Dendroclimatological potential of three juniper species from the Turkestan range, northwestern Pamir-Alay Mountains...

Article *in* Trees · October 2015

DOI: 10.1007/s00468-015-1316-y

Andrea Seim
University of Gothenburg

Gulzar Omurova
Central Asian Institute for Applied Geosciences

Hans W. Linderholm
University of Gothenburg

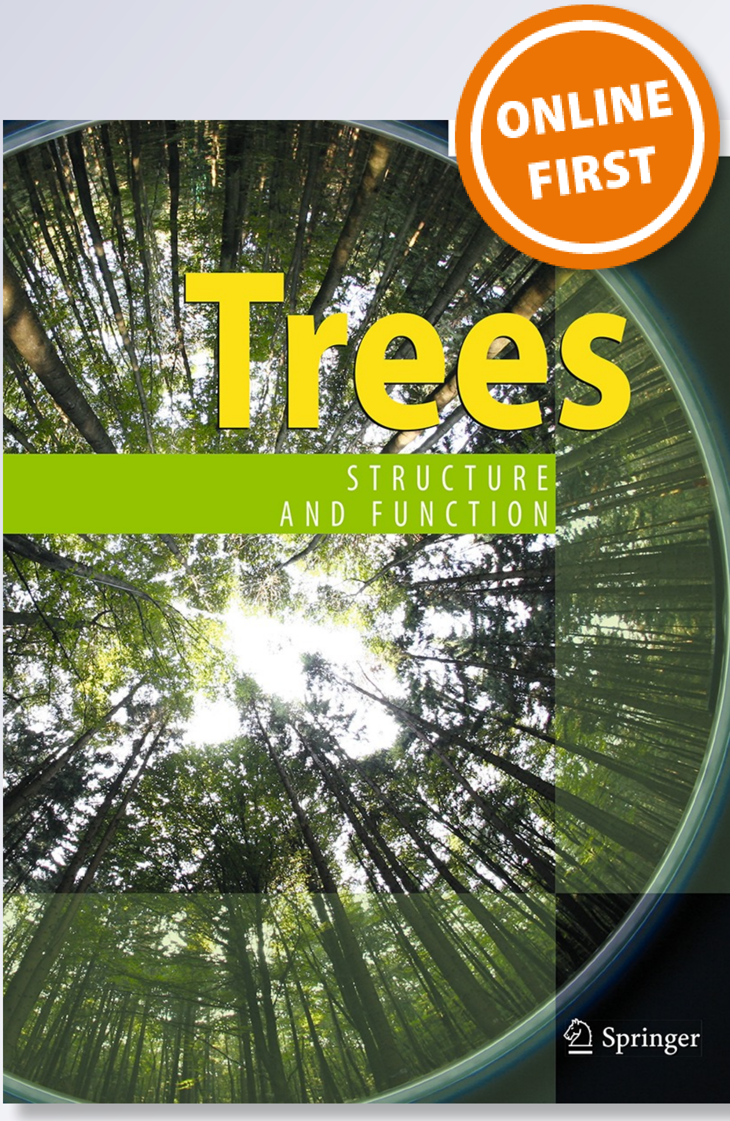
Dendroclimatological potential of three juniper species from the Turkestan range, northwestern Pamir-Alay Mountains, Uzbekistan

Andrea Seim, Timur Tulyaganov, Gulzar Omurova, Lyutsian Nikolyai, Evgeniy Botman & Hans W. Linderholm

Trees
Structure and Function

ISSN 0931-1890

Trees
DOI 10.1007/s00468-015-1316-y



Springer

Trees
DOI 10.1007/s00468-015-1316-y

ORIGINAL ARTICLE

Dendroclimatological potential of three juniper species from the Turkestan range, northwestern Pamir-Alay Mountains, Uzbekistan

Andrea Seim[1] · Timur Tulyaganov[2] · Gulzar Omurova[3] · Lyutsian Nikolyai[2] · Evgeniy Botman[2] · Hans W. Linderholm[1]

Received: 31 March 2015 / Revised: 22 July 2015 / Accepted: 9 October 2015

Abstract

Key message **Intensity and magnitude of the growth-climate relationship depends on juniper species and sites. *Juniperus seravschanica* at low elevations shows highest potential for April–September drought reconstruction in the Turkestan range (Pamir-Alay), Uzbekistan.**

Abstract We present a detailed dendroclimatological study of three juniper species, *Juniperus seravschanica* Kom., *Juniperus semiglobosa* Regel *and Juniperus turkistanica* Kom., sampled at six sites of different elevation (2100–2700 m a.s.l.), exposition (west and south) and steepness (10°–30°) in the Zaamin National Park, Turkestan range, Pamir-Alay mountain system in eastern Uzbekistan. Simple correlation statistics and redundancy analyses were applied to detect species- and site-specific climate responses during the twentieth century, which were additionally investigated in the high-frequency domain by identifying extreme growth years. Our results show that tree-ring formation of *J. seravschanica* at our low-elevation site is strongly limited by April to September drought conditions, while *J. semiglobosa* inherits a weak and variable climate response with respect to elevation. *J. turkistanica* growth at high altitudes is positively associated with warm spring and summer temperatures. Species-specific growth extremes are triggered by incoming air masses from the Atlantic and Arctic, highlighting the connection of synoptic climate regimes across Eurasia. From a dendroclimatic perspective, *J. seravschanica* exhibits a high potential for reconstructing past drought and pluvials, but under sustained temperature rise also *J. semiglobosa* will likely increase its sensitivity to drought. Moreover, *J. turkistanica* at its distribution limit at the tree line is a suitable proxy of summer temperature. Our findings clearly demonstrate that a careful selection of the site, overall topography and elevation as well as the different juniper species are important for successfully reconstructing past climate in Uzbekistan.

Keywords Dendroclimatology · Extreme growth years · *Juniperus* spp. · Northwestern Pamir-Alay · Tree-ring width · Uzbekistan

Communicated by A. Braeuning.

✉ Andrea Seim
andrea.seim@gvc.gu.se

[1] Regional Climate Group, Department of Earth Science, University of Gothenburg, Gothenburg, Sweden

[2] Republican Scientific Production Centre for Decorative Gardening and Forestry, Tashkent, Uzbekistan

[3] Central-Asian Institute for Applied Geosciences (CAIAG) and Kyrgyz National Agrarian University (KNAU), Bishkek, Kyrgyzstan

Introduction

Globally, many regions are confronted with present and predicted changes in climate, which poses adaptation challenges for societies and ecosystems alike. Particularly, for the landlocked and semi-arid countries of Central Asia, an increase in heat wave frequency during the summer, accompanied by a rise in annual and winter (November–March) temperatures, is expected (Stocker et al. 2013). Analyses based on available meteorological data show an increase of winter temperatures by 2.4 °C during the 1901–2009 period (Stocker et al. 2013), while modelled annual temperatures are likely to increase further by 1–2 °C by 2023–2050 (Lioubimtseva et al. 2005).

Published online: 30 October 2015

These tendencies are also observed for the double-land-locked country, Uzbekistan (NC Uzbekistan 2009). Changes in precipitation over the past 50–60 years do not show uniform trends across the country due to a wide variety of landscapes and land-use changes (Lioubimtseva et al. 2005; Stocker et al. 2013). Observed alterations in the hydrological cycle include a precipitation decrease in the west and a slight increase in the east of the country, as well as around irrigated fields due to increased evaporation (Lioubimtseva and Henebry 2009; NC Uzbekistan 2009). The resulting consequences of regional climate change are of both physical and ecological nature and are enhanced by socio-economic causes. Climate change related impacts include a potential decrease in agricultural crop productivity, increased health risks (NC Uzbekistan 2009), increase in desertification (Saiko and Zonn 2000), increase in flood events associated with torrential rainfalls and glacier recession (Savitsky et al. 2007), potential changes in species occurrence, including latitudinal and altitudinal range shifts (as observed elsewhere by, e.g., Lenoir et al. 2008; Parmesan and Yohe 2003) and decrease in forest vitality (e.g., Allen et al. 2010; Breshears et al. 2005; Fisher 1997).

In Uzbekistan, Botman (2008) identified that under future climate change scenarios (A2 and B2) the mountain coniferous forest ecosystems will be the most affected. Here, mountain forests are primarily occupied by the genus juniper (*Juniperus* spp.), which accounts for around 80 % of the forested area of all mountain systems in Central Asia. In Uzbekistan, three juniper species occur, which largely follow an altitudinal zonation from low to high: *J. seravschanica* Kom. (JUSE; syn. *J. polycarpos* var. *seravschanica* (Kom.) Kitam.), *J. semiglobosa* Regel (JUSM) and *J. turkistanica* Kom. (JUTU; syn. *J. pseudosabina* Fischer & C.A. Meyer). Increase in temperature and precipitation are likely to shift these juniper belts to higher altitudes by circa 350–400 m, while the total area is likely to decrease by 350 m, especially for JUTU, due to less favourable pedogenic conditions at the tree lines (Botman 2008). These conditions are likely to have considerable effects on productivity and establishment of vital forest stands.

Since long and continuous meteorological data are largely lacking in Uzbekistan, a dense proxy data network is needed to better understand past natural and anthropogenic induced climate variability, as well as its consequences for forestry. In Uzbekistan, so far only one study has attempted a dendroclimatological investigation of 12 juniper trees from two sites in the western Tien Shan (Glazirin and Gorlanova 2005; Fig. 1). On the contrary, numerous studies using not only juniper (e.g., Esper 2000; Esper et al. 2002, 2007; Graybill et al. 1992; Fig. 1) but also other tree species such as spruce (e.g., Glazovskiy and Solomina 1989; Solomina et al. 2014; Zhang et al. 2014) or walnut (e.g., Winter et al. 2009) exist for the neighbouring country of Kyrgyzstan.

Here, we present 158 new tree-ring width (TRW) series from 107 trees of three juniper species (JUSE, JUSM and JUTU) that grow within the same region of the Zaamin National Park, in the Turkestan range (Pamir-Alay), eastern Uzbekistan. Eight juniper TRW chronologies were developed with respect to species and ecological site conditions and investigated regarding climate sensitivity and climate signal strength. Additionally, site- and species-specific extreme years were identified and compared to observed climate conditions and set in a regional context.

Materials and methods

Geographical setting and tree-ring data

The Zaamin National Park in Uzbekistan was established in 1976, covers 241.1 km^2 (Botman 2009) and is located at the northern edge of the Pamir-Alay mountain system, the Turkestan range, bordering Tajikistan to its east and south ($\sim$39.61°N, $\sim$68.50°E; Fig. 1). Here juniper trees reach heights of up to 8 m and form open forest stands on lithomorphic soils, shallow soils developed over argillite (schistous clay), at elevations of up to 3000 m a.s.l. A total of 107 trees were identified based on morphological features (according to Adams 2011) in the field and sampled by extracting two cores per tree using 5 mm increment borers. All three juniper species existing in Uzbekistan co-occur in this region: *J. seravschanica* (JUSE), *J. semiglobosa* (JUSM), and *J. turkistanica* (JUTU), and were sampled at six sub-sites with variations in slope, exposure, and elevation (Fig. 2; Table 1).

