

Divergence in responses of juniper tree rings to climate conditions along a high-mountain transect in the semi-arid Fann Mountains, Pamir-Alay, western Tajikistan

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ABSTRACT

This paper reports on a detailed dendrochronological and dendroclimatological study of juniper trees (*Juniperus seravschanica* Kom. and *J. semiglobosa* Regel), sampled at seven sites having different elevations (2200 – 3100 m) and exposures (south-north) in the Pamir-Alay mountains, north-western Tajikistan. We developed seven new, well-replicated ring-width chronologies extending back over the last 219–1320 years. Our results confirm that the main climate factor influencing radial growth in this semi-arid region is variability in precipitation. However, they also indicate that there is a divergence in dendroclimatic responses between low- and high-elevation sites, where different limiting factors play a dominant role. The radial growth of *J. semiglobosa* at the uppermost treeline locations is the most sensitive to winter precipitation. Tree-ring formation in *J. seravschanica* at low-elevation sites is strongly limited by spring-summer drought conditions and by winter temperatures. The results of PCA analysis indicate that the relationships between growth and climate are linked more to elevation than to exposure. It was also found that negative growth extremes at low elevation sites may be triggered by strong dust storm events. Our findings clearly show that precisely planned selections of topographically differentiated sites, including elevation and exposure, are crucial for the possible reconstruction of different climatic elements in the high mountains of Central Asia for the last hundreds to thousands of years.

1. Introduction

The high mountains of Central Asia are a key region as regards the study of past climate variability. Unfortunately, the few time series of meteorological observations currently available for this region are short and incomplete, making it difficult to evaluate the full range of climate variability over the last hundreds to thousands of years or in some cases even at the decadal time scale. Therefore, long-term climate series based on high-resolution proxy data need to be developed. A growing number of studies from Central Asia have demonstrated that this region has a great potential for dendroclimatic studies owing to the existence of extensive forest areas supporting long-lived species such as *Juniperus polycarpus*, *Cedrus deodara* and *Pinus gerardiana* in the Himalayas (e.g. Bhattacharyya et al. 1988, Yadav 2009), *Sabina przewalskii* on the

Tibetan Plateau (e.g. Brauning 1994, 2001, Zhang and Qiu 2007), *Juniperus turkestanica* in the Karakorum Mts (e.g. Bilham et al. 1983, Esper 2000) and *Juniperus semiglobosa* in the Pamir-Alay Mts (e.g. Mukhamedshin and Talancev 1982, Opała et al. 2017, Opała-Owczarek et al., 2018b). A recent tree-ring-based reconstruction of precipitation for the past two thousand years revealed a series of dry and wet stages in Central Asia, leading to the rapid transformation of the hydrological regime as well as the rise and fall of civilizations (Owczarek et al. 2018, Opała-Owczarek and Niedźwiedź 2019, Opała-Owczarek and Owczarek 2019, Chen et al. 2021).

In general, trees growing at the margins of their ecological range exhibit the strongest relationships between climate and tree radial growth. Fritts (1976) reported that the upper forest limit is controlled primarily by low air temperatures, whereas precipitation is more

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influential at low elevations. However, recent studies from Central Asia are inconsistent with the general principles of dendroclimatology, implying that these relations are much more complex and dependent on local conditions. Many studies have demonstrated that precipitation is the most important factor limiting tree radial growth along the entire elevation gradient, also near the treeline under arid/drier site conditions (e.g. Wang et al. 2010, Liu et al. 2006, Yang et al. 2013, Qin et al. 2013, Panthi et al., 2020). By contrast, results obtained for altitudinal gradients on the north-eastern Tibetan Plateau indicate that temperature is the major limiting factor for tree-growth at the upper treeline, although precipitation is the major limiting factor at lower elevation belts under the semi-arid site conditions of the Qaidam Basin (Yin et al. 2016).

Owing to the broad diversity of landscape and ecological conditions, many signs of climatological, geomorphological, meteorological and geophysical threats can be found in the trees growing in the mountains of Central Asia (Esper et al. 2002, Solomina 2002, Opała et al. 2017, Owczarek et al. 2017, Chen et al. 2022). Juniper trees are one of the most common species in the semi-arid Pamir Alay (Rahmonov et al. 2017). Dendroclimatological and dendrogeomorphological research carried out to date has demonstrated that junipers are highly sensitive to changes in the natural environment (Opała et al. 2017, Owczarek et al. 2017, Opała-Owczarek and Niedźwiedź 2019, Chen et al. 2019, Opała-Owczarek 2019, Opała-Owczarek and Owczarek 2019). It has to be borne in mind, however, that those studies took place at single sites without any differentiation of altitudinal, climatic or landscape transects. Although several individual site-specific studies have already been conducted across the Pamir-Alay mountains, the novel aspect of the present study is the analysis of climate sensitivity along an elevational transect. The elevational transect approach provides an opportunity for studying vegetation dynamics and tree growth responses to climate change, as climatic variables vary with altitude (Körner, 2007; Fan et al., 2009; Panthi et al., 2018, 2020). A better understanding of tree species'

growth responses to climate across differing elevations is important for robust reconstructions of past climates, appropriate forest management and conservation (Zhang et al. 2012, Gaire et al. 2020). Some recent tree-ring studies along elevational transects from High Asia were carried out in the Tibetan Plateau (e.g. Liang et al. 2010, Lyu et al. 2016, Yin et al. 2016), the Himalayas (e.g. Panthi et al. 2020, Gaire et al. 2020), the Hengduan Mountains (e.g. Panthi et al. 2018), the Tianshan Mountains (e.g. Qi et al. 2015) and the Qilian Mountains (e.g. Yang et al. 2013). Detailed investigations are needed for different mountain massifs, especially as there is a knowledge gap regarding growth-climate relationships at different elevations in various regions.

This study investigated the complex influences of elevation, aspect and site characteristics on climate-tree growth relationships based on samples of Himalayan pencil juniper (*Juniperus semiglobosa* Regel) and Afghan juniper (*Juniperus seravschanica* Kom.) collected along an altitudinal gradient in the Zarafshan Range, in the western Pamir-Alay, where climate variability strongly differs within short distances due to the extremely high and complex topography.

The objectives of this study were: (1) to develop several tree-ring chronologies at different elevations and slope exposure, (2) to analyse the tree-ring chronology parameters within the high-elevation network, (3) to investigate their relationships with precipitation and temperature, (4) to assess variations in climatic sensitivity and detect which sampling situations permit maximization of the climatic signal.

2. Study area

2.1. General description

This study was conducted in the Zarafshan (Zeravshan) Range, in the western Pamir-Alay Mts. (NW Tajikistan) (Fig. 1). The Pamir-Alay forms the transition zone between the Pamir and Tian-Shan Mountains. This

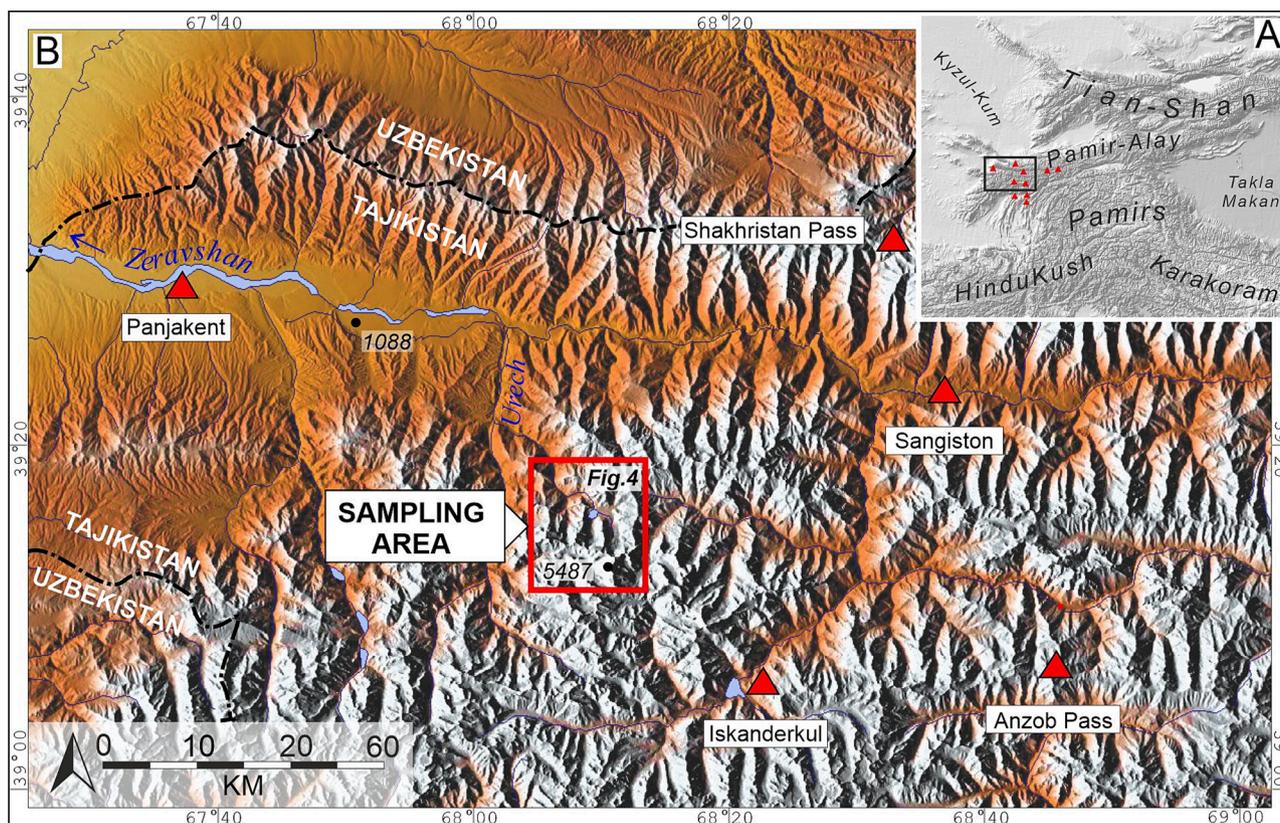


Fig. 1. (A) The study area within mountain systems in Central Asia and location of 10 meteorological stations used in this study (red triangles). (B) Location of the dendrochronological sampling area and nearest climate stations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mountain system used to be known as the Alai or Gissar-Alai mountains (Antropov 1959). To the west the mountains border the mid-latitude Central Asian desert system (Kyzyl-Kum, Kara-Kum) and to the east, through the tectonic Alay Valley and northern Pamir (trans-Alay), they adjoin the Tarim Basin and the Taklamakan Desert (Fig. 1). Even though the mountains were finally uplifted during the Alpine orogeny, neotectonic processes continue to be recorded (Ivanova and Trifonov 2005). This region is characterized by a high level of seismicity, which is a consequence of its position in the vicinity of the frontal Pamir thrust system (Schurr et al. 2014, Owczarek et al. 2017). The research area is located in the western part of the Zarafshan Range known as the Fann Mountains (Chimtarga Peak – 5487 m).

