1
Signal-to-noise ratio	4.56	2.33	2.41
First year where EPS > 0.85 (no of cores)	1891 (6)	1955 (7)	1957 (5)

Results

Chronology

The tree-ring width chronologies are shown in Figure 2. They are the longest records now available in the Gulcha River Basin, ranging from 66 to 176 years in duration. A summary of the standardized chronologies is given in Table 2. Ring-width chronologies exhibit relatively low mean sensitivities (0.19–0.21) and standard deviations (0.17–0.28). These data indicate rather moderate interannual variations in the ring-width series. The variances in the first eigenvector (29.9–43.1%) indicate that rather moderate common signals exist among trees. The first-order autocorrelation of tree-ring width chronologies from GUL and GUD ranged from 0.41 to 0.42. However, the first-order autocorrelation of tree-ring width chronology from GUR is very low. The chronologies were truncated prior to 1891 (GUL), 1955 (GUR) and 1957 (GUD) respectively, based on the minimum EPS threshold of 0.85.

Climate analyses

The chronology of the GUL site correlates positively with May–June precipitation of the current growing season and September precipitation of the previous year, but negatively with temperatures of prior July, current May and July (Fig. 3). The chronology of the GUL site is negatively correlated with December precipitation of the previous year. Moreover, Ring width at GUL site also correlates positively with PDSI from prior July to current September. All the above-mentioned correlations are significant at the 95% level in two-tailed tests; PDSI from prior July to current September are significant at the 99% level.

We found strong positive correlations between the chronology from the GUR site and precipitation of current May and September. The chronology from the GUR site is also negatively correlated with temperature of current June and July. However, correlations between the chronology from the GUR site and PDSI are found to be non-significant. Ring width at GUD site is negatively correlated with temperature of the current May and July, and positively correlated with precipitation of prior December and current September, with the significance at the 95% level for the correlation analyses. The high level of autocorrelation in PDSI produces monthly series which change slowly over time, but despite this the ring width at GUD site has some significant positive relationships to PDSI from May to September.

To investigate the climate–tree-ring relationship in more detail, we screened the tree-ring chronologies in correlation analysis with the seasonal combinations of temperatures, precipitation and PDSI from previous July to current September. The chronology from the GUL site shows significant positive response to PDSI. The highest correlation was found between the standard GUL chronology and mean PDSI from the previous August to the current July (r=0.540, N=111, p<0.001).

Assessment of potential for drought reconstruction

Based on the climate response analysis results at the GUL site only, mean PDSI from the previous August to the current July is the most appropriate seasonal predictand for reconstructions (Fig. 4). The linear regression model between tree-ring indices and mean August–July PDSI for the 1902–2012 calibration period was significant (F = 44.928, P<0.0001). The period from 1902 to 1957 was used for calibration and 1958–2012 for verification; this