Following visual crossdating, ring-width variations were measured with an accuracy of 0.01 mm using the LINTAB measuring station and TSAPwin program (Rinn 1996), and subsequently statistically verified using the COFECHA software (Holmes 1983). Some juniper hybrids were sorted based on best statistical (Student's *t* test and year-to-year synchronicity) and visual agreement to the raw mean chronology of the individual species. A cubic smoothing spline with a 100-year frequency cut-off was used to eliminate age-related growth trends from the TRW series (ARSTAN 44xp version; Cook and Krusic 2005). Reducing first-year autocorrelation effects and extreme variance fluctuations due to temporal uneven sample replication, pre-whitened residual chronologies were developed after power transformation (Cook and Peters 1997) and variance stabilization. Interseries correlation (Rbar), representing the degree of coherency between the series, and the expressed population signal (EPS; Wigley et al. 1984) calculated over a 50-year window with 25-year of overlap, were used to evaluate the signal strength inherent in the TRW chronologies.

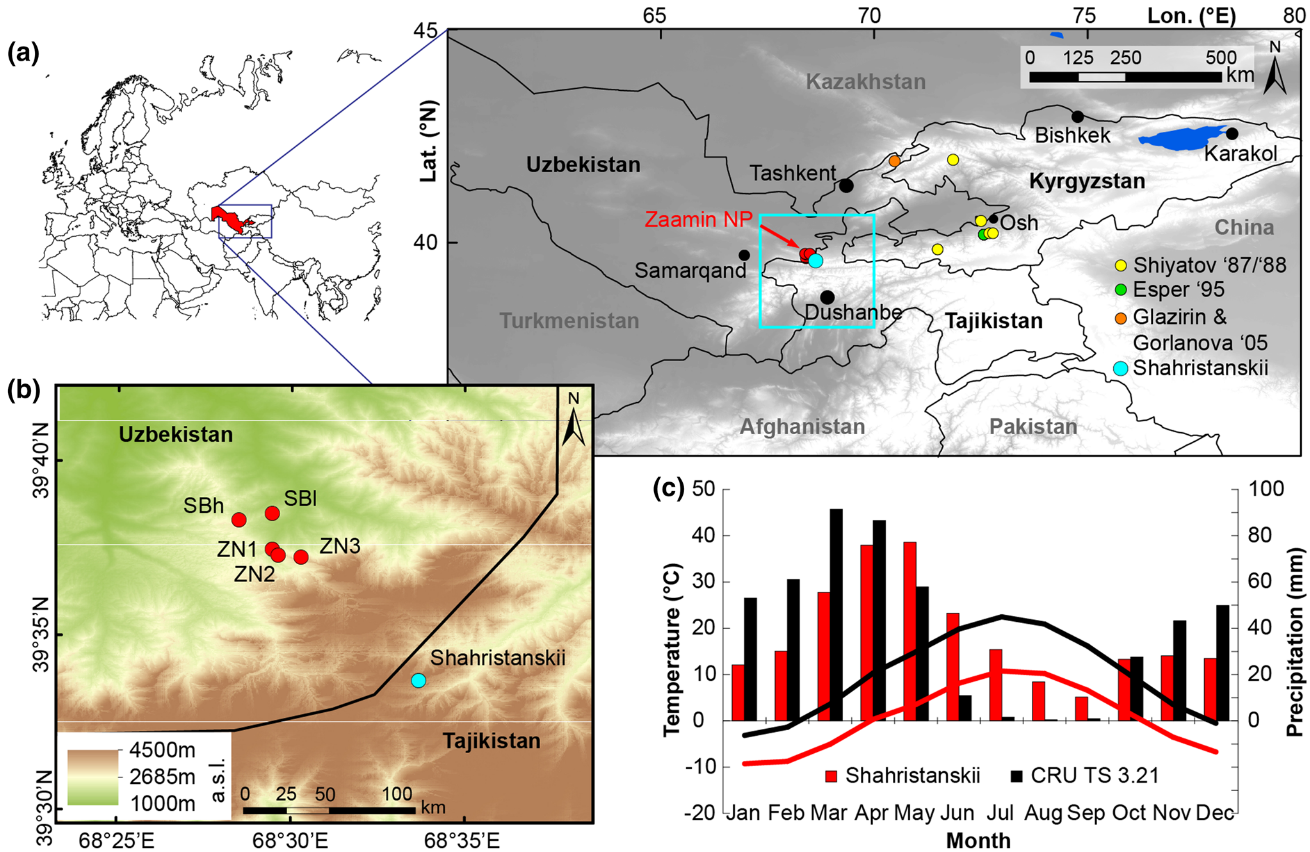


Fig. 1 Location of the sampling sites (*red dots*) in **a** Uzbekistan in the context of existing juniper TRW chronologies and meteorological station data (*turquois dot*) and gridded data (CRU TS 3.21, *turquois square*) and **b** within in the Zaamin National Park and closest meteorological station (*turquois dot*). The comparison between the Shahristanskii station and gridded data for the climatological period AD 1951–1980 is shown in **c**

Climate and instrumental data

Uzbekistan's landlocked location and far distance to oceanic sources of moisture makes the climate extremely continental with hot, dry summers and cold winters. The climate is primarily controlled by cold north and north-westerly air-masses as well as moist westerly inflow of air from the Atlantic via the Mediterranean (Shahgedanova 2002). In the mountain areas, average annual temperatures are about 10 °C with a maximum of 22 °C in July. Maximum precipitation occurs during spring (March–April) with around 90 mm and the annual total precipitation amounts to 485 mm per year (1950–1981, CRU TS 3.21; Fig. 1c). Since summer precipitation is scarce, drought stress is expected to be one of the main growth limiting factors for the trees.

Meteorological data were obtained from the Shahristanskii Pereval station in Tajikistan (39.57°N, 68.58°E, 3143 m a.s.l.), which is 11 km away (linear distance) from our study site, and include monthly temperature means (AD 1934–1992) and precipitation sums (AD 1950–1992). These were compared to monthly 0.5° × 0.5° gridded climate variables obtained from the Climate Research Unit (CRU TS 3.21, Mitchell and Jones 2005; Fig. 1) and averaged for the region 38–41°N and 67–70°E. This region was chosen to equally represent the climate of mountainous as well as low elevations in this area.

Gridded datasets include temperature means (T), precipitation sums (P) and self-calibrated Palmer Severity Drought Indices (S; van der Schrier et al. 2006). Additionally, maximum (xT) and minimum temperatures (nT) as well as their difference (dtrT), cloud cover (CC) and vapour pressure (VP; as indicator for air humidity) were used to test if other climate variables may have a stronger impact on the tree-growth variability (these were all derived from the new CRU TS 3.22 data set). All climate parameters were normalized over the 1951–1980 period.

Applied statistics

To identify the climatic signal recorded in the three juniper species, Pearson correlation coefficients were calculated for each month and seasonal [i.e., previous December to current year February (pDFJ), March to May (MAM), June

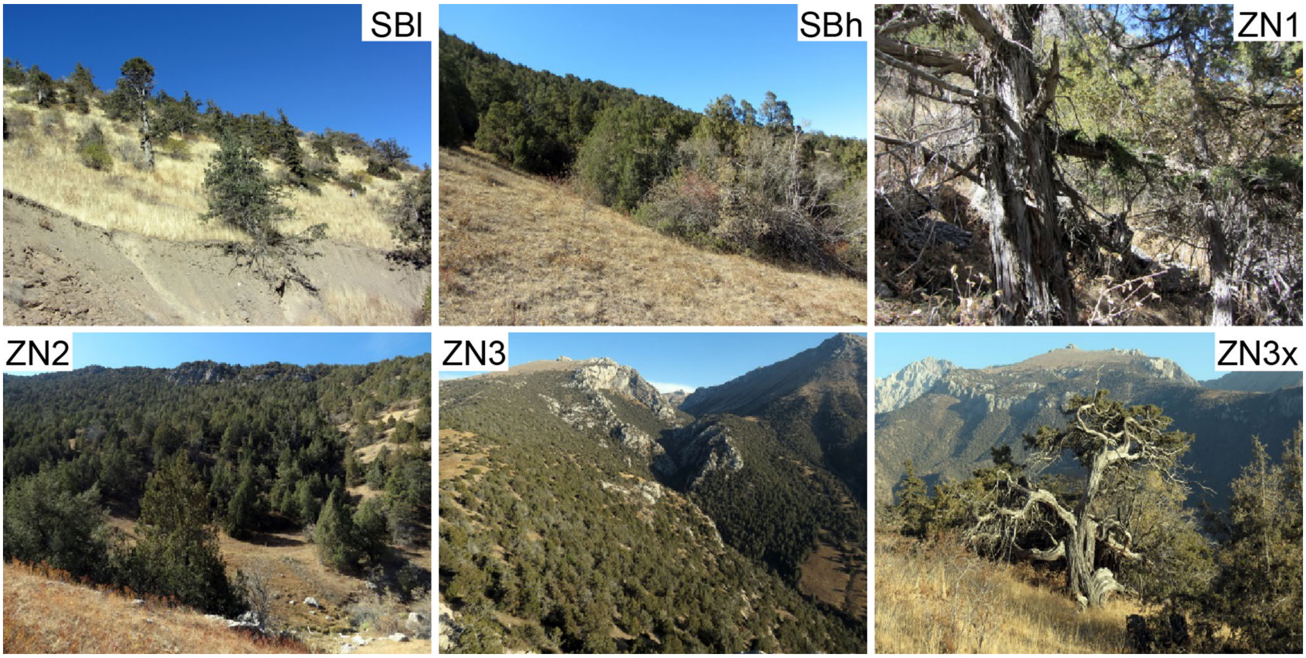


Fig. 2 Juniper trees at the different sub-sites in the Zaamin National Park (see Table 1 for site code and species) (Photos taken by AS and LN)

to August (JJA), September to November (SON), and April to September (A–S)] means and sums of the current year of tree growth for the common 1950–1992 period. The species-specific climate response was additionally examined over an extended period, 1901–2012, with the full set of gridded climate variables for the above mentioned seasonal sums and means using redundancy analysis (RDA, Legendre and Legendre 1998). RDA, which is based on linear regression and computed using principal component analysis, shows linear dependencies between the response (TRW chronologies) and explanatory (climate) variables for *n* samples (years). Each seasonal RDA result was tested for statistical significance of the canonical axes using a Monte Carlo permutation test with 999 random permutations (Legendre et al. 2011). For all models, either only the first RDA axis or the first two RDA axes were significant at $p < 0.001$. High collinearity ($r > 0.75$) among the climate variables were highlighted and considered in the interpretation of the results. The statistical analyses were performed with the R software (R Development Core Team 2008) using the package 'vegan' (Oksanen et al. 2013).