Lower Silurian and Middle Devonian rocks, mainly limestones, dolomites and different types of schists predominate here (Antropov 1959, Vlasov et al. 1991, Vinnichenko and Tadzhibekov 2010). The research area consists of a high-mountain relief characterized by steep slopes and deep valleys, which are drained by the rivers belonging to the Zarafshan River catchment area (Fig. 1). The highest parts are occupied by small valley and cirque glaciers. The lateral and frontal moraines lying at different altitudes along the main valleys dissecting the massif provide evidence of intensive glacial processes during the Pleistocene.

The Zarafshan Mountains are characterized by large differences in altitude within relatively small distances. This undoubtedly has a large impact on pedodiversity and its mosaic-like character. High steep ridges and deep narrow valleys foster processes of intense downwash, which destroy the soil cover down to the bedrock. Specific physiogeographic features of the research area determine the formation of distinctive types of mountain soils (Kuteminskiy and Leontyeva 1966).

Four vegetation zones can be distinguished in the Zarafshan geobotanical region: (1) a zone of sage and saltwort deserts with dominant *Artemisia tenuisecta* and *A. porrecta* (1200–2000 m a.s.l.), 2 – a zone of sage desert and juniper forests, mostly *Juniperus seravschanica* (2000–2700 m a.s.l.), 3 – a zone of steppe juniper forests and thorny vegetation with *J. turcestanica*, *Festuca sulcata*, *Onobrychis echidna* (2700–3400 m a.s.l.), 4 – a zone of cushion plants and thorny vegetation (3400–4000 m a.s.l.) with *Oxytropis savellanica*, *Potentilla flabellate* and many species from the genus *Cousina* (Zapryagaeva 1976, Rahmonov et al. 2017).

2.2. Climatic conditions

The Pamir region lies in the transition zone between two atmospheric circulation systems, the Westerlies and the Indian summer monsoon (ISM) (Lydolph 1977, Holmes et al. 2009, Wang et al. 2010), albeit a more distinct influence exerted by the Westerlies in the Pamir region since the Late Holocene has been proven (Lei et al. 2014). Weather conditions during winter are influenced by the Asiatic High inducing a north-easterly flow of air across Central Asia, while in summer the south-eastern periphery of the Azores High causes a northerly and north-westerly flow of air. The high mountain ranges of Pamir-Alay and trans-Alay in northern Tajikistan create significant barriers to air flow (Lydolph 1977).

Extreme local climatic contrasts occur depending on altitude, landforms, the forest canopy, cold-air pooling and local water bodies. The climate conditions of the Zarafshan Range are diverse, depending on the altitude, which rises to 5489 m on the Chimtarga Peak in the Fann Mountains. Above the upper tree line of juniper forests (about 3300 m), the climate is typical of mountain tundra (ET type) according to the Köppen and Geiger climate classification (Kottek et al. 2006). In the lower parts of the mountains, the climate is cold temperate, with wet springs and dry summers (Dsb type). Parts of the valley bottoms and mountain foreland experience a cold, semi-arid steppe climate (BSk) (Panjakent, 1016 m) with an annual precipitation of <400 mm and four extremely dry months (June–September). The climate of the lowest part of the region (Dushanbe, 800 m; Samarkand, 724 m) is similar to that of Mediterranean regions (Csa) with very hot, dry summers.

Mean temperatures are c. 15–16 °C (max. 25–26 °C) in summer and from –5 to –8 °C (min. –25 to –26 °C) in winter. There are 90–100 days a year without ground frost or air frost (Sadikov, 2012). The warmest month of the year is July (less frequently August). The vertical gradient of the mean warmest month temperature is –0.69 °C/100 m and is larger than the yearly gradient. The temperature in July ranges from c. 21 °C at 1700 m to 10 °C at 3300 m near the upper juniper forest tree line (Fig. 2).

The mean yearly precipitation for the area in question is 400–500 mm on peaks and slopes at altitudes of c. 3000–3400 m (418 mm on the Anzob Pass 3373 m). In basins and deep valleys (altitudes from 2200 to 2500 m), the precipitation drops to 250–300 mm. Most precipitation occurs in spring (60–70 mm in April or May), while winter snowfall is minimal (Fig. 2).

The results of the trend analysis presented by Aalto et al. (2017) show that the mean annual temperatures have risen in Tajikistan since the 1930 s, the average rate of change being approximately 0.1 °C per decade. For precipitation, only a weak signal of change over the entire country could be detected. In NW Tajikistan a weak wetting trend is present, significant only at two stations (Aalto et al. 2017). The CRU gridded data show that the temperature trends have increased significantly in both summer and winter (0.18 and 0.25 °C/decade), and also that the precipitation trends have increased significantly (12 mm/decade) in winter; there is no well-defined trend in the case of summer precipitation data, however (Fig. 1 Supplementary Materials). Comparison of temperature grid data (NW Tajikistan) with station data (Anzob Pass meteorological station, calculations made by Gulakhmadov et al. 2020) indicates increasing trends for annual grid data, but an insignificant trend for the annual temperature measured at the Anzob station, which has even become a decreasing one over the last three decades. For annual precipitation, the trend is increasing for gridded precipitation (23 mm/decade), but decreasing for station data (-4.8 mm/decade). These data are purely informative and should be treated with some caution. It should be noted that the analysis of trends may be subject to an unknown error resulting from the unavailability of meta-data, limited maintenance of the meteorological network, and the failure to homogenize the station data (Aalto et al. 2017). Also, trends in precipitation based on modelled grid data for this area are highly uncertain and subject to considerable variation, depending on microclimates and the period covered by the records (Climate Risk Country Profile: Tajikistan, 2021).

3. Materials and methods

3.1. Tree-ring material

Mountain forests in the Zarafshan Range consist of *Juniperus seravschanica* and *Juniperus semiglobosa* – the occurrence of which depends on the altitude. *Juniperus seravschanica* (Afghan juniper) is usually 5–10 m tall with a dense crown, forming juniper woods in the lower and middle parts of the timber zone (2000–2700 m), in pure stands or mixed with *J. semiglobosa*. *Juniperus semiglobosa* (Himalayan pencil juniper) is a tree reaching heights of 10 m, with a rather loose and narrow, weeping crown. This species sometimes grows singly, sometimes with other juniper species, forming open juniper woods on dry mountain slopes, moraine deposits and lakeshore terraces. It occupies the higher parts of the timber zone up to the tree line (2500–3300 m) (Fig. 3A,B) (Adams 2014).

In 2014 and 2015 seven sampling sites for detailed research were established along an altitudinal gradient from 2200 to 3100 m (Table 1, Figs. 3, 4). In the very diverse terrain of the Urech River valley, five north-facing sites were selected at 100–250 m height intervals, depending on local conditions and the availability of woody material (Fig. 3C,D,E,F Fig. 4A,B). Additionally, at two elevations – 2500 and 3000 m – trees from slopes with opposite exposures (south-facing vs north-facing) were also sampled (see: Profile 1 and 2 on Fig. 4A,B). The