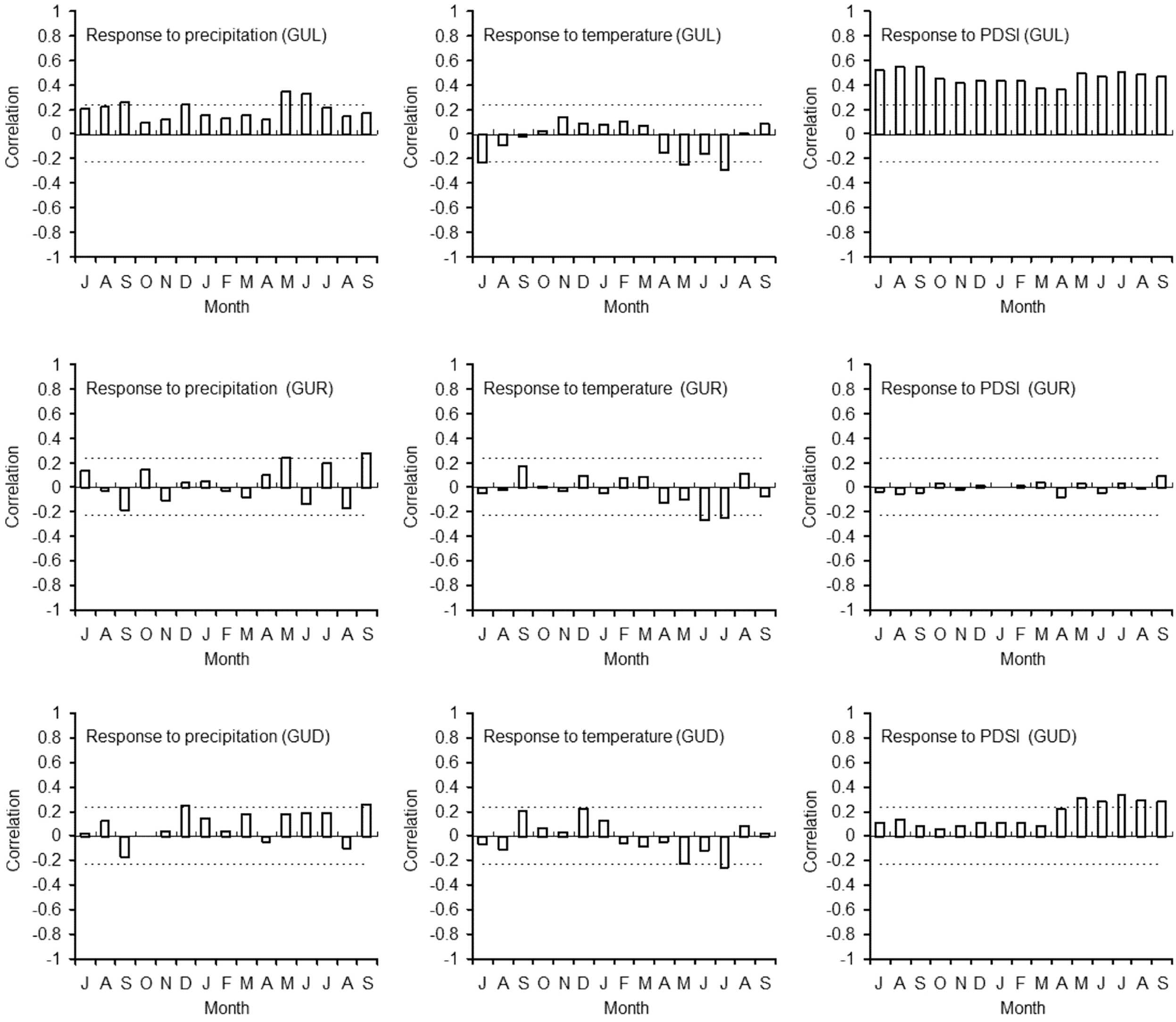

Fig. 3. Simple correlations of the standard chronologies with the monthly climate data (precipitation, temperature and PDSI) from previous July to current September over their overlapping periods. The dotted lines indicate significant variables (p<0.05)

process was then reversed. The variance explained by the regression on tree-ring variables during the period 1958–2012 for mean August–July PDSI is 36% ($p<0.001$). The statistical properties of verification tests and calibration equations are presented in Table 3. During the verification period (1902–1957), the correlations between estimated and observed series are significant ($r=0.53$, $p<0.01$), indicating good reliability for the reconstructed series. Positive values for the reduction of error and coefficient of efficiency indicate stability of the reconstruction. The sign test and first-order sign test also show high values in the PDSI reconstruction.

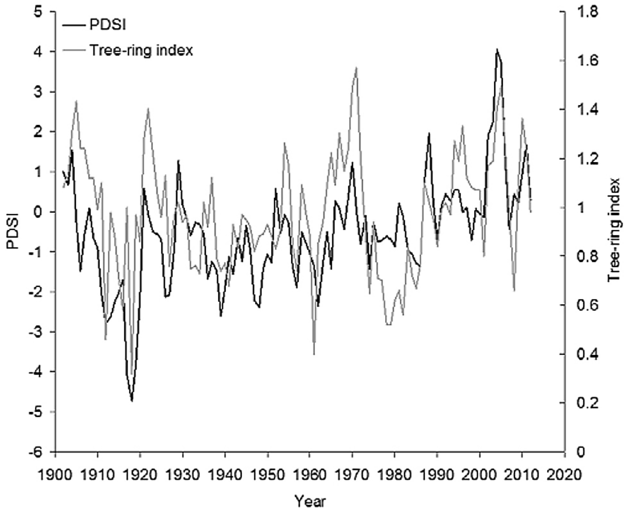

Fig. 4. Comparison of the GUL chronology and the actual mean PDSI from the previous August to the current July

Table 3. Calibration and verification analysis of reconstructed August–July PDSI using tree-ring width chronology from the GUL site

	Calibration (1958–2012)	Verification (1902–1957)	Calibration (1902–1957)	Verification (1958–2012)	Full calibration (1902–2012)
r	0.60	0.53	0.53	0.60	0.54
r^2	0.36	0.28	0.28	0.36	0.29
Reduction of error		0.12		0.16	
Coefficient of efficiency		0.11		0.15	
Sign test		38+/18–		42+/13–	82+/29–
First-order sign test		36+/19–		35+/19–	71+/39–

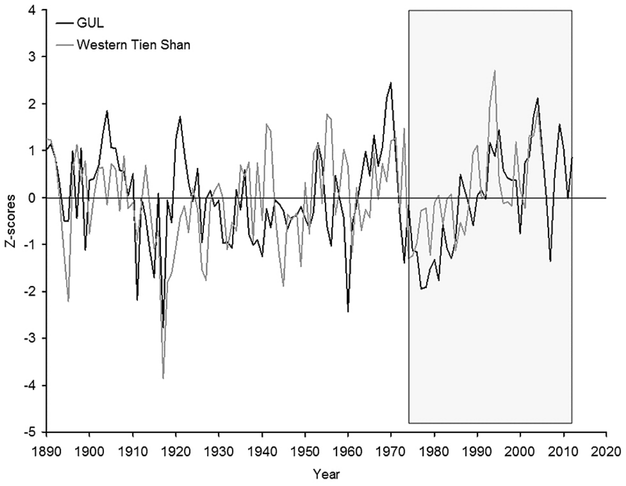

Fig. 5. Comparison between the GUL chronology and the January–May PDSI reconstruction for western Tien Shan