Statistically significant growth–climate relationships were evaluated for its temporal stability by applying a 31-year running correlation window. Spatial correlation patterns were generated using the KNMI climate explorer (http://climexp.knmi.nl, van Oldenborgh and Burgers 2005). Additionally, an extreme year analysis was applied to all individual as well as composite juniper TRW chronologies to investigate the coherency in the high-frequency domain for the common 1900–2012 period (constrained by sub-site ZN2_JUSE). This was done on 10-year high-pass filtered records, and years exceeding the threshold of one standard deviation were compared with climate data and results obtained from paleoclimate studies from Central Asia (Esper et al. 2002; Chen et al. 2013; Solomina et al. 2014), northern Iran (Pourtahmasi et al. 2007), the Tibetan Plateau (Qin et al. 2011) and Mediterranean Basin (Seim et al. 2014).

Results

TRW chronologies

From a total of 107 sampled trees, TRW series from 158 cores were successfully crossdated leading to the development of eight species-specific TRW chronologies for six slightly different sites, as well as three composite TRW chronologies for each juniper species (Table 1). The oldest tree, which could be crossdated, was 531 years old and found at the SBl site with the lowest elevation (JUSE; 2100–2200 m a.s.l.), followed by JUSM, of age 430 years, at the ZN3 site. Forest structure of the sampled plots slightly varied depending on site characteristics, stand dynamics and human influences such as grazing. Species-specific differences between the stand structures were largely absent, showing old, slow-grown JUSE trees at the lowest elevations of SBl/ZN1 with mean segment lengths

Table 1 Species distribution of JUSE (*J. seravschanica*), JUSM (*J. semiglobosa*), and JUTU (*J. turkistanica*) at their respective sites with information about the location (Lat = latitude, Long = longitude, Exp = exposition) and chronology characteristics including mean segment length (MSL), interseries correlation (Rbar), average growth rates (AGR), mean sensitivity (MS) and first-order autocorrelation (AC)

Site	Site code	Species	Lat (°N)	Long (°E)	Elev (m a.s.l.)	Exp	Slope (°)	Trees (series)	Period (≥5)	Length (≥5)	MSL (years)	Rbar	AGR (mm/year)	MS	AC
Sher Bulak, low	SBl	JUSE	39.64	68.49	2100–2200	S	~30	36 (43)	1482 (1705)–2012	531 (308)	162	0.58	0.92	0.36	0.47
Sher Bulak, high	SBh	JUSE	39.64	68.47	2340–2415	S	~30	11 (16)	1851 (1857)–2012	162 (156)	123	0.53	1.15	0.26	0.38
		JUSM						11 (14)	1818 (1877)–2012	195 (136)	115	0.50	1.21	0.26	0.50
Sharskara	ZN1	JUSE	39.62	68.49	2110–2267	S	~25	8 (12)	1744 (1853)–2012	269 (160)	165	0.55	0.98	0.29	0.43
Sharskara	ZN2	JUSE	39.62	68.49	2310–2400	W	~15	8 (16)	1741 (1900)–2012	272 (113)	102	0.53	1.51	0.25	0.37
Sharskara incl. extreme rocky site	ZN3	JUSM	39.62	68.50	2660–2700	W	~10–25	6 (11)	1583 (1705)–2012	430 (308)	257	0.53	0.72	0.25	0.73
		JUTU						13 (24)	1668 (1800)–2012	345 (213)	174	0.45	0.64	0.29	0.33
	ZN3x	JUTU						14 (22)	1655 (1738)–2012	358 (275)	194	0.46	0.72	0.30	0.40
Composite TRW chronologies		JUSE						63 (87)	1482 (1705)–2012	531 (308)	144	0.53	1.14	0.32	0.44
		JUSM						17 (25)	1583 (1705)–2012	430 (308)	177	0.50	0.97	0.25	0.64
		JUTU						27 (46)	1655 (1724)–2012	358 (289)	183	0.46	0.68	0.30	0.36

(MSL) of 162/160 years and an average growth rate (AGR) of 0.92/0.98 mm per year, respectively (Table 1). The oldest forest stand, however, was found at the highest elevation at the ZN3 site with MSL of 183/257 years and an AGR of 0.68/0.72 mm per year for JUTU and JUSM, respectively. The mean sensitivity, which expresses the degree of variance fluctuation, was highest at the lowest site (SBl_JUSE: 0.36; Table 1). Additionally, the highest number of completely or partly missing rings was found for JUSE with 97 rings, which accounts for 0.77 % of all rings. JUTU trees at higher elevation had 45 missing or wedging rings (0.53 %), and JUSM 15 missing rings (0.34 %).

The Rbar at the sub-site level varied from 0.45 for JUTU at ZN3 to 0.58 for JUSE at SBl, highlighting the dependency of successful crossdating from the tree age and sample replication of the juniper species. The EPS, which evaluates the Rbar with the number of samples, showed common signal strengths for the composite chronologies from AD 1640 for JUSM with a drop during the 1840–1865 period, AD 1735 for JUTU except at around AD 1785 and from only AD 1815 onwards for JUSE despite highest sample replication of 20 series until AD 1700 (Fig. 3).

For the common period 1900–2012, the individual JUSE site chronologies showed common growth pattern with correlations ranging from $r = 0.43$ (ZN1–ZN2) to $r = 0.71$ (SBl–ZN1; all $p < 0.001$; Fig. 4). The correlation between the two JUSM chronologies was $r = 0.46$ and the mean correlation among the two JUTU chronologies was $r = 0.7$, both exceeding the 99.9 significance level. Statistically significant correlations ($p < 0.001$) were obtained when comparing species from the same sites: SBh_JUSE and SBh_JUSM ($r = 0.65$) and ZN3_JUSM with JUTU from ZN3 and ZN3x ($r = 0.63$). Over the longer 1724–2012 period, the composite JUSM and JUTU TRW chronologies showed the strongest agreement with $r = 0.61$, followed by JUTU–JUSE with $r = 0.45$ and JUSM–JUSE with $r = 0.36$ (all $p < 0.001$).

First-order autocorrelation (AC) determines the influence of the previous year growing conditions on the current year of growth and is expected to be higher at higher altitudes. Our results point to differences based on species with JUSM yielding highest values of 0.73 at ZN3 and 0.50 at SBh (Table 1). JUSE and even JUTU showed moderate dependencies on previous year's climate conditions, although JUSE at the driest site (SBl), reached the highest values of 0.47 while JUTU at ZN3 showed the lowest AC of 0.33.

Climate sensitivity

Examination of the growth–climate relationship between the individual and species-specific composite TRW

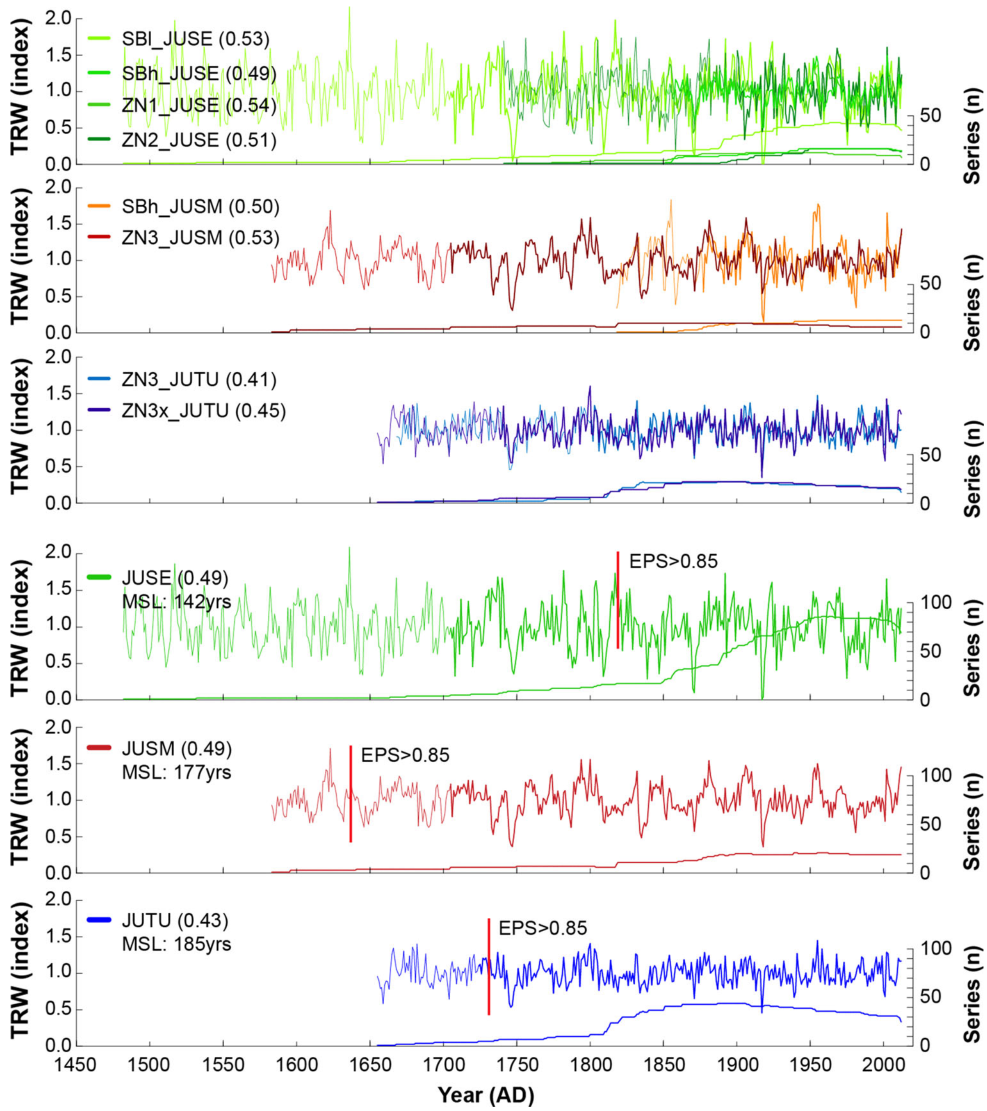


Fig. 3 Signal strength of the power transformed and 100-year spline detrended TRW chronologies of all sub-site and composite chronologies separated by species. Interseries correlation is given in the brackets and MSL is mean segment length

chronologies was conducted using the Shahristanskii meteorological station data for a shorter period (1950–1992; Fig. 5) and averaged CRU TS 3.21 gridded data for both the short (Fig. 5) and a longer period (1901–2012; not shown). Despite the differences in the climate data similar correlation results were found.