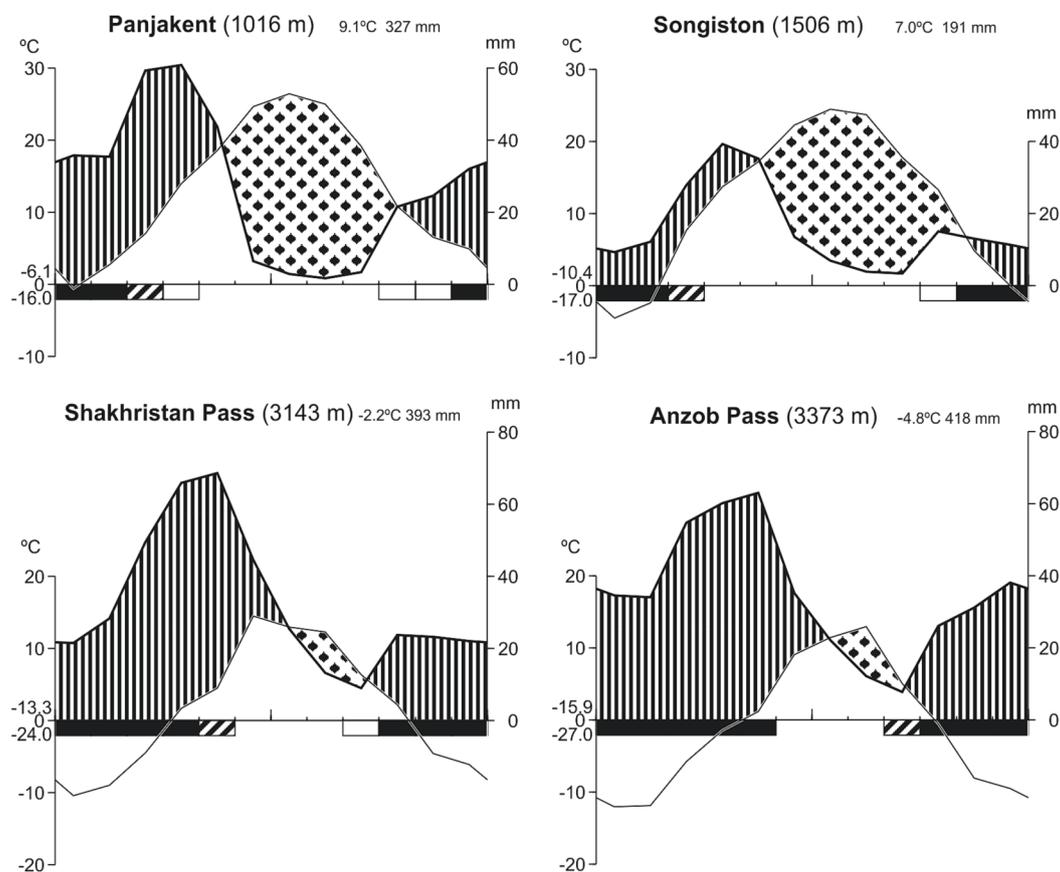


Fig. 2. Walter-Lieth climate diagrams of four Tajik meteorological stations (1951–1990): Panjakent, Songiston, Shakhristan Pass, and Anzob Pass showing differences in the course of basic meteorological elements and representing typical climate conditions on different altitudes from 1000 to 3330 m asl in the studied region. The temperature course is marked by normal line, and precipitation by bold line. Dotted areas indicate arid period, lined areas indicate humid period. Months are shown along the x-axis, where black box indicate months with a mean daily minimum temperature below 0 °C, hatched box for a “definite” frost, white bar for “likely” frost. The temperature values on the left side of the graph indicate mean daily temperature of the coldest month, and absolute minimum temperature.

uppermost sites (sites 5, 6, 7) were situated within the extensive Kulikalon basin, enclosed from the south by the rim of the Chimtarga Peak (Fig. 3A,B; Fig. 4). The basin consists of two large glacial cirques and a few smaller ones, the bottoms of which are partially filled by moraine lakes. Below the basin, where research sites 1, 2, 3 and 4 were situated, the Urech flows along a typical U-shaped valley separated by Pleistocene frontal moraines (Fig. 4B).

One or two cores were extracted at breast height from each tree using 5.15 mm diameter increment borers. At least 30 cores were taken from each site, yielding a total of 261 samples. Table 1 provides general information relating to the sampling sites.

All the samples were processed using standard procedures: air drying, mounting the cores into wooden blocks and polishing the surface (Stokes and Smiley 1968). Next, the cores were scanned in a high-definition optical scanner EPSON Perfection V700 Photo Scanner (with an optical resolution 2400 DPI) and the annual ring widths (TRW) were measured using semi-automatic image-analysis software WinDendro (Regent Instruments Inc. 2006). Cross-dating was performed among samples of a given site and the results confirmed using COFECHA software (Grissino-Mayer 2001). TRW series were standardized and transformed with ARSTAN software (Cook and Holmes 1986). The raw data were fitted to negative exponential curves or linear regression lines to remove growth trends. The measured values were divided by the fitted curve values to obtain standardized series. Autoregressive modelling was used to remove high autocorrelation within series. Chronologies were averaged on a site-by-site basis using the biweight mean. Standard and Residual versions of the chronologies were used in the subsequent analysis. Furthermore, descriptive statistics were

calculated for the chronologies: expressed population signal (EPS), average inter-series correlation (Rbar), mean sensitivity (MS), first-order serial autocorrelation (AC1) and percentage variance explained by the first principal component (PC1).

The correlation matrix of the TRW indices for all sites over a common 100-year period (1915–2014) was examined to quantify the similarities in the signals. To elucidate patterns in the tree-ring chronologies at seven different sites, which are expected to reflect the variety of climate influences, principal component analysis (PCA) was used as a clustering technique. PCA was successively computed on the tree-ring chronology indices matrix for the 100-year period common to all populations. These components were rotated according to the varimax criterion. A varimax rotation was used to interpret the individual site loadings on each eigenvector. The normalized varimax method of rotating eigenvectors preserves the orthogonality of the factor loadings but makes them easier to interpret (Leal et al., 2007). Additionally, correlations between parameters, i.e. number of years, mean growth rate, mean sensitivity, and mean series intercorrelation and elevation were calculated and illustrated graphically.

For analysing extreme years, those years exceeding the threshold of one standard deviation were selected from TRW indexed series (± 1 SD). Next, we focused on the 10 most extreme years (characterized by the greatest deviation), which we tried to explain by extreme meteorological conditions. Taking into account the possible impact of dust storm events on tree rings, we compared the meteorological data concerning dust storms, dust hazes and the horizontal visibility range with growth-ring chronologies within our transect. In the next step, we constructed a composite chronology for low- and mid-elevation sites, which we



Fig. 3. General view of the sampled juniper trees in the study sites: (A) – the uppermost site near Maria Glacier (Site 7_KGL), (B) – view on the Bib-Jihonat Lake and Chimtarga Peak with location of the Site 6_KBJ and Site 5_KPU, (C) – dry open forest in the southern slope of the Urech river valley (Site 4_ISP), (D) – relatively wet juniper forest community near Kuczurak Lake (Site 3_KUC), (E) – juniper forest in the middle (Site 2_BAC) and (F) the lowest part of the study section of the Urech river valley (Site 1_IGU).

compared with dust storm events by means of correlation analysis. Statistical analyses were performed with the STATISTICA 13 software (TIBCO Software Inc. 2017).

3.2. Meteorological data

Weather data were obtained from five meteorological stations: Panjakent (1016 m), Sangiston (1502 m), Iskanderkul (2204 m), the Shakhristan Pass (3143 m) and the Anzob Pass (3373 m). These were the closest meteorological stations to the study sites and at a similar altitude (Fig. 1). Nevertheless, only the climate records from the Anzob Pass Station (50-year reliable period 1941–1990) were used for the dendroclimatological analysis, because large amounts of data were missing for the other stations. The limited availability of meteorological data is

due to the political situation in the region. From May 1992 to July 1997 the Tajik Civil War took place, as a result of which gaps appeared in the meteorological measurements for this period. In subsequent years, too, the data are discontinuous or inhomogeneous. For comparison and validation of the dendroclimatological analysis, we used CRU v. 4.06 mean monthly gridded temperatures and mean precipitation totals (Harris et al., 2020) covering NW Tajikistan (latitude-longitude grid: 68.25°–39.25°). With regard to the proximity to the sampling sites, elevation, and extent of climate records, we also selected data from 10 other meteorological stations (Fig. 1) (1930–1990) in order to compile a regional precipitation series (Opala-Owczarek and Niedźwiedz 2019) which was then used for comparisons with extreme years. The monthly mean, maximum and minimum temperatures and precipitation totals were obtained from the Central Asia Temperature and Precipitation

Table 1
General description of the sampling sites along the elevational gradient in the Urech Valley.

Site code	Site name	Elevation (m a.s.l.)	Geographical coordinates	Slope inclination (°)	Aspect	Number of cored trees	Site characteristics
1_IGU	Iguroz	2200	39°16'58.47 68°07'04.85	35,2	N	40	<i>Type of soil:</i> Cambisols, brown mountain soil <i>Relief:</i> straight slope without traces of mass movements <i>Geology:</i> Silurian limestones and dolomites covered by Holocene coarse-grained slope deposits <i>Type of forest:</i> dense with domination of <i>J. seravshanica</i>
2_BAC	Base Camp	2300	39°16'13.45 68°08'02.83	30,4	N	30	<i>Type of soil:</i> Cambisols, brown mountain soil <i>Relief:</i> lateral moraine with large angular rock blocks <i>Geology:</i> Silurian limestones covered by Pleistocene unsorted glacial deposits <i>Type of forest:</i> dense with domination of <i>J. seravshanica</i>
3_KUC	Kuczurak Lake	2500	39°15'43.44 68°08'02.46	28,9	N	35	<i>Type of soil:</i> Cambisols, brown mountain soil <i>Relief:</i> steep stable slope with inactive erosional channels <i>Geology:</i> Silurian schists, limestones, dolomites covered by Holocene coarse-grained unsorted slope deposits <i>Type of forest:</i> open with domination of <i>J. seravshanica</i>
4_ISP	Isputa	2500	39°16'54.96 68°08'29.22	27,8	S	40	<i>Type of soil:</i> Cambisols, brown mountain soil <i>Relief:</i> stepped slope with flat and steep sections, small bedrock outcrops <i>Geology:</i> Silurian limestones, dolomites, schists covered by coarse-grained Holocene unsorted slope deposits <i>Type of forest:</i> open with domination of <i>J. seravshanica</i>
5_KPU	Kulikalon plateau	2850	39°15'12.55 68°11'33.69	2,3	N	46	<i>Type of soil:</i> Regosols, initial skeleton-humus soil <i>Relief:</i> ground moraine with irregular topography <i>Geology:</i> Silurian limestones and dolomites covered by Pleistocene unsorted glacial deposits with large rock blocks <i>Type of forest:</i> open with domination of <i>J. semiglobosa</i>
6_KBJ	Kulikalon Bibi-Jonat	3000	39°15'29.55 68°12'00.56	32,6	SW	30	<i>Type of soil:</i> Regosols, isolated initial skeleton-humus soil <i>Relief:</i> straight slope <i>Geology:</i> Silurian limestones and dolomites covered by Pleistocene and Holocene unsorted glacial and slope deposits <i>Type of forest:</i> open with domination of <i>J. semiglobosa</i> , tree line
7_KGL	Kulikalon glacier	3100	39°14'44.70 68°11'51.91	15,7	N	40	<i>Type of soil:</i> Regosols, isolated initial skeleton-humus soil <i>Relief:</i> degraded lateral moraine partly covered by talus cones deposits <i>Geology:</i> Devonian limestones covered by Pleistocene unsorted glacial deposits <i>Type of forest:</i> open with domination of <i>J. semiglobosa</i> , tree line

Database (Williams and Kononov 2008). Besides temperature and precipitation datasets, Palmer Drought Severity Index (PDSI) data were employed to detect whether regional moisture conditions influenced tree-ring growth. Pearson's correlation analyses were used to explore the climate-growth relationships. A 99 % confidence level criterion was used to determine the statistical significance of the correlations. These analyses between residual tree-ring chronologies and climate variables were examined for 15 months beginning in June of the previous growth year to August of the following growth year. Calculations were also made for grouped months and seasons. For seasons, only the results with the highest correlations are presented, different for temperature and precipitation. For the sake of clarity, not all the results are given in the text. Data on dust storms, dust haze and horizontal visibility range were taken from the Agency on Hydrometeorology of Tajikistan, after Abdullaev and Sokolik (2019) and the Ogimet database (Valor and López 2017).