Discussion

Responses to climatic factors

Results suggest that optimal growth at the GUL site depends on wet springs and cool, wet summers. The apparent importance of the precipitation during the first growing season months (May–June) is consistent with the dry climate of the Gulcha River Basin and location of the GUL site. Evaporation increases with the rise in temperatures of May and July, which accelerates the already existing water stress. Above-average moisture during early autumn (September) may promote storage of carbohydrates and bud formation, thus enhancing growth during the following year (D'Arrigo et al. 2001; Chen et al. 2013). The correlation results between ring widths and climate variables indicated that the winter moisture availability was also a limiting factor for tree growth. Because the precipitation at the GUL site in winter falls as snow, the positive correlations with December precipitation may represent a relationship with snowpack and its subsequent effects on soil moisture. Tree-growth benefits from the former winter snow, which increases the soil moisture content during the early phase of the growing season (Chen et al. 2013). Higher correlations were found between ring width of the GUL site and PDSI rather than with precipitation records. This may be because the PDSI is a direct metric of moisture conditions taking both precipitation and temperature into account (Van der Schrier et al. 2011). The GUD chronology shows similar but weaker responses to climatic factors (Fig. 3).

The low relationships between PDSI and tree-ring width at the GUR site suggest that juniper trees are not subjected to much water-deficit stress, although precipitation is the growth-limiting factors at the GUR site. The soils of the GUR site with humid conditions might not limit the availability of water. This may also be linked with the depth and fluctuations of the water table. Trees growing on natural peatlands and riverbed are highly dependent on depth and fluctuations of the water table (Boggie 1972; Linderholm 2001). Relatively abundant and stable groundwater recharge from the Gulcha river source glaciers can provide sufficient water for tree growth. Therefore, the drought history of the study area is not recorded by the GUR chronology.

Growth responses to recent wetting trend

The above analysis of calibration and verification indicates that the calibration equation may provide useful estimates of the drought history of the study area. However, the actual PDSI reconstruction of the study area prior to the instrumental period using these equations has not yet been attempted because of the lack of adequate replication of tree-ring data for years prior to the instrumental record. Despite this current limitation, the GUL chronology demonstrates the wet and dry changes of the Gulcha River Basin during the 20th century.

Comparison of the GUL chronology with the January–May PDSI reconstruction for Tien Shan (Chen et al. 2013) shows that there are significant consistencies ($r=0.38$, $p<0.001$), and revealed that the growth of spruce and juniper trees captures recent wetting trend (Fig. 5). Other moisture sensitive tree-ring series from high Asia, included northeastern Tibetan Plateau (Yang et al. 2014) and northern Pakistan

(Treydte et al. 2006) also revealed the similar wetting trend began in the late 20th century, and showed the late twentieth century was the wettest period in the two region over the past millennium. In addition, some temperature sensitive tree-ring chronologies of juniper trees from high Asia have increased in temperature sensitivity, and showed the upward trends resulted from global warming (Esper et al. 2003; Fang et al. 2009). This means rapid tree growth in high Asia may be linked with the warming and wetting trend during the recent decadal years. Evaporation increased with the climate warming which accelerates the water stress, and the growth of juniper trees have increased in moisture sensitivity and well recorded the wetting trend (Table 3). The GUL chronology allows detecting the recent wetting in a long-term context in the Gulcha River Basin.

Conclusions

We have developed three tree-ring width chronologies of *J. turkestanica* at the three sites in the Gulcha River Basin, Kyrgyzstan. This study examines the potential utility of tree-ring widths of *J. turkestanica* for dendroclimatic studies. The climate response analysis shows that tree-ring widths of *J. turkestanica* can potentially be exploited as indicators for dendroclimatological studies because of their strong responses to PDSI. The chronology at the GUR site with the wet soil has low correlated with PDSI in some circumstances during the current year, despite a similar response to precipitation and temperature. The sensitivity of recent tree-growth to PDSI in the Gulcha River Basin was not significantly reduced under climate warming. Tree-rings of *J. turkestanica* allow detecting the recently observed wetting trend and putting it into the long-term climatic context in the Gulcha River Basin. Tree-ring data from the different sites further confirmed the existence of the recent warming and wetting trend of high Asia, while showed a positive impact of this wetting trend on tree growth. Continued work in this direction should enable us to understand better the growth change of juniper trees under global warming and the past climate variability of high Asia over long temporal and large spatial scales.

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