At the sub-site level, strongest negative correlations for JUSE were obtained with summer temperature (June–July, JJ and June–August, JJA) with a maximum of $r = -0.42$ ($p < 0.01$) using the Shahristanskii station data. Also, positive associations were found with precipitation ranging from $r = 0.30$ ($p < 0.05$) to $r = 0.44$ ($p < 0.01$; Fig. 5). Favoured tree growth during wet climate conditions could even be noted for the entire year, with $r = 0.39$–0.49, but was highest during the April to September (A–S) period with maximum positive correlations of $r = 0.50$ for sub-site SBl and $r = 0.55$ for ZN2 ($p < 0.01$). Similar results are obtained for the CRU data, where the JUSE composite yielded highest negative correlations for JJA temperature with $r = -0.50$ and positive correlations with precipitation of $r = 0.51$ for the longer A–S period (both $p < 0.01$). The strong drought response of the JUSE trees, i.e., growth suppression during hot and dry summers, is underlined by positive correlations with A–S drought indices of $r = 0.45$ for the 1950–1992 period (Fig. 5) and $r = 0.55$ for the 1901–2012 period (not shown), exceeding the 99 % significance level.

The climate sensitivity for the JUSM sub-site and composite chronologies was less pronounced. The results suggested that tree growth at the higher elevation site (ZN3) was favoured by (1) warmer temperatures in February ($r = 0.39$; $p < 0.01$) and (2) high spring (March–May) precipitation amounts ($r = 0.35$; $p < 0.05$). When using the grid point data, only correlations between ZN3

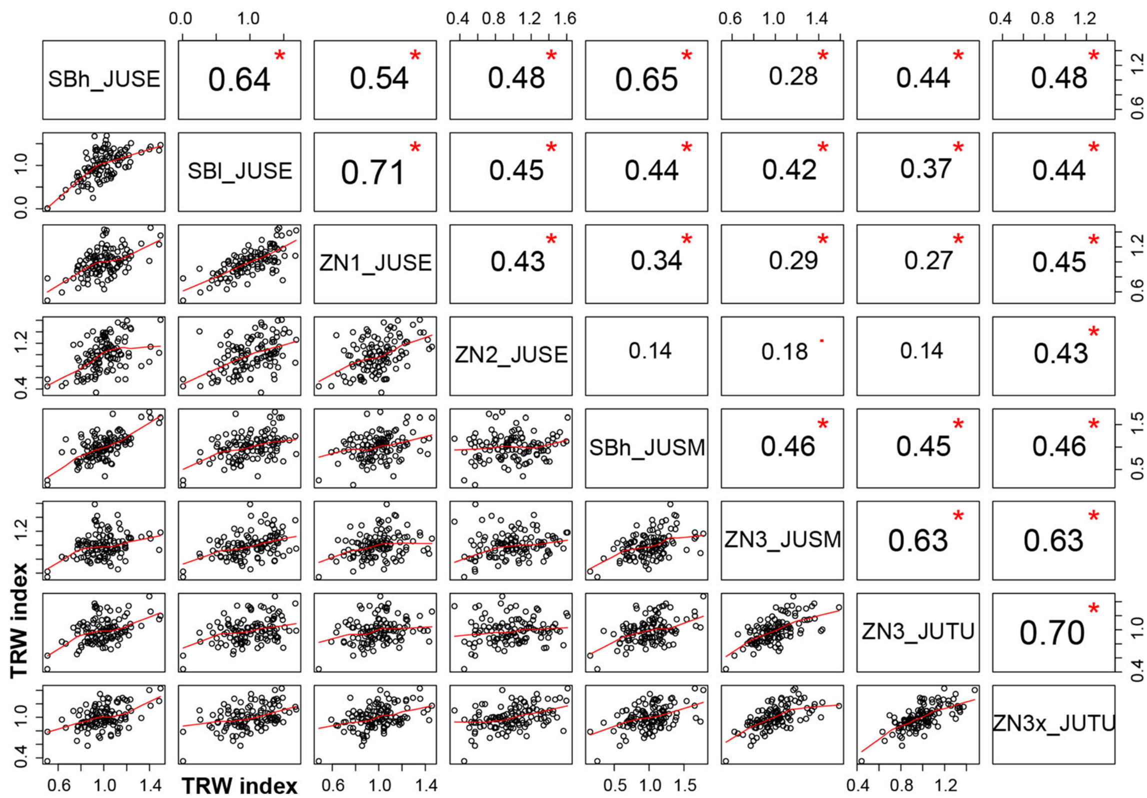


Fig. 4 Comparison between the species-specific site TRW indices (*black circles*) together with the model of best fit (*red lines*) at the *lower left part of the panel* and cross-correlation statistics showing the Pearson correlation coefficients (r) for the common AD 1900–2012 period. *Stars* (*dot*) represent(s) correlation values exceeding the 99.9 % (95 %) significance level

and temperature in February were consistent with $r = 0.40$ ($p < 0.01$; Fig. 5). For the 1901–2012 period, all JUSM trees showed a positive association with spring precipitation ($r = 0.25$; $p < 0.01$), which persists into the summer (JJ: $r = 0.27$; $p < 0.01$) and a longer A–S season ($r = 0.23$; $p < 0.05$; not shown).

For the higher altitude JUTU trees, significant positive correlations were found for temperature in April with values ranging from $r = 0.30$ (ZN3x) to $r = 0.37$ (JUTU composite) and February for the ZN3x site only, with $r = 0.30$ (all $p < 0.05$). Additionally, positive correlations with March precipitation were exceptional with $r = 0.51$ ($p < 0.01$) for the extreme rocky site ZN3x. Considering the gridded data, results point to a positive influence of warm February temperatures on tree growth with $r = 0.35$ ($p < 0.05$) for ZN3x and $r = 0.33$ ($p < 0.05$) for JUTU, while the correlations with spring precipitation were not significant at the 95 % level. On the contrary, the insignificant positive correlation with summer (June–August) precipitation for the Shahristanskii data became significant when using the CRU data with $r = 0.33$ ($p < 0.05$) for 1950–1992 (Fig. 5), and $r = 0.34$ ($p < 0.01$) for AD 1901–2012 (not shown). Moreover, positive correlations with March–May precipitation reemerged for ZN3x with $r = 0.36$ and were reflected in all JUTU chronologies with $r = 0.35$ ($p < 0.01$; not shown).

Focusing on the seasonal climate response of each species by including more climate variables, the RDA results are presented in Fig. 6. Generally, the species-specific site chronologies were negatively loaded on the first RDA axis for all seasons (Fig. 6a–e) demonstrating the high coherency among the TRW chronologies (Fig. 4). The individual growth responses to climate factors are expressed based on positive or negative loadings along the second RDA axis. For winter, the JUSM and JUTU sites were clearly separated from the JUSE sites with positive loadings (except SBl_JUSE). The strongest relationships were found for ZN1_JUSE and ZN2_JUSE to temperature (T, xT and nT) and VP, and for SBl_JUSE to drought (S) (Fig. 6a). About 25 % of the variability in the tree-ring data could be explained by climate variables in spring, and strong positive associations were found between ZN2_JUSE and VP (Fig. 6b). The climate parameters during summer explained 23 % of the total variability in the TRW data, and two groups were distinguished: one including all JUSE sites (positive

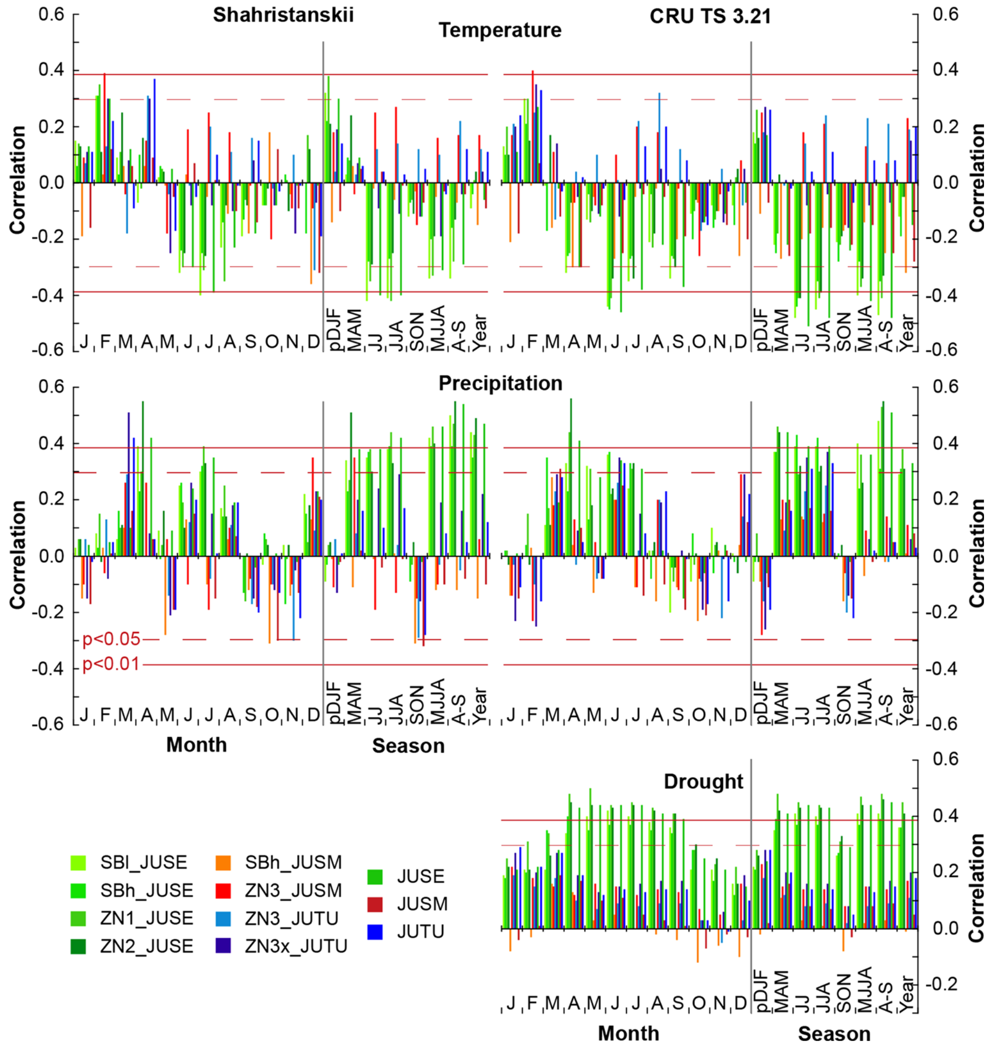


Fig. 5 Climate response of the sub-site and composite TRW chronologies with respect to the individual juniper species using Shahristanskii station data (*left* temperature and precipitation) and CRU TS 3.21 gridded climate data [*right* temperature, precipitation and drought (self-calibrated Palmer Drought Severity Index)] for the AD 1950–1992 period

loadings) and the other with JUSM and the JUTU sites (negative loadings; Fig. 6c). Strong positive correlations were obtained for SBl_JUSE and drought and for JUSM and JUTU chronologies with temperature, while strong negative associations were seen between ZN2_JUSE and temperature (T, nT, xT). The RDA output for autumn (Fig. 6d) was more diverse and dominated by positive correlations for JUSE (SBl, ZN1, ZN2) with drought, which were complemented by negative, but low correlations with temperature (T, nT). Both the JUSM and ZN3_JUTU chronologies were positively influenced by dtrT, while at the same time, CC and VP had a negative growth impact (Fig. 6d). Summarizing the climate response over the entire vegetation period, the strong negative associations between SBl_JUSE and precipitation/drought were striking, while JUSM and JUTU form a cluster that suggests positive associations with temperature (T, xT, nT; Fig. 6e).