4. Results

4.1. Tree-ring chronologies

The tree-ring material from 261 trees enabled the construction of seven site chronologies from sites located along the elevational transect (Table 2, Fig. 5). Three chronologies from the highest-altitude sites covered more than 1000 years. The longest chronology was built for the 7_KGL site spanning 1320 years, from A.D. 696 to 2015. Chronologies from mid- and low altitudes (2200–2500 m) had a shorter time range,

spanning about 100–200 years. Junipers from the lowest site had the widest annual rings, while those from the highest sites had the slowest growth rate resulting from the exceptional age of the trees. The age of the trees, and thus the average width of increments, correspond strictly to the elevation, as can be seen in Fig. 6. Other parameters, like sensitivity, do not seem to be strictly related to elevation.

Comparison of the long-term variations of the seven chronologies yielded a number of similarities and differences. The main similarities are discernible in the periods of slow growth, i.e. the first half of the 20th century, the 1860 s and the 1640 s, and of fast growth, i.e. the end of the 19th century, the 1790 s and the second half of the 17th century. Interestingly, the period of cooling known as the Maunder Minimum (1645–1717) was not conspicuous in these chronologies: this period was characterized by a series of rather wide growth rings, whereas there was a distinct decline in growth only in the first decade of the 18th century. A significantly different course can be seen in the KPU chronology, which was characterized by slow growth in the first half of the 11th century, i.e. the period of the Oort Minimum. The drought-sensitive KBJ chronology is characterized by a series of very wide rings in the second half of the 11th century and very narrow ones during the second half of the 14th century, not present in other chronologies. Analysis of the early part of the chronology should be treated with caution as it is based on a small number of trees. However, such long records are unique and can be useful for later comparisons and further development of this research. In both the low- and high-elevation chronologies, the clear transition from very wide increments (especially evident for sites 3_KUC and 5_KPU) in the 1990 s to narrow rings in the successive years of the 21st

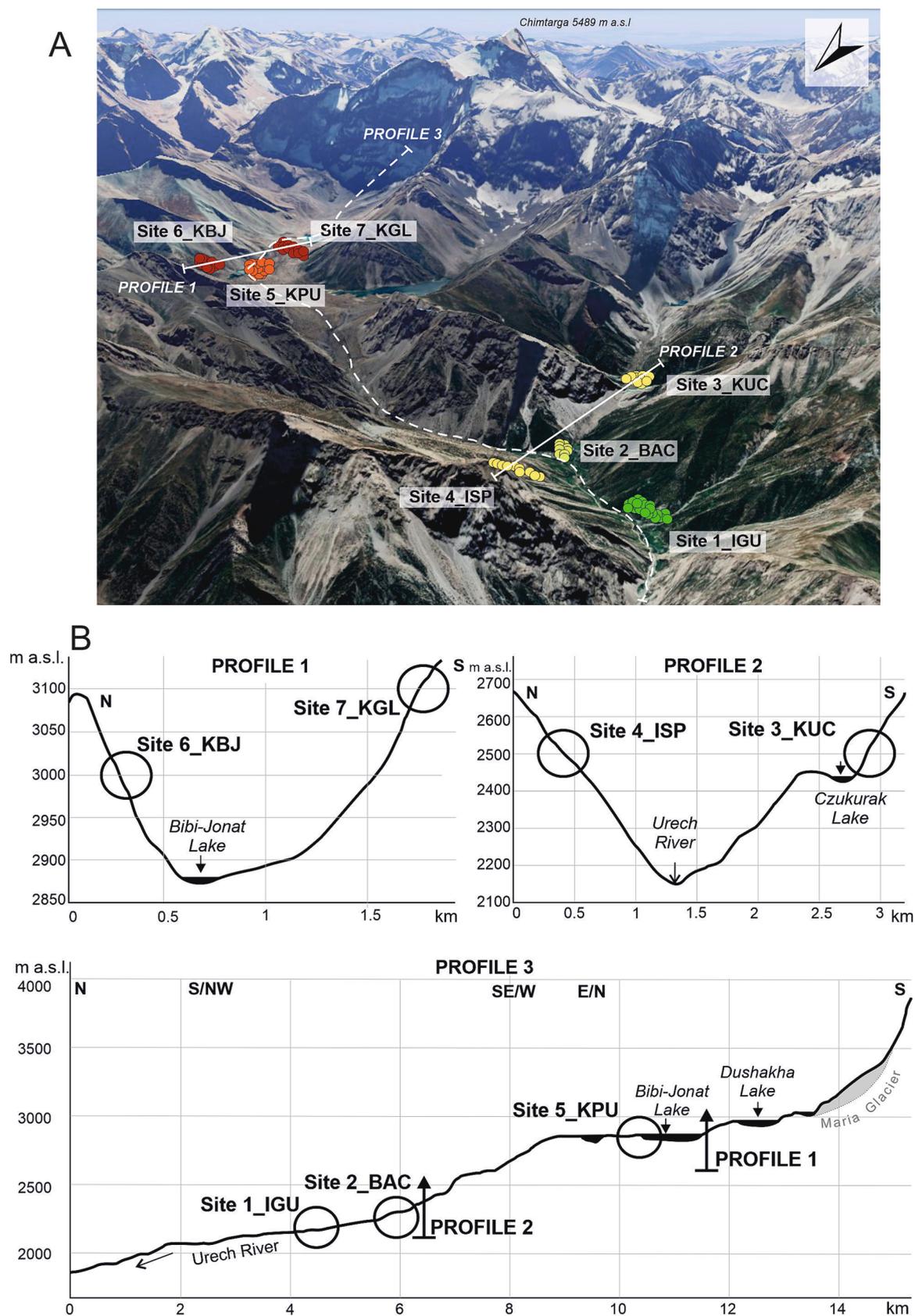


Fig. 4. (A) 3D visualization of the study area and location of the study sites in the upper part of the Urech River catchment along longitudinal and cross-sections profiles (source of map: Google Earth, Landsat/Copernicus, 2019), (B) Longitudinal and cross-sections profiles showing the location of sample collection points.

Table 2
Statistical characteristics of juniper tree-ring data along the elevational gradient.

Site code	Chronology length (number of years)	EPS greater than 0.85 since	Number of trees	Mean series length	Mean correlation between series	Average ring-width in mm (standard deviation)	Mean sensitivity	Percentage of absent rings	Autocorrelation Unfiltered / filtered
1_IGU	1795–2014 (219)	1879	20	103	0.598	1.47 (0.767)	0.295	0.00	0.295/-0.011
2_BAC	1796–2014 (218)	1903	20	124	0.536	0.98 (0.500)	0.312	0.81	0.668/-0.009
3_KUC	1597–2014 (418)	1880	17	209	0.560	0.66 (0.337)	0.363	0.00	0.603/ 0.005
4_ISP	1770–2014 (245)	1893	15	129	0.549	1.01 (0.474)	0.303	0.15	0.660/-0.014
5_KPU	900–2014 (1115)	1531	35	423	0.456	0.28 (0.128)	0.266	0.40	0.750/ 0.006
6_KBJ	1004–2014 (1011)	1506	23	364	0.542	0.35 (0.174)	0.270	0.68	0.794/ -0.013
7_KGL	696–2015 (1320)	1343	29	626	0.504	0.27 (0.125)	0.258	0.32	0.776/-0.006

century indicates deteriorating growth conditions. However, the magnitude of these changes is different at every site, particularly at the ISP site where, in contrast to the other sites, this transition is gradual and gentle (Fig. 5).

The correlation matrix between the seven chronologies for the well-replicated common 111-year period (1903–2014) reflects differences caused by vertical distance among sites and is associated with ecological differences (Table 3). The mid- and low-elevation juniper chronologies (1_IGU, 2_BAC, 3_KUC, 4_ISP) exhibit high between-site correlations ($r = 0.80$, $P < 0.01$). The three high-elevation site chronologies (5_KPU, 6_KBJ, 7_KGL) are more heterogeneous and display slightly lower correlations between sites. The correlation coefficient between the plateau (KPU) and the site with a northerly exposure (KGL) is higher than for the one with a southerly exposure (KBJ). Principal component analysis was performed for a deeper understanding of the observed clustering. The first principal component explained 56.8 % of the variance, whereas PC2 and PC3 contributed 23.4 % and 7.3 %, respectively. Ordination along the two axes revealed certain patterns: the low- and high-elevation chronologies are clearly separated. Four sites are loaded positively on the first component, showing that PC1 represents common information spanning the low elevation chronologies. The high elevation chronologies are grouped around PC2, and the two chronologies for the highest-altitude sites are especially consistent (Fig. 7).

4.2. Relationships between climate and tree-ring widths

The largest positive r -value (0.78, $p < 0.01$) was obtained between the chronology from site 6_KBJ and winter precipitation sums from the Anzob Pass station (Fig. 8), and the 5_KPU chronology was significantly positively correlated with winter precipitation (0.71, $p < 0.01$). A positive correlation with winter precipitation was found for another high-elevation site (7_KGL) and also the mid-elevation 4_ISP site, but the signal was less pronounced. At the low elevation sites 1_IGU and 2_BAC, spring/summer precipitation was important for growth, the highest correlation being with precipitation in June and July. Most outliers are the results for site 3_KUC, where there are no clear relationships between growth and precipitation, and weak correlations only for October and November of the previous growing season.

For temperature, we found particularly strong positive correlations between the low elevation sites 1_IGU, 2_BAC, 3_KUC and 4_ISP, and the temperature in December of the previous year. For the highest lying sites, the temperatures in November of the previous year and in June of the current year were more important. However, only at site 7_KGL was there a clear positive impact of the May–August temperature on growth. Furthermore, we found a significant impact of drought stress at site 4_ISP, where the previous September's precipitation had a positive impact but temperature a negative one. There was a similar dendroclimatic reaction at the two lowest sites (1_IGU and 2_BAC) in June and July, which indicates strong drought stress at those sites during the summer months (Fig. 8). We also investigated the correlations between seven chronologies and the seasonally averaged PDSI: the strongest one had mean May–September PDSI for sites 4_ISP and 6_KBJ which have a southern exposure.

Furthermore, in order to validate and support the results for recent decades, we checked climate-sensitivity analyses against gridded CRU data for the 74 years between 1941 and 2015 (Fig. 8D and 8F). The results of the correlation analysis betrayed slight differences between the data from the meteorological stations and the grid data. However, the general pattern of climate sensitivity was confirmed, i.e. the importance of seasonal (the previous June to the current August) sums of precipitation for juniper growth, and especially of winter precipitation for tree growth at high elevations. At low elevations, spring precipitation was important for growth. The same applies to the relationship between TRI and gridded mean temperature. Apart from minor differences (the importance of May temperatures instead of June/July temperatures at low elevations), the results for gridded data covering a more recent period confirm the results for a single station located in the sampling area. At low elevation sites, the correlation between TRI and December temperatures is positive but the influence of summer temperatures is negative. Summer temperatures have a positive influence at high elevation sites, with higher values at sites with a northern exposure.

4.3. Extreme weather conditions

According to our TRW chronologies, negative years in common were 2014, 2011, 2008, 2001, 2000, 1975, 1950, 1948 and 1939. There were some negative years in low- and mid-elevation chronologies (1944, 1957 and 1971), while others were present only in high-elevation chronologies (1979, 1987 and 2013). Analysis of post-1930 s meteorological data shows that most of the extremely negative years occurring in the TRW chronologies were caused by extremely dry conditions: 1939 (the driest year in the Zarafshan Mts., 50 % of the annual mean, the driest spring and previous June to the current September season), 1944 (a very dry summer), 1975 (a very dry summer), 1971 (the driest year in the Samarkand meteorological series), 2000 and 2001 (two consecutive very dry years, with an exceptionally dry spring, very dry summer and dust storm in 2001). Some of the negative years can be related to very low winter temperatures, as in 1957, 1984 and 2008 (the coldest winter in the last 25 years), or very low spring temperatures (1979). One of the negative years present in the high elevation chronologies, for which meteorological causes are hard to find, is 1987; in this case, the research should be extended to include a thorough analysis of daily data. Some of the extreme years occurred in the years in which strong dust storms were recorded: 1950, 1989, 2001, 2008, 2011. Analyses relating the occurrence of dust storms to ring-width indices showed a statistically significant negative correlation ($r = -0.45$, $p < 0.01$, over the period 1985–2014).

5. Discussion

5.1. Tree-ring chronologies

The slow growth of juniper trees at high altitudes is due mainly to their extremely old age, but as the trees in the different sites are not the same age, their growth rates cannot be compared. The decrease in

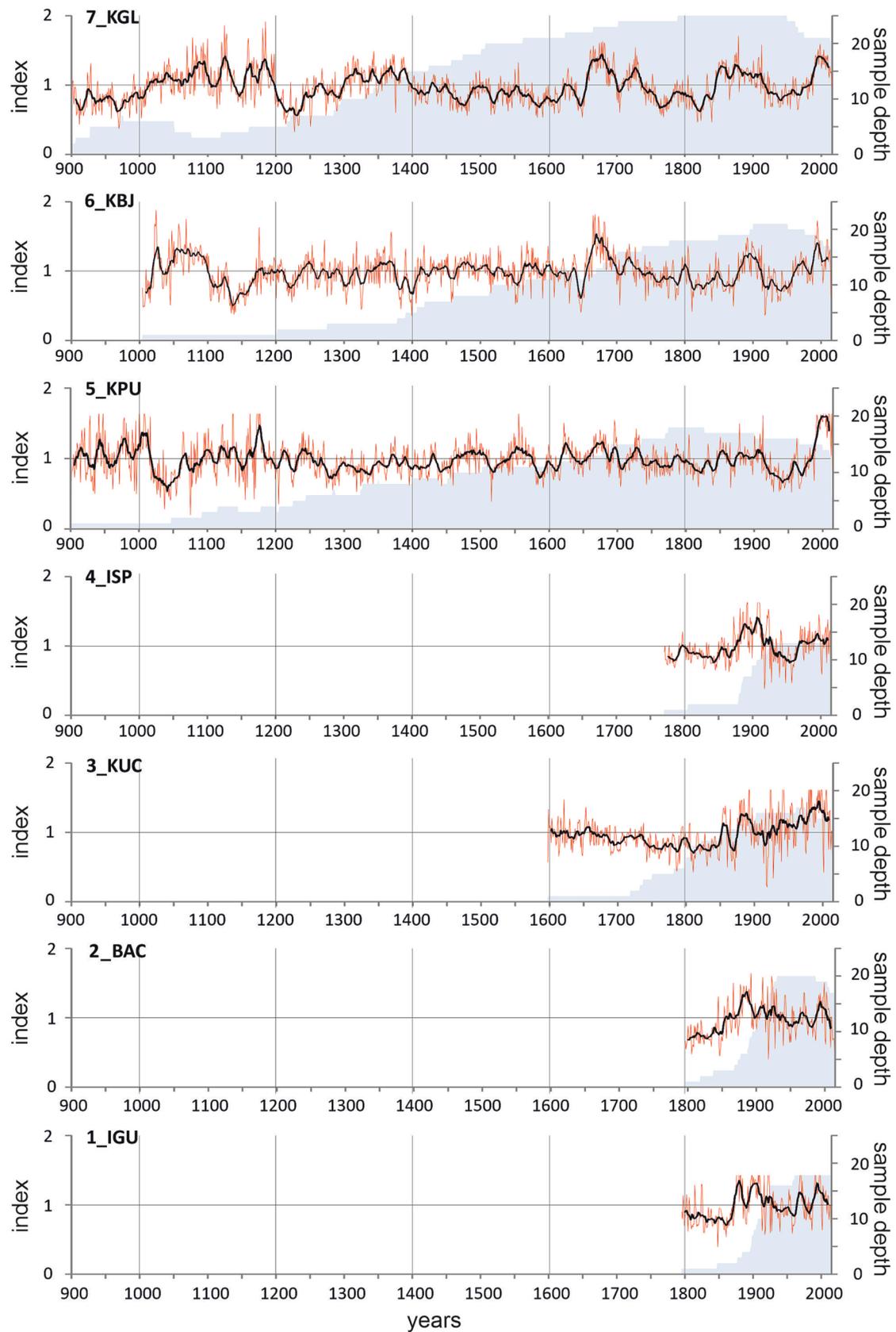


Fig. 5. Seven juniper tree-ring standardized chronologies (red line) with their associated 11-year running averaged series (black line) and corresponding samples replication, compiled with increasing altitude. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

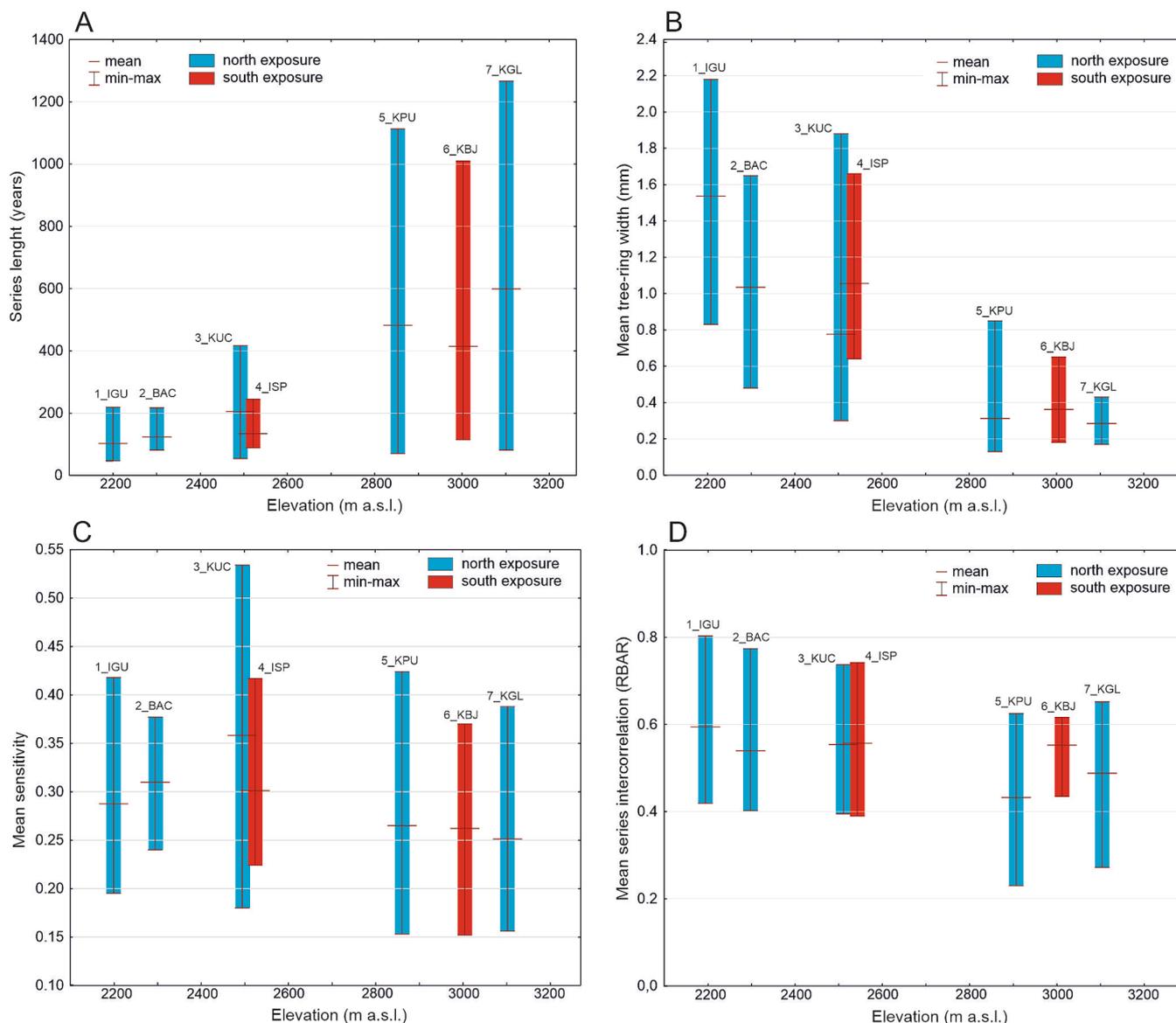


Fig. 6. Comparison of altitude-related effects on standardized tree ring series parameters: series length (A), mean tree-ring width (B), mean sensitivity (C) and mean series intercorrelation (D).