Using different statistical approaches, the relationship between JUSE and April–September drought indices was shown to be prominent and consistent over the 1901–2012 period (Fig. 7a, b). Pearson's correlation coefficients exceeded the 99 and 99.9 % significance level for the composite JUSE chronology ($r = 0.55$) and SBl_JUSE chronology ($r = 0.53$), respectively. Spatially, the drought response extends over large parts of the interior of Central Asia, covering northern Afghanistan and eastern Turkmenistan and Uzbekistan, south-central Kazakhstan, entire Kyrgyzstan and Tajikistan (Fig. 7c). The only other robust and positive relationship was found between ZN2_JUSE chronology and the vapour pressure during spring (March to May) with $r = 0.40$ ($p < 0.05$; Fig. 7d, e). The positive effect of high air humidity on tree-growth at the beginning of the growing season seems to be characteristic for an even larger area covering entire Central Asia (except northern Kazakhstan) and continues far into China (Fig. 7f).

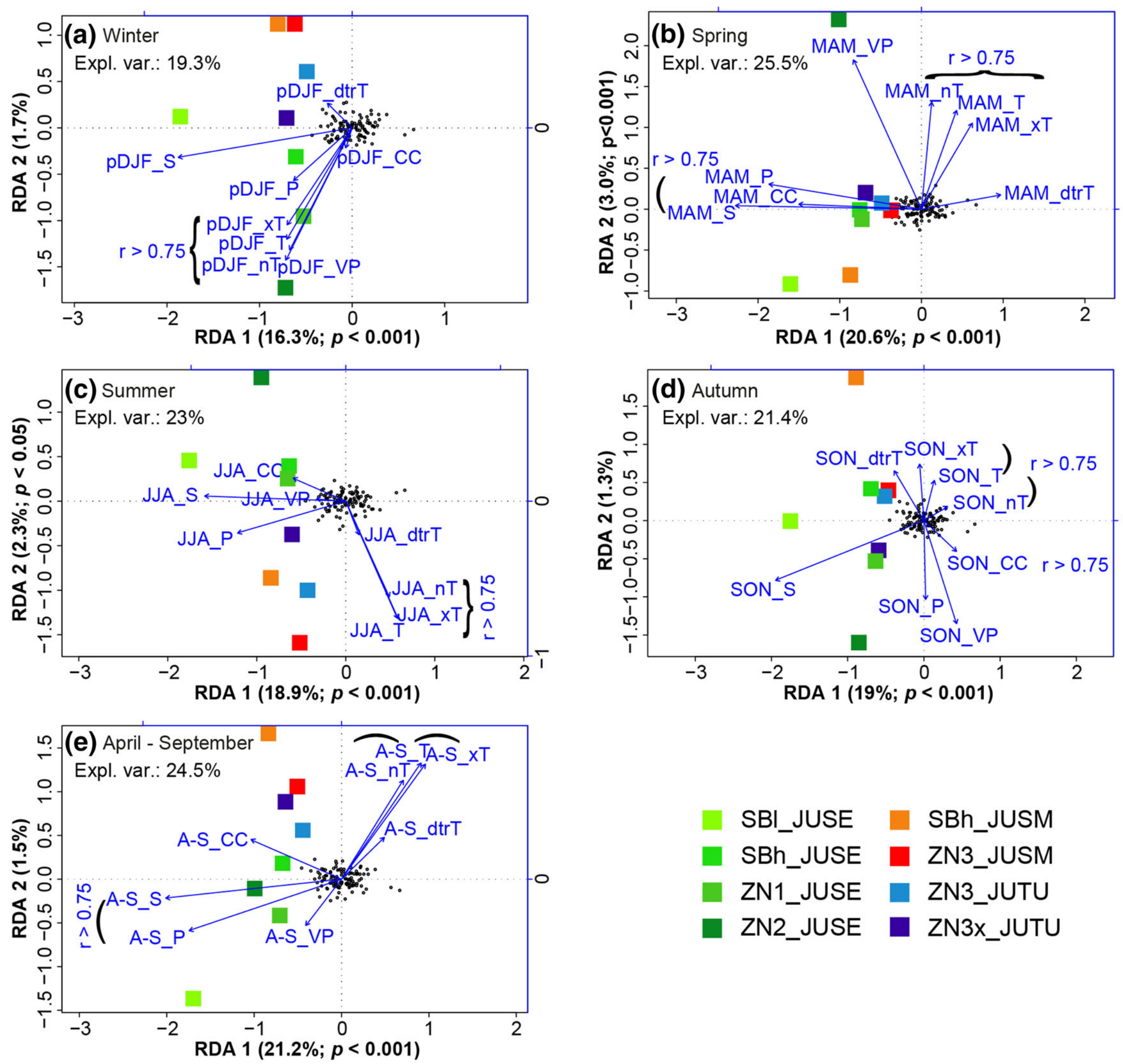


Fig. 6 Correlation biplot of redundancy analysis (RDA) of eight species-specific TRW chronologies (see legend) and seasonal **a** previous December to current year February (pDFJ), **b** March to May (MAM), **c** June to August (JJA), **d** September to November (SON), and **e** April to September (A–S) pooled climate variables (CRU TS 3.22) for the AD 1901–2012 period. Maximum (xT), minimum (nT), their difference (dtrT) and average (T) temperatures, precipitation (P), drought index (S), cloud cover (CC), and vapour pressure (VP) are used as explanatory variables. Length of *arrows* (vectors) corresponds to strength of influence of the climate data on species-specific TRW sites while the direction indicates the sign of correlation. *Round* (*curly*) *brackets* denote the single (group) climate variables with high collinearity ($r > 0.75$)

Extreme growth years

Extreme growth years calculated for all the site and composite juniper chronologies and the concurrent climate conditions are listed in Table 2. By setting a rather low threshold of one standard deviation, numerous years were identified, where some were only recorded in individual site chronologies, for example in the first decade of the twentieth century or in the 1990s. However, years that exclusively affected individual species included 1925, 1927 and 1975 with low annual growth for JUSE due to hot and dry April–September seasons. Common negative (1939, 1940, 1957) and positive (1955, 1958, 1973) growth years were also found for JUTU. Low growth rates can be explained by cold or dry climate conditions, and high growth rate years by wet or warm climate conditions. Opposite growth patterns among the juniper species were found in 1976, 1981 and 1989 (Table 2).

Within the past century, eleven (eight) positive (negative) extreme growth years were recorded in the JUTU composite chronology, followed by five (seven) positive (negative) extreme years in the JUSE composite and two (five) positive (negative) extreme years in the JUSM composite (Table 2). Clearly, JUSM showed the least number of extreme years during the past century. Exceptional periods of extreme growth years were found in the

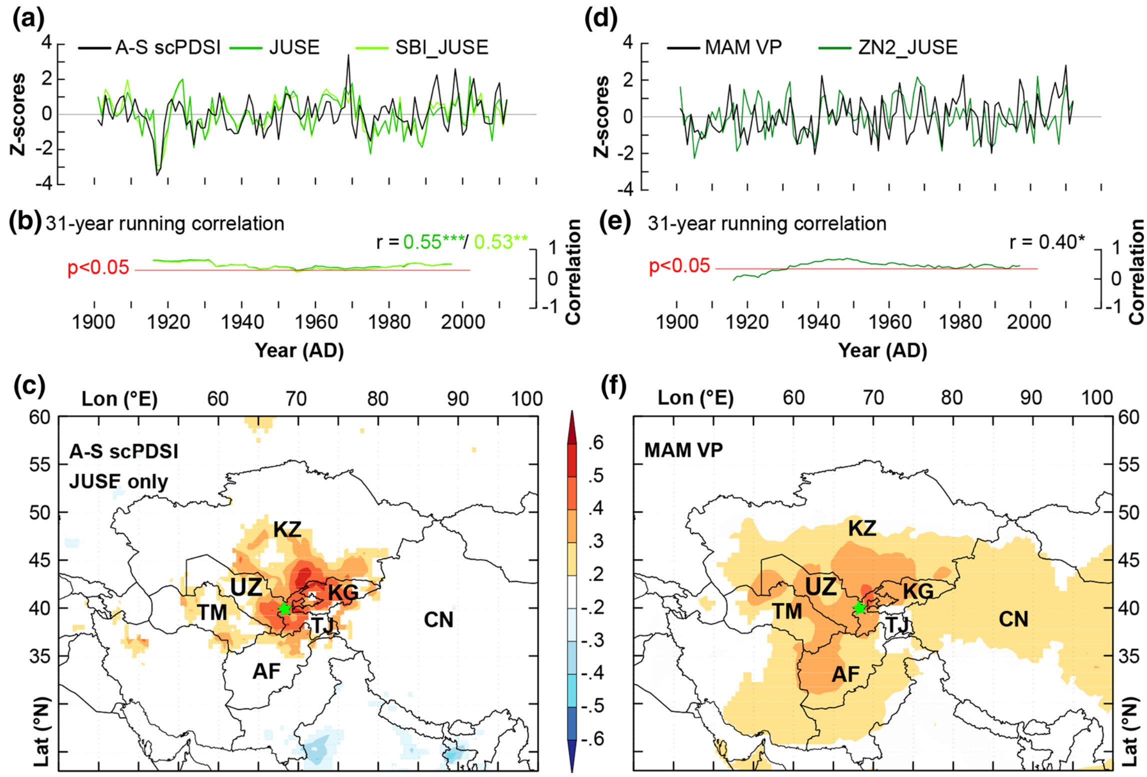


Fig. 7 Comparison between **a** SBI_JUSE and JUSE composite TRW chronology and gridded scPDSI data (April–September; CRU TS 3.21) and **d** ZN2_JUSE and March to May vapour pressure (VP; CRU TS 3.22), its **b** and **e** temporal coherency using a 31-year running correlation, and **c** and **f** the spatial extend of the correlation for the AD 1901–2012 period, respectively. 95, 99, 99.9 % significance levels for Pearson correlation coefficients (*r*) are denoted by one, two and three *stars*, respectively

1920s, which are present at inter-regional scale and in the first decade of the twenty-first century (Table 2). Those two decades show extreme changes in the year-to-year climate, which was mainly dominated by very dry (wet) conditions during the vegetation period, and hence, responsible for the very low (high) growth rates.