Table 3
Correlation matrix between the seven standard chronologies over the common reliable period of CE 1903–2014.

	1_IGU	2_BAC	3_KUC	4_ISP	5_KPU	6_KBJ	7_KGL
1_IGU	x	0,81	0,80	0,80	0,19	0,31	0,20
2_BAC		x	0,77	0,73	0,20	0,41	0,22
3_KUC			x	0,81	0,23	0,32	0,21
4_ISP				x	0,16	0,27	0,16
5_KPU					x	0,46	0,69
6_KBJ						x	0,40
7_KGL							x

average growth rates with increasing elevation is probably due to differences in tree age. Changes in the age of trees with altitude can be due to human influences. Trees from the lowest elevations are used for building and fuel, especially from sites near human settlements. It is also thought that wind exposure, shallow soil, low nutrient availability, low temperatures and limited access to water may retard physiological processes such as photosynthesis and respiration rates, which are responsible for tissue formation (Körner 2003, Liang et al. 2010).

In western Central Asia, cold and dry conditions near the upper treeline are responsible for the exceptional longevity of trees. Junipers are one of the species older than 1000 years. In addition to our research demonstrating junipers to be 1320 years old (Opala-Owczarek 2019), investigations of other 1000-year old specimens in different areas of high Central Asia clearly indicate that such ancient trees occur mainly at the upper edge of the forest (Maksimov and Grebenyuk 1972, Mukhamedshin 1978, Mukhamedshin, and Sarbaev 1988, Esper 2000, Bräuning 2001, Zang et al. 2003, Yadav et al. 2006). On the other hand, recent research on junipers in Tajikistan enabled a dendrochronological record covering the last few centuries to be constructed (Chen et al. 2019, Yang et al. 2020, Fan et al. 2021). This clearly indicates the importance of detailed research taking into account different locations, with their diverse topographic and topoclimatic conditions.

5.2. Climate sensitivity

It is generally hypothesized that tree growth at the upper treeline is normally governed by temperature whereas at the lower treeline it is precipitation-limited (drought signals embedded in tree-ring data) (e.g.,

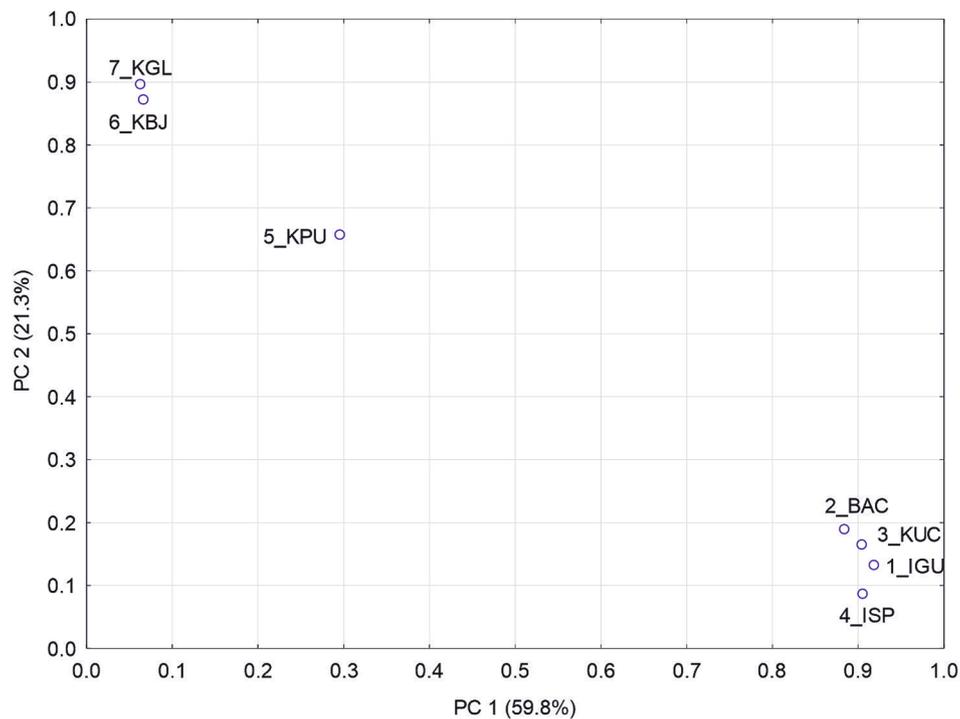


Fig. 7. Principal component analysis (PCA) (after Varimax rotation) scatterplots of the loadings derived from each standard chronology of the PC1 and PC2 over the common reliable period of CE 1903–2014. Axis labels report the percentage of variance expressed by each component.

LaMarche 1974, Fritts 1976). Our results do not fully confirm this concept. The implication of the present results is that moisture conditions are much more strongly correlated with growth-ring widths in junipers than temperature, particularly at high-elevation sites. Similar relationships have been demonstrated for junipers from arid and semi-arid regions of Central Asia (e.g., Tian et al. 2007, Davi et al. 2009, Liang et al. 2010, Liu et al. 2006, Yang et al. 2013, Gou et al. 2015), and were also confirmed in our recent and previous studies in the western Pamir-Alay (Opała et al. 2017, Opała-Owczarek and Niedźwiedz 2019). Following the general assumption of changing climate sensitivity with elevation, a clear difference can be found in the dendroclimatic reaction of trees at sites from high elevations and mid- to low-elevation sites in the studied region. Our study of junipers from low-elevation sites showed significant positive correlations with current June–July precipitation and a negative correlation with the temperatures in June–July. Chen et al. (2019) presented similar results from low-elevation juniper sites in the Kuramin Range (N Tajikistan) but highlighted a wider window of dendroclimatic response: April–July for precipitation and May–June for temperature. Also, Seim et al. (2016), investigating the dendroclimatic reaction of low-elevation junipers from the Turkestan range (E Uzbekistan), found a mixed signal: negative correlations for June–July temperatures, and positive associations with precipitation from April to September. For mid-elevation sites, the signal is more complex and strongly dependent on local site conditions. Analysis of *J. turkestanica* samples from Shahrstan (N Tajikistan) highlights the weak influence of the previous and current year's precipitation (Yang et al. 2020).

The results obtained by Fan et al. (2021) are more difficult to compare in terms of changing climate sensitivity with elevation, as those authors averaged site chronologies from the north-western Pamir-Alay from different elevations (1175–3249 m) into one chronology. However, the climatic signal obtained was similar to that in other low-elevation studies.

Further comparisons with high-elevation chronologies from the Pamir-Alay Mountains, Tajikistan, are impossible because there is no comparative material. The records from the Zarafshan Range are the

only high-elevation chronologies available for this area. The nearest high-elevation chronologies of juniper, developed by Esper (2000) and Esper et al. (2002, 2007) from Tien Shan and Karakorum, were not calibrated against climate because of the lack of reliable high-elevation observational data. It could only be confirmed that the junipers from the lower-elevation sites showed mixed growth-climate associations, while the annual growth of high-elevation trees was predominantly influenced by summer temperature (Esper et al. 2003), in contrast to the Pamir-Alay sites, where precipitation in winter is extremely important for growth at high elevation sites.

The latest dendroclimatic research along altitude transects in the European Alps emphasizes the advantage of maximum latewood density over tree-ring width, as its temperature sensitivity is more stable (Hartl et al. 2022). Future research in the Pamir-Alay Mountains should thus be expanded to include other tree-ring parameters.

5.3. Influence of topography

Our results of dendroclimatological studies from seven sites across the topographical transect clearly indicated the great importance of altitude, aspect and local ecological conditions on the climate response of junipers from the Fann Mountains. This issue was addressed earlier with respect to other regions across the world, e.g. the French Alps (Desplanque et al. 1999, Saulnier et al. 2019), the central European Alps (Oberhuber and Kofler 2000, Leonelli et al. 2009), the Tibetan Plateau (Liang et al. 2006), the White Mountains of California (Salzer et al. 2014), the eastern Carpathians (Romania) (Sidor et al. 2015), western Uzbekistan (Seim et al. 2016), south-western United States (Klesse et al. 2018), the Sudetes Mountains (Opała-Owczarek et al., 2018a), the Western Sayan Mountains (Zhirnova et al. 2020) and the Jalisco Mountains in Mexico (Guerrero-Hernández et al. 2022). On the other hand, the study by Yang et al. (2013) from the northern Tibetan Plateau demonstrated that altitude had no influence on tree growth-climate associations.

Our results from the Fann Mountains show clearly that appropriate site selection can emphasize the embedded climate signal in the tree-

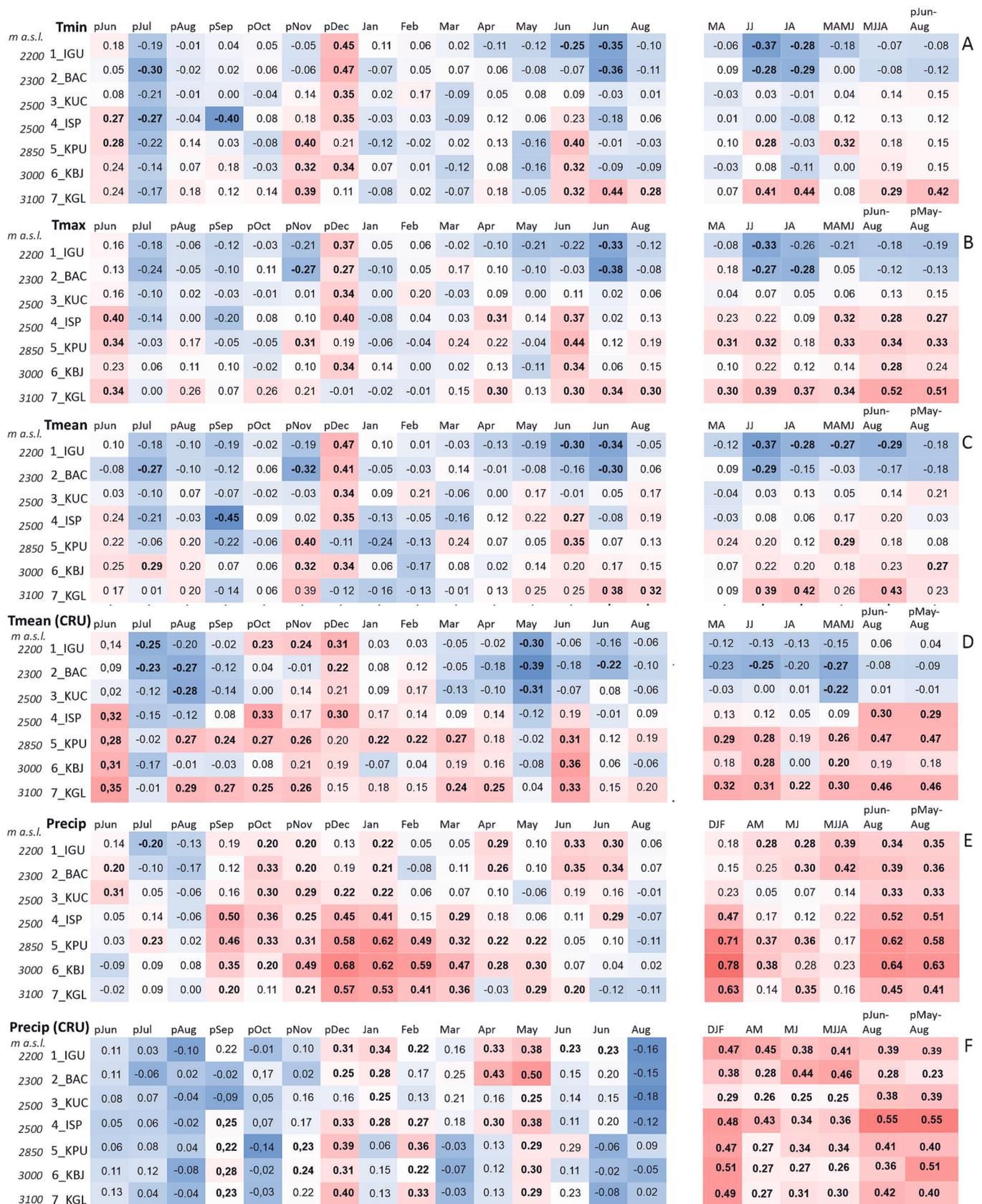


Fig. 8. Correlations between monthly and seasonal climate data and seven STD chronologies at different elevations. Presented correlations were calculated against data from Anzob Pass meteorological station (A, B, C, E) over the most reliable common period (1941–1990) and CRU data (D, F) over the period 1941–2015. The bold values denote the statistically significant values ($p < 0.05$). Numbers in the columns correspond to months of the previous (p) year and the growth year. Abbreviations in the column names on the right panel correspond to the grouped months).

ring width record. Junipers from the southern exposed mid-elevation site 4_ISP, which was exceptionally dry with shallow soil cover, exhibited the strongest drought response of all the sites investigated: the positive influence of precipitation in the previous year's September and the negative influence of temperature in the previous year's September ($r_{\text{Precip, pSep}} = 0.50$, $r_{\text{Tempmean, pSep}} = -0.45$) made the trees from this site suitable for a drought reconstruction. In contrast, trees from the opposite, northern exposed site 3_KUC from the same mid-elevation, displayed a very weak climatic signal, as this stand is not influenced by thermal or precipitation stress. Comparison of the southern (site 6_KBJ) and northern (7_KGL) aspects from high elevations shows that the differences in dendroclimatic signal become ever starker. The site exposed to the south showed the strongest, statistically significant, response to precipitation ($r_{\text{DJF}} = 0.78$) from the previous year's November to the current year's March. Because of the high level of solar radiation, trees growing on a steep south-facing slope combined a low water storage capacity with extreme sensitivity to precipitation, which is available mainly in the winter months. This was discussed in detail by Opala-Owczarek and Niedzwiedz (2019). At the same altitude but from a different aspect (N), juniper growth at 7_KGL is more dependent on summer and annual temperatures: as the strongest temperature signal is recorded within the investigated transect, a temperature reconstruction can be attempted (Opala-Owczarek 2019). Despite these significant effects of the local factors, our results of PCA grouping (Fig. 7) and correlation analysis (Fig. 8) for the entire transect indicate that the shift in relationships between growth and climate conditions is related more to elevation than to exposure.

5.4. The influence of dust storms

The arid zones of Tajikistan are constantly exposed to dust particles resulting from dust storm and dust haze events extending over thousands of kilometres. The well-known aridity of the Tajikistan region is a major factor promoting such storms. These are favoured by prolonged dry periods, the presence of loess soils in the foothills, loose sand in the desert and frequent gales. The main local sources of dust are the Kyzyl-Kum, Kara-Kum, and Aral-Kum Deserts (Romanov 1960, Mack-Cynon 1993). In Tajikistan, the so-called "Afghan", a strong dust storm that occurs in the warm seasons, has diverse impacts on the region's environment and climate, mainly by reducing direct solar radiation and thereby significantly attenuating photosynthesis in the vegetation. Dust

storms can reduce daytime temperatures by up to 16°C and increase night-time temperatures by up to 7°C compared to a clear day (Nazarov et al. 2016, Abdullaev and Sokolik 2019).

These additional factors were particularly important in the years when it was difficult to pinpoint extreme weather conditions that could have had an impact on the formation of narrow rings. The occurrence of some negative years, despite normal meteorological conditions during the year, can be associated with strong dust storms. This was the case in 1950, when the horizontal visibility range was <1 km for 16 % of the year. Also, in 2011, a "normal year", the slow growth rate could have been the result of a strong dust storm, which decreased the horizontal visibility range to 200 m in July-August 2011 (also in August 2010) (Fig. 9). After the end of a dust haze event, there is no rainfall and dust particles remain in the surface layer of the atmosphere for a long time, reducing photosynthesis (Farmer 1993). Other strong dust storms occurred in September 1989 and October 1990 (subsequently followed by precipitation), and in the summer-autumn of 2001 (the dust haze in Dushanbe persisted for a record 29 days), August 2008 and August 2009, when after prolonged dust haze episodes, dust particles were deposited on the ground without any precipitation. Interestingly, dust storm events are recorded as a sharp decline in the incremental curve only at low and mid-elevation sites; they are less pronounced at the highest sites above c. 3000 m (Fig. 9), as this may be related to the height of the inversion layer. The temperature inversion at an altitude of 3400 m (for Dushanbe) becomes more pronounced and "locks up" the aerosol distribution (Abdullaev and Sokolik 2019).

The statistically significant relationships and logical link between TRW and dust storm occurrence would allow the frequency of dust storms in western Tajikistan to be reconstructed back in time on the basis of tree-ring signals. However, these analyses require further detailed investigation of wood formation. To the best of our knowledge, the only study which reports on the effect of dust storms on growth rings and the anatomical properties of wood relates to Persian oak from Iran. Najia and Taherpoura (2019) demonstrated a clear reduction in annual ring width in simulated conditions within a dust chamber. Cambial activity and wood cell formation are closely related to the accessibility of photo-assimilates. By inducing environmental stresses such as dust storms, the photosynthesis rate is decreased and assimilate translocation is adjusted, which ultimately impacts on cambial activity (Eilmann et al. 2006). Dust deposition affects the availability of light for photosynthesis and clogs the stomata for air exchange, thus increasing the level of stress

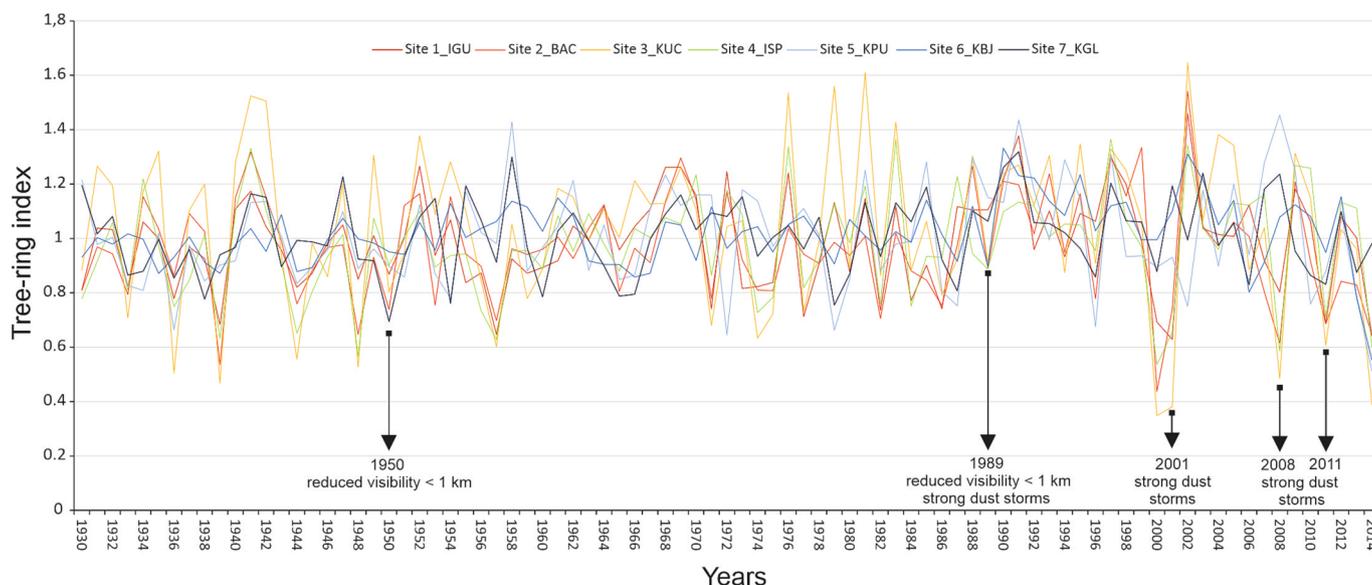


Fig. 9. Linkage between the occurrence of strong dust storms and negative extreme years at seven altitude chronologies from Pamir-Alay, northern Tajikistan (1930–2014).

on plant metabolism (Keller and Lamprecht 1995).