Discussion

Data quality

Juniperus is the dominant conifer genus in the arid and semi-arid mountain forests in Central Asia and can reach ages of up to 2000 years in the Tien Shan, Kyrgyzstan (Esper 2000; Mukhamedshin 1977). Our sampling sites were fairly easily accessible and, surprisingly, up to 531-year-old individuals were found (Table 1). However, the crossdating was challenging, especially for the JUSE and JUTU trees. High growth variability between trees restricted the development of long and robust TRW chronologies (Fig. 3). JUSE showed the highest among-tree variability and despite the largest number of samples, a robust signal coherency only exists back to AD 1815. This indicates that more samples from older trees are needed if longer chronologies with high signal strengths are to be developed of this particular sub-species. The highest synchronicity was found among JUSM trees, yielding a robust common signal until AD 1640 for the composite TRW chronology with the least number of dated series ($n = 25$; Fig. 3). Generally, strong common growth variability between the species and different sites can be observed (Table 1), which is consistent with the findings by Esper (2000) for juniper sites in the Alay range, western Tien Shan in Kyrgyzstan.

It has to be mentioned that the availability and quality of existing meteorological station data are far from ideal for a dendroclimatological analysis in this region. However, this issue is addressed in various analyses using climate data for Central Asia (e.g., Schiemann et al. 2008; Stocker et al. 2013). At our sites, the utilized gridded climate data might slightly overestimate temperatures but underestimate precipitation. On the other hand, the closest meteorological station (Shahristanskii Pereval, Tajikistan) has an altitudinal difference of circa 450 m to our highest site and should better represent the mountainous climate conditions of the inner Pamir-Alay range (Fig. 1b), compared to other available stations. Although using Shahristanskii Pereval

Table 2 Negative (blue) and positive (red) extreme years identified in the individual and composite juniper TRW chronologies exceeding one (shaded) and 1.5 (full colour) standard deviations, which are compared to gridded climate data [CRU, and if available, Shahristanskii station station (Sha)] and results obtained for Central Asia (Esper et al. (2002): inter-regional negative (NEG) and positive (POS) pointer years are highlighted in bold; Solomina et al. (2014): cold (C), warm (W) and dry (D) years; Chen et al. (2013): extreme wet and dry years), for northern Iran (N Iran; Pourtahmasi et al. 2007), for the European Mediterranean region (Medit.; Seim et al. 2014): identified for the East (E), West (W) or entire region (Med)), and for flood (F) and drought (D) events (and its magnitude) from the northeastern Tibetan Plateau (NE Tib. Plateau; Qin et al. 2011)

year	SBh_ JUSE	SBl_ JUSE	ZN1_ JUSE	ZN2_ JUSE	JUSE	SBh_ JUSM	ZN3_ JUSM	JUSM	ZN3_ JUTU	ZN3x_ JUTU	JUTU	Climate	Central Asia	N Iran	Medit.	NE Tib. Plateau
2010												wet A-S				
2008												high A-S temp				
2006												high A-S/ annual temp				
2003												wet A-S				
2002												wet A-S/ Year, high Aug & annual temp				
2001												dry A-S, high Apr & annual temp				
2000												dry A-S, high Apr & A-S temp			NEG (E)	F (1)
1999												high Feb & Aug temp				F (3)
1995													W; Wet	NEG		D (1)
1994													W; Wet			F (2)
1989												dry Apr (Sha)	C			
1987												wet A-S (Sha), warm Aug			NEG (E)	F (1)
1985												dry A-S (Sha)		NEG		
1984												dry A-S (Sha), cold Feb, high Aug temp	W			
1983												high Aug temp			POS (E)	F (2)
1981												wet A-S (Sha)		POS		F (1)
1978												high A-S temp	W			
1976																
1975												dry A-S		NEG		F (2)
1973														POS		
1972												low A-S/ annual temp	C			F (1)
1971														NEG		D (1)
1968												wet Mar (Sha)				D (1)
1967																F (1)
1966												high Feb temp & Mar (Sha) precip				D (1)
1965													NEG	NEG		
1962																D (2)
1960												cold Apr				
1958												wet A-S			POS (W)	
1957												cold year (Sha+CRU)	C		NEG (Med)	D (2)
1956												high A-S temp (Sha)				
1955												high Mar temp (Sha)		POS		F (1)
1954												wet A-S				
1952														POS		
1941												high annual temp (Sha+CRU)	POS		POS (E)	
1940														POS		
1939												cold Apr				
1934												low A-S/ annual (Sha+CRU) temp & wet A–S				D (2)
1932												low Aug temp				D (1)
1931												cold Feb				
1927												dry A-S	Dry			D (2)
1926												cold Apr, high Aug temp	POS; W; Dry			D (3)
1925													NEG			
1924												low A-S temp				
1922															POS (E)	
1920												low A-S temp	C			F (1)
1919													POS; Dry			
1918												A-S drought, cold Apr	NEG; Dry			D (2)
1917												A-S drought, high Feb & annual temp	**NEG**; D; Dry	NEG		
1916												high Aug temp	**POS**; W/D		NEG (E)	D (1)
1915												high annual temp	POS			
1913												cold Apr		NEG		
1912																
1909												warm Apr			NEG (Med)	
1907																
1905												cold Feb			POS (W)	
1904															POS (Med)	F (1)
1903																F (2)
1902													NEG		POS (E)	F (1)

may lead to an overestimation of total rainfall amounts, and at the same time slightly underestimating temperatures, at our site (Fig. 1c), we argue that the obtained growth–climate relationships are robust.

Species-specific climate sensitivity

The strongest growth–climate relationship was observed between drought and the JUSE composite chronology, which is largely dominated by trees from the lowest and driest site SBl (Figs. 5, 6e). In the only dendroclimatological study from Uzbekistan, Glasirin and Gorlanova (2005) found that the radial growth of JUSE in the western Tien Shan, Uzbekistan, at 2720 m a.s.l., was limited by summer (mainly June) drought. This supports our findings; however, the results of Glasirin and Gorlanova (2005) were preliminary and the analysis was based on a very low number of samples. The results obtained for JUSM were ambiguous, and the two site TRW chronologies showed contrasting, and insignificant, climatic responses (Fig. 5): the SBh_JUSM seemed to be limited by summer drought corresponding to JUSE while ZN3_JUSM recorded a summer temperature signal similar to that of JUTU. The combined JUSM record incorporated a very weak summer drought signal (Fig. 5), strongly influenced by drought conditions of the previous year summer (July to September) condition ($r = 0.36$; $p < 0.01$; not shown).

At higher elevations, JUTU showed that warmer winter (February), spring (April) and summer temperatures have positive influences on tree growth. Interesting is the positive effect of warmer winter/spring temperatures on tree growth, which is reported for conifers at high altitudes, especially for eastern Asia (e.g., Bräuning 1994; Fan et al. 2009; Gao et al. 2013; Liang et al. 2006) or other species at their latitudinal distribution limits (e.g., Pederson et al. 2004). Multiple reasons are found for this positive relationship such as less root damage due to frost (e.g., Gou et al. 2008), more available carbohydrates and growth hormones in the soil for the coming growing season (e.g., Oberhuber 2004) and an earlier start of the growing season by initiating physiological activity (e.g., Dullinger et al. 2004; Havranek and Tranquillini 1995).

Overall, our results for JUTU differ slightly from the findings of Glazirin and Gorlanova (2005), who found statistically significant negative correlations with July temperature for eight JUTU trees at 2850–3250 m a.s.l. This might be related to the more mountainous location of their sampling sites in the western Tien Shan, northeastern Uzbekistan (Fig. 1a), compared to ours. Nevertheless, a strong positive influence of late winter/early spring (March) temperatures on JUTU growth was also identified by Glazirin and Gorlanova (2005) and Esper (2000). Our summer temperature signal, though weak, of JUTU in the Turkestan range, Pamir-Alay, is coherent with results obtained for high-elevation JUTU from the Alay range, southern Kyrgyzstan, by Esper (2000) and Esper et al. (2002).

Our findings show species-specific climate sensitivity of JUSE, JUSM and JUTU (Fig. 6), contradicting the results found in a similar study by Esper (2000). JUSE inhabits lower elevations (Adams 2011; Botman 2008) and following the general assumption of changing climate sensitivity with elevation (e.g., Fritts 1976; Tranquillini 1964), drought was assumed to be the main limiting factor of ring formation. On the other hand, JUTU is growing at higher altitudes and naturally dominates the tree line ecotone, where temperature usually controls tree growth (Fritts 1976). Since our study was conducted within a relatively small area, only little variation in the microclimate among the sampling sites can be expected; yet, a clear separation between the climatic response of JUSE and JUSM together with JUTU was observed, especially in the RDA result for the summer (JJA) and the growing season (April–September; Fig. 6c, e). JUSM seems to cluster with JUTU by sharing a positive, though weak, influence of higher summer temperatures on tree growth (Figs. 5, 6a). This, however, concurs with findings by Esper (2000) and Esper et al. (2002) for juniper from the Tien Shan sites, where the junipers from the lower elevation sites showed more equivocal growth–climate associations while annual growth of high-elevation trees (JUTU) were predominantly attributed to a positive summer temperature response.

Referring to common ring-width variations of juniper in Central Asia, Esper et al. (2007) questioned the overall dendroclimatological assumption of changing temperature signals in juniper tree rings with respect of elevation as formulated by Fritts (1976). In fact, they proposed that cloud cover has a strong influence on juniper growth in western Central Asia. Our RDA analysis revealed that indeed cloud cover and even vapour pressure affect variations in growth patterns for the different species and seasons (Fig. 6). However, statistically stable growth–climate relations were only found between JUSE (and SBl_JUSE) and April–September drought, and positive influence of high air humidity (i.e. high evaporative capacity due to high rainfall and warmer spring temperatures) on tree growth for ZN2_JUSE during the spring season over the 1901–2012 period (Fig. 7). Additionally, the RDA analysis demonstrated that a large part of the tree-ring variability cannot be explained solely by climate or by one climate parameter alone.

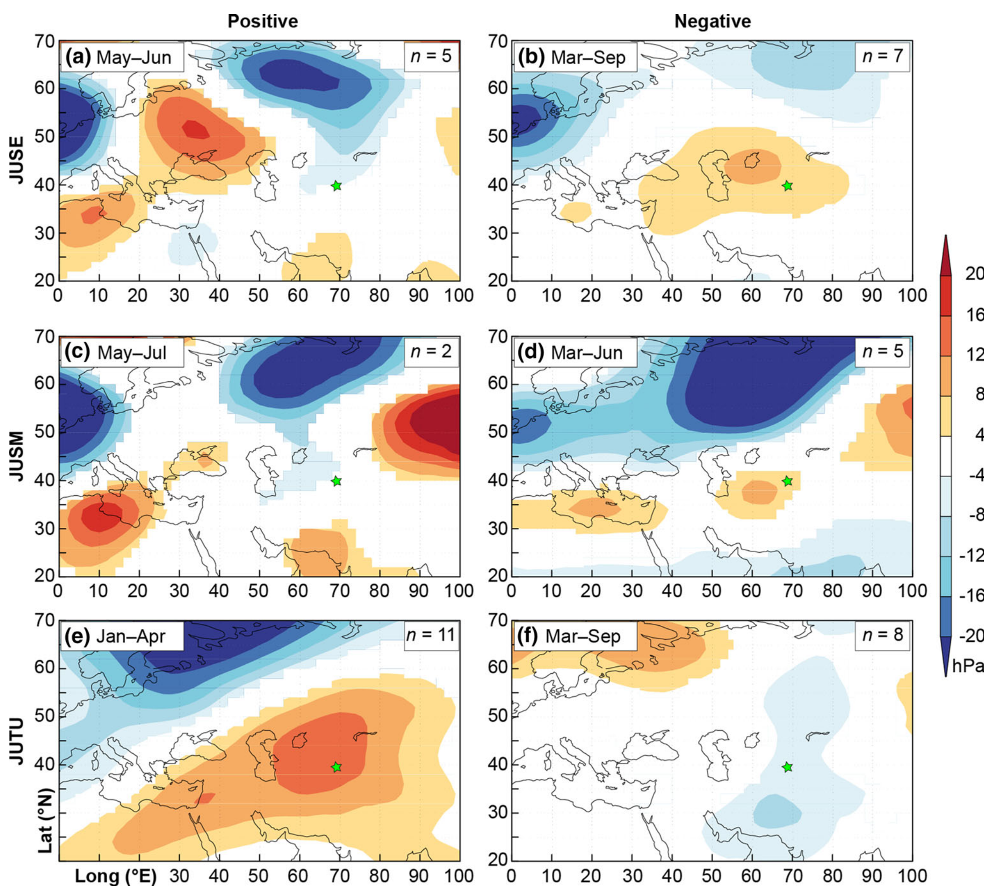
Site influences on the climate signal strength

The influence of topography (aspect, slope) and altitude, as partly discussed in the previous section, on the signal strength of species have been identified for different regions (e.g. Fan et al. 2009; Fritts et al. 1965; Liang et al. 2006; Oberhuber and Kofler 2000). Considering the same species but from differing sites in terms of topography (Table 1; Fig. 6), it is evident that site selection (Fritts 1976) plays a crucial role in achieving the maximum climate response for juniper. Among the JUSE sites, the lowest site (SBl) shows the strongest drought response, which was stable throughout the twentieth century, making trees from this site suitable for a drought reconstruction (Fig. 7). Here, trees grow on steep south-facing slopes (Fig. 2; Table 1) and thus, high solar radiation combined with high run-off and low water storage capacity of the shallow soils most likely contribute to the trees drought stress. Of the JUSM sites, the trees at the highest elevation (2660–2700 m a.s.l.) on the west-facing slopes (ZN3_JUSM) showed the strongest positive response to February temperatures (Fig. 5) and summer (JJA) temperatures comparable to ZN3_JUTU (Fig. 6). However, ZN3_JUSM exhibited the highest autocorrelation to the previous year, which likely masks the strength of the climatic signal (Vaganov et al. 2009 and references therein) due to an enhanced capacity of water and nutrient storage (Ewers et al. 1999). A "biological memory" has been reported for other conifer species, e.g., in the Hengduan Mountains, southwestern China (Fan et al. 2009) or the European Alps (e.g., Carrer et al. 2007). For JUTU, no consistent difference in the climate response can be found (Fig. 5) despite the more exposed environment (i.e., mountain top) of the trees at ZN3x. It should be noted, however, that our JUTU sites were sampled at 2700 m a.s.l., which is below the upper tree line (at 3000 to 3500 m a.s.l.) and a very strong temperature signal in the tree-ring data was not expected. To maximize the summer temperature signal, JUTU trees closer to the tree line need to be targeted.

Spatial scale of extreme growth events

The number of extreme growth years for all eight TRW records reflects the strength of the climate sensitivity, where a high number of extreme (i.e., pointer) years indicate higher climate sensitivity and vice versa. In our case, JUSM shows the lowest number of extreme growth years (two positive and five negative extreme years) during the analysed common 1900–2012 period (Table 2), which concurs with the weak and indistinct climatic signal found using simple correlation and RDA statistics. By comparing

Fig. 8 Composite maps for positive (*left*) and negative (*right*) extreme growth years for JUSE, JUSM and JUTU (see Table 2) and 500 hPa geopotential height fields for the AD 1901–2012 period. Seasonal pressure anomalies were averaged showing its maximal intensity and magnitude, which deviates from the period of climate response obtained via Pearson correlation statistics



the different years with extreme low or high growth rates, a rather high number of years are unique to only one site and species as seen for example during the 1980s (Table 2). In the Swiss Alps, Neuwirth et al. (2004) defined such years as "site pointer years" and they were attributed to dominant influences of topographical conditions rather than a dominant climatic forcing. Nevertheless, common species-specific positive (negative) growth extremes were found for JUSE, which are likely related to unusually wet (dry) climate condition during April–September. Common positive JUTU growth anomalies were assigned either to a warm spring (e.g., 1955) or to high summer/annual temperatures (e.g., 1916, 1941). Those years, identified in the high-frequency records, highlight the species-specific climate response as described above.

Extreme growth years that were common to all species, and thus likely controlled by large-scale climatology, were found in 1916 and 2002 for positive growth and 1917, 1918, and 2001 for extreme suppressed juniper growth. A higher occurrence of missing rings coincide with those negative extreme growth years: three missing rings for JUSE and one for JUTU in 1971, four rings for JUSE in 1918, and two rings in 2000 and one in 2001 for JUTU.

To highlight the synoptic conditions during selected extreme growth years, composite maps of 500 hPa geopotential height anomaliy maps were generated (Fig. 8). It has to be mentioned that the spatial correlations were computed for slightly different seasons to highlight the associated atmospheric circulation patterns. Positive extreme years recorded for JUSE, and to a lesser extent for JUSM (Fig. 8a, c), can be related to the propagation of Artic air into Central Asia providing this region with cooler than usual weather during summer, as described by Shahgedanova (2002). Additionally, the findings by Solomina et al. (2014), showing significant correlations between reconstructed temperature and sea level pressure across high latitude Eurasia, support our results. This is, for example, the case for 1916, where our records (Table 2), Esper et al. (2002) for juniper and also Solomina et al. (2014) for spruce from tree-line sites in Kyrgyzstan identified higher than normal growth rates. In the same year, high-pressures anomalies over the Mediterranean Basin and eastern Europe and northeastern Tibetan Plateau led to limited ring formation due to drought (Seim et al. 2014; Qin et al. 2011). On the other hand, extreme low growth for both JUSE and JUSM seems to be related to anomalous high pressure systems over Central Asia and the Mediterranean Basin (Fig. 8b, d). This was the case in 1917, and suppressed growth was also observed in the Tien Shan (Chen et al. 2013; Esper et al. 2002; Solomina et al. 2014) and northern Iran (Pourtahmasi et al. 2007). Favourable growth conditions for JUTU trees are related to warm winter–spring temperatures (Fig. 8e), and the observed positive JUTU growth anomaly in 1941 corresponds to favourable growth conditions in the eastern Mediterranean Basin (Seim et al. 2014) and western Central Asia (Esper et al. 2002). On the contrary, cold summer restrain JUTU ring formation, possibly related to low-pressure anomalies across Kazakhstan and Pakistan (Fig. 8f). Our analysis shows the importance of the large-scale circulation on regionally expressed extreme growth events and that such events can be connected across the European Mediterranean region, Central Asia and China, either agreeing or showing opposite growth reactions, depending on the prevailing circulation patterns.

Conclusion

We provided the first comprehensive overview of climate, site- and species-specific controls on juniper growth from the Zaamin National Park, Uzbekistan, using eight newly developed TRW chronologies. Contrary to previous findings, we identified different climatic responses for the three analysed juniper species (JUSE, JUSM, JUTU). JUSE showed a strong and temporally stable sensitivity to April–September drought for the lowest sampling site as well as the composite chronology. The climate signal for JUSM was more diverse due to its intermediate position between the low-elevation JUSE and high-elevation JUTU zones. The growth of JUTU trees, sampled at the highest elevations in the study area, was favoured by warm spring and summer temperatures. Extreme growth years common to the studied species reflected large-scale climate conditions related to the propagation of air masses from the Atlantic or the Artic.

Based on our results, only JUSE was regarded to be a suitable juniper species for climate reconstructions in the region, specifically of growing season (April–September) drought variability. Nevertheless, there is also a potential to use JUTU to infer past summer temperature variability, provided that it is sampled at the upper timberline. JUSM should not be mixed with the other species since it might weaken the dominant climate signal. However, considering climate changes scenarios and possible altitudinal range shifts, JUSM will likely become more sensitive to drought in the future.

Author contribution statement This study was realized in collaboration between all authors: AS, TT, GO and LN carried out field work. AS prepared the data, designed the study, computed and analysed the data. The text was written by AS with contributions from all co-authors.

Acknowledgments We are grateful to Almazbek Orozumbekov (†) and Alisher Shukurov for organizational support and Pavel Danilov for measuring site ZN3. The study was funded by Kungliga Vetenskapsakademien (KVA, including the Margit Althins Stipendiefond), Svenska Sällskapet för Antropologi och Geografi (SSAG), Wilhelm och Martina Lundgrens Vetenskapsfond and Swedish International Development Cooperation Agency SIDA (project SWE-2009-245).

Compliance with ethical standards

Conflict of interest All authors declare no conflict of interest.

References

Adams RP (2011) Junipers of the World: the genus *Juniperus*, 3rd edn. Trafford Publishing Co, Bloomington

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshears DD, Hogg EH, González P, Fensham R, Zhang Z, Castro J, Demidova N, Lim JH, Allard G, Running SW, Semerci A, Cobb N (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecol Manag 259:660–684

Botman E (2008) Vulnerability of juniper formations to climate change on the territory of Uzbekistan. In: SANIGMI (ed) Climate change consequences in Uzbekistan, adaptation issues. Information on fulfillment of commitments to the UNFCCC by Uzbekistan, 7th edn. Tashkent, pp 68–75

Botman E (2009) Forest rehabilitation in the Republic of Uzbekistan. In: Lee DK, Kleine M (eds) IUFRO World Series. IUFRO (International Union of Forestry Research Organizations) Secretariat, Vienna, pp 253–299

Bräuning A (1994) Dendrochronology for the last 1400 years in eastern Tibet. GeoJournal 34(1):75–95

Breshears DD, Cobb NS, Rich PM, Price KP, Allen CD, Balice RG, Romme WH, Kastens JH, Floyd ML, Belnap J, Anderson JJ, Myers OB, Meyer CW (2005) Regional vegetation die-off in response to global-change-type drought. Proc Natl Acad Sci USA 102(42):15144–15148

Carrer M, Nola P, Eduard JL, Motta R, Urbinati C (2007) Regional variability of climate—growth relationships in *Pinus cembra* high elevation forests in the Alps. J Ecol 95:1072–1083

Chen F, Yuan YJ, Chen FH, Wei WS, Yu SL, Chen XJ, Fan ZA, Zhang RB, Zhang TW, Shang HM, Qin L (2013) A 426-year drought history for Western Tian Shan, Central Asia, inferred from tree rings and linkages to the North Atlantic and Indo-Pacific Oceans. Holocene 42:1008–1021

Cook ER, Krusic PJ (2005) Program ARSTAN: A tree-ring standardization program based on detrending and autoregressive time series modelling, with interactive graphics. Tree-Ring Laboratory, Lamont-Doherty Earth Observatory of Columbia University, Palisades

Cook ER, Peters K (1997) Calculating unbiased tree-ring indices for the study of climatic and environmental change. Holocene 7:361–370

Development Core Team R (2008) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna

Dullinger S, Dirnbock T, Grabherr G (2004) Modelling climate change-driven treeline shifts: relative effects of temperature increase, dispersal and invisibility. J Ecol 92:241–252

Esper J (2000) Palaoklimatische Untersuchungen an Jahrringen im Karakorum und Tien Shan Gebirge (Zentralasien). Bonner Geographische Abhandlungen 103:137

Esper J, Treydte K, Gärtner H, Neuwirth B (2002) A tree ring reconstruction of climatic extreme years since 1427 AD for Western Central Asia. Paleobotanist 50:141–152

Esper J, Frank DC, Wilson RJ, Büntgen U, Treydte K (2007) Uniform growth trends among central Asian low-and high-elevation juniper tree sites. Trees 21(2):141–150

Ewers BE, Oren R, Albaugh TJ, Dougherty PM (1999) Carry-over effects of water and nutrient supply on water use of *Pinus taeda*. Ecol Appl 9(2):513–525

Fan ZX, Bräuning A, Cao KF, Zhu SD (2009) Growth–climate responses of high-elevation conifers in the central Hengduan Mountains, southwestern China. For Ecol Manag 258:306–313

Fisher M (1997) Decline in the juniper woodlands of Raydah reserve in southwestern Saudi Arabia: a response to climate changes? Global Ecol Biogeogr 6:379–386

Fritts HC (1976) Tree-rings and climate. Academic, London

Fritts HC, Smith DG, Cardis JW, Budelsky CA (1965) Tree-ring characteristics along a vegetation gradient in northern Arizona. Ecology 46(4):394–401

Gao L, Gou X, Deng Y, Liu W, Yang M, Zhao Z (2013) Climate–growth analysis of Qilian juniper across an altitudinal gradient in the central Qilian Mountains, northwest China. Trees 27(2):379–388

Glazirin GE, Gorlanova LA (2005) Опыт дендроклиматического исследования стланиковых можжевельников на Западном Тянь-Шане (Experience of dendrochronological research of prostrate junipers in the western Tien Shan). NIGMI Proceedings 5(250):24–42

Glazovskiy AF, Solomina ON (1989) Glacier fluctuations and *Picea shrenkiana* tree-ring growth at the northern slope of Terskey Alatoo. Materiali Glytsiologicheskikh Issledovany (in Russian) 65:103–110

Gou XH, Chen FH, Yang MX, Jacoby G, Fang KY, Tian QH (2008) Asymmetric variability between maximum and minimum temperatures in Northeastern Tibetan Plateau: evidence from tree rings. Sci China Ser D 51(1):41–55

Graybill DA, Shiyatov SG, Burmistrov VF (1992) Recent dendrochronological investigations in Kirghizia, USSR. Lundqua Rep 34:123–127

Havranek M, Tranquillini W (1995) Physiological processes during their winter dormancy and their ecological significance. In: Smith WK, Hinkley TM (eds) Ecophysiology of coniferous forest. Academic Press, New York, pp 95–124

Holmes RL (1983) Computer-assisted quality control in tree-ring dating and measurement. Tree Ring Bull 43:69–78

Legendre P, Legendre L (1998) Numerical ecology. Elsevier Science BV, Amsterdam

Legendre P, Oksanen J, ter Braak CJF (2011) Testing the significance of canonical axis in redundancy analysis. Method Ecol Evol 2(3):269–277

Lenoir J, Gégout JC, Marquet PA, de Ruffray P, Brisse H (2008) A significant upward shift in plant species optimum elevation during the 20th century. Science 320:1768–1771

Liang EY, Shao XM, Eckstein D, Huang L, Liu XH (2006) Topography- and species- dependent growth responses of *Sabina przewalskii* and *Picea crassifolia* to climate on the northeast Tibetan Plateau. For Ecol Manag 236:268–277

Lioubimtseva E, Henebry GM (2009) Climate and environmental change in arid Central Asia: impacts, vulnerability, and adaptations. J Arid Environ 73(11):963–977

Lioubimtseva E, Cole R, Adams JM, Kapustin G (2005) Impacts of climate and land-cover changes in arid lands of Central Asia. J Arid Environ 62(2):285–308

Mitchell TD, Jones PD (2005) An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int J Climatol 25:693–712

Mukhamedshin KD (1977) Tien Shan juniper forests and their economic significance (Archevniki Tian'-Shanya I ikh lesokhoziaistvennoye znacheniye). Ilim, Frunze

NC Uzbekistan (2009) Second National Communication of the Republic of Uzbekistan under the United Nations framework convention on climate change, Tashkent

Neuwirth B, Esper J, Schweingruber FH, Winiger M (2004) Site ecological differences to the climatic forcing of spruce pointer years from the Lötschental, Switzerland. Dendrochronologia 21:69–78

Oberhuber W (2004) Influence of climate on radial growth of *Pinus cembra* within the alpine timberline ecotone. Tree Physiol 24:291–301

Oberhuber W, Kofler W (2000) Topographic influences on radial growth of Scots pine (*Pinus sylvestris* L.) at small spatial scales. Plant Ecol 146(2):229–238

Oksanen J, Blanchet G, Kindt R, Legendre P, Minchin PR, O'Hara RB, Simpson GL, Solymos P, Stevens M, Wagner H (2013) Package 'vegan'. R packag ver 254:20–8

Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. Nature 421:37–42

Pederson N, Cook ER, Jacoby GC, Peteet DM, Griffin KL (2004) The influence of winter temperatures on the annual radial growth of six northern range margin species. Dendrochronologia 22:7–29

Pourtahmasi K, Parsapajouh D, Bräuning A, Esper J, Schweingruber FH (2007) Climatic analysis of pointer years in tree-ring chronologies from northern Iran and neighboring high mountain areas. Geoöko 28:27–42

Qin C, Yang B, Bräuning A, Sonechkin DM, Huang K (2011) Regional extreme climate events on the northeastern Tibetan Plateau since AD 1450 inferred from tree rings. Global Planet Change 75:143–154

Rinn F (1996) TSAPWin. Time series analysis and presentation for dendrochronology and related applications, RINNTECH, Heidelberg

Saiko TA, Zonn IS (2000) Irrigation expansion and dynamics of desertification in the Circum-Aral region of Central Asia. Appl Geogr 20(4):349–367

Savitsky AG, Schlüter M, Taryannikova RV, Agaltseva NA, Chub VE (2007) Current and future impacts of climate change on river runoff in the Central Asian river basins. In: Pahl-Wostl C, Kabat P, Moeltgen J (eds) Adaptive and integrated water management—coping with complexity and uncertainty. Springer, Berlin

Schiemann R, Lüthi D, Vidale PL, Schär C (2008) The precipitation climate of Central Asia—intercomparison of observational and numerical data sources in a remote semiarid region. Int J Climatol 28(3):295–314

Seim A, Kerstin Treydte K, Trouet V, Fank D, Fonti P, Tegel W, Panayotov M, Fernández- Donado L, Krusic P, Büntgen U (2014) Climate sensitivity of Mediterranean pine growth reveals distinct east–west dipole. Int J Climatol. doi:10.1002/joc.4137

Shahgedanova M (2002) Climate at Present and historical past. In: Shahgedanova M (ed) The physical geography of Northern Eurasia. Oxford University Press, Oxford, p 571

Solomina O, Maximova O, Cook E (2014) *Picea schrenkiana* ring width and density at the upper and lower tree limits in the Tien Shan mts Kyrgyz republic as a source of paleoclimatic information. Geogr Environ Sustain 1(7):66–79

Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (2013) Climate change 2013: The physical science basis. Intergovernmental Panel on Climate Change, Working Group I Contribution to the IPCC Fifth Assessment Report (AR5)

Tranquillini W (1964) The physiology of plants at high altitudes. Annu Rev Plant Physiol 15:345–362

Vaganov EA, Schulze ED, Skomarkova MV, Knohl A, Brand WA, Roscher C (2009) Intra- annual variability of anatomical structure and δ13C values within tree rings of spruce and pine in alpine, temperate and boreal Europe. Oecologia 161(4):729–745

van der Schrier G, Briffa KR, Jones PD, Osborn TJ (2006) Summer moisture variability across Europe. Int J Climatol 19:2818–2834

van Oldenborgh GJ, Burgers G (2005) Searching for decadal variations in ENSO precipitation teleconnections. Geophys Res Lett 32(15):L15701. doi:10.1029/2005GL023110

Wigley TML, Briffa KR, Jones PD (1984) On the average of correlated time series, with applications in dendroclimatology and hydrometeorology. J Clim Appl Meteorol 23:201–213

Winter M-B, Wolff B, Gottschling H, Cherubini P (2009) The impact of climate on radial growth and nut production of Persian walnut (*Juglans regia* L.) in Southern Kyrgyzstan. Eur J Forest Res 128:531–542

Zhang T, Yuan Y, He Q, Wei W, Diushen M, Shang H, Zhang R (2014) Development of tree- ring width chronologies and tree-growth response to climate in the mountains surrounding the Issyk-Kul Lake, Central Asia. Dendrochronologia 32(3):230–236