6. Conclusions

The material presented here is the most detailed study yet of the relationship between climatic conditions and the set of juniper tree-ring width chronologies from the Pamir-Alay region, including different topographic conditions. Within the juniper transect, a significant elevation-dependent variation in the climatic sensitivity was demonstrated. Our study highlights the fact that the highest correlations are found at the upper treeline. The influence of temperature is more important at the site with a northern exposure, but correlation coefficients with rainfall are higher at those exposed to the south. Summer precipitation and also summer temperature are important for growth at low elevations, indicating the importance of the water balance. In addition, a warm winter is beneficial for juniper growth, especially at low-elevation sites. Elevation is thus responsible for stronger differences in the climatic response than slope exposure.

Our results indicate that junipers growing in the study region can be a suitable source of paleoclimatic information about drought during growing seasons, deduced from low-elevation juniper records, as well as winter precipitation and summer temperature from high-elevation chronologies. Owing to the documented very high potential of this material, further field campaigns are recommended to collect dead wood and timber samples from different elevations in order to extend the length of dendroclimatic reconstructions for Tajikistan and the Pamir-Alay Region.

Aalto et al. (2017) are of the opinion that, by the end of this century, the multi-model mean air temperature will be from c. 2 °C (RCP2.6) to 7 °C (RCP8.5) higher compared to 1961–1990, and precipitation scenarios anticipate increases in the eastern part of the country but decreases in the west. Analyses of historical time series covering the last 80 years show that temperatures in Tajikistan have increased by 0.1 °C per decade, the change being the most prominent at low elevations. This increase in the average temperature is significantly impacting not only the state of the region's glaciers and water resources but also conditions in the forests. Tree-ring sampling conducted along elevational transects could be useful for acquiring an understanding of species' ecological amplitudes in the conditions of ongoing/future climate change. In the light of current and predicted climate changes in Tajikistan, it can be assumed that such temperature increases could favour tree growth, but if rainfall levels decrease further, growth may decline, a situation which would be especially detrimental at low-elevation sites. Our results also show that dust storms as a source of environmental pollution can adversely affect juniper growth. This is an important finding for further research on the state of forests affected by dust storms arising from local and external sources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolind.2023.110280>.

References

- Aalto, J., Kämäräinen, M., Shodmonov, M., Rajabov, N., Venäläinen, A., 2017. Features of Tajikistan's past and future climate. *Int. J. Climatol* 37, 4949–4961. <https://doi.org/10.1002/joc.5135>.
- Abdullaev, S.F., Sokolik, I.N., 2019. Main Characteristics of Dust Storms and Their Radiative Impacts: With a Focus on Tajikistan. *J Atmos Sci* 02, 02, 10.30564/jasr.v2i2.352.
- Adams, R.P., 2014. *Junipers of the World: The Genus Juniperus*, 4th Edition., Trafford Publishing, pp. 283–288.
- Antropov, P.Y. (ed.), 1959. *Geology of USSR*, vol. XXIV, Tajik SSR. Ministry of Geology and Subsoil Protection of USSR, State Scientific and Technical Publishing House. Moscow (in Russian).
- Bhattacharyya, A., LaMarche, V.C., Telewski, F.W., 1988. Dendrochronological reconnaissance of the conifers of northwest India. *Tree Ring Bull* 48, 21–30.
- Bilham, R., Pant, G.B., Jacoby, G.C., 1983. Dendroclimatic potential of juniper trees from the Sir Sar range in the Karakoram. *Hausam* 7, 45–50.
- Brauning, A., 1994. Dendrochronology for the last 1400 years in Eastern Tibet. *GeoJournal* 34 (1), 75–95.
- Brauning, A., 2001. Climate history of the Tibetan Plateau during the last 1000 years derived from a network of Juniper chronologies. *Dendrochronologia* 19 (1), 127–137.
- Chen, F., Yu, S., Shang, H., Zhang, R., Zhang, T., Zhang, H., et al., 2021. The productivity of low-elevation juniper forests in Central Asia increased under moderate warming scenarios. *JGR: Biogeosciences*, 126, e2021JG006269. [10.1029/2021JG006269](https://doi.org/10.1029/2021JG006269).
- Chen, F., Zhang, T., Seim, A., Yu, S., Zhang, R., Linderholm, H.W., Kobuliev, Z.V., Ahmadov, A., Kodirov, A., 2019. Juniper Tree-Ring Data from the Kuramin Range (Northern Tajikistan) Reveals Changing Summer Drought Signals in Western Central Asia. *Forests* 10, 505. <https://doi.org/10.3390/f10060505>.
- Chen, F., Yuan, Y.J., Trouet, V., Buntgen, U., Esper, J., Chen, F.H., Yu, S.L., Shen, M.G., Zhang, R.B., Shang, H.M., Chen, Y.P., Zhang, H.L., 2022. Ecological and societal effects of Central Asian streamflow variation over the past eight centuries. *npj Climate and Atmospheric Science* 5 (1), 27. <https://doi.org/10.1038/s41612-022-00239-5>.
- Cook, E., Holmes, R.H., 1986. *Users manual for program ARSTAN*. In: Holmes, R., Adams, R.K., Fritts, H.C. (Eds.), *Tree-ring Chronologies of Western North America: California, Eastern Oregon and Northern Great Basin*. The University of Arizona, Tucson, Arizona, Laboratory of Tree-Ring Research, pp. 50–60.
- Climate Risk Country Profile: Tajikistan. 2021. The World Bank Group and the Asian Development Bank.
- Desplanque, C., Rolland, C., Schweingruber, F., 1999. Influence of species and abiotic factors on extreme tree ring modulation. *Trees* 13, 218–227.
- Eilmann, B., Weber, P., Rigling, A., Eckstein, D., 2006. Growth reactions of *Pinus sylvestris* L. and *Quercus pubescens* Willd. To drought years at a xeric site in Valais, Switzerland. *Dendrochronologia* 23, 121–132. <https://doi.org/10.1016/j.dendro.2005.10.002>.
- Esper, J., 2000. Long-term tree-ring variations in *Juniperus* at the upper timber-line in the Karakorum (Pakistan). *Holocene* 10, 253–260.
- Esper, J., Schweingruber, F.H., Winiger, M., 2002. 1300 years of climatic history for Western Central Asia inferred from tree-rings. *Holocene* 12 (3), 267–277.
- Esper, J., Cook, E.R., Krusic, P.J., Peters, K., Schweingruber, F.H., 2003. Tests of the RCS method for preserving low-frequency variability in long tree-ring chronologies. *Tree-Ring Res* 59, 81–98.
- Esper, J., Frank, D.C., Wilson, R.J.S., Buntgen, U., Treydte, K., 2007. Uniform growth trends among central Asian low and high elevation juniper tree sites. *Trees* 21, 141–150.
- Fan, Z.-X., Brauning, A., Cao, K.-F., Zhu, S.-D., 2009. Growth-climate responses of high elevation conifers in the central Hengduan Mountains region, southwestern China. *For. Ecol. Manage.* 258, 306–313. <https://doi.org/10.1016/j.foreco.2009.04.017>.
- Fan, Y., Shang, H., Yu, S., Wu, Y., Li, Q., 2021. Understanding the Representativeness of Tree Rings and Their Carbon Isotopes in Characterizing the Climate Signal of Tajikistan. *Forests* 12, 1215. <https://doi.org/10.3390/f12091215>.
- Farmer, A.M., 1993. The effects of dust on vegetation a review. *Environmental Pollution* 79, 63–75.
- Fritts, H.C., 1976. *Tree-rings and climate*. Academic Press, New York, London, San Francisco, p. 567.
- Gaire, P.G., Fan, Z.-X., Brauning, A., Panthi, S., Rana, P., Shrestha, A., Bhujju, D.R., 2020. *Abies spectabilis* shows stable growth relations to temperature, but changing response to moisture conditions along an elevation gradient in the central Himalaya. *Dendrochronologia* 60, 125675.
- Grissino-Mayer, H., 2001. Research Report Evaluating Crossdating Accuracy: A Manual And Tutorial for The Computer Program Cofecha. *Tree -Ring Res* 57 (2), 205–221.
- Guerrero-Hernández, R., Muñoz-Castro, M.A., Villanueva-Díaz, J., Hernández-Vera, G., Vázquez-García, J.A., Ruiz-Corral, J.A., 2022. Tree-Ring Patterns and Growth Response of *Abies jaliscana* to Climate along Elevational Gradients in the Mountains of Western Jalisco. Mexico. *Forests* 13, 981. <https://doi.org/10.3390/f13070981>.
- Gulakhmadov, A., Chen, X., Gulakhmadov, N., Liu, T., Davlyatov, R., Sharofiddinov, S., Gulakhmadov, M., 2020. Long-Term Hydro-Climatic Trends in the Mountainous

- Kofarnihon River Basin in Central Asia. *Water* 12 (8), 2140. <https://doi.org/10.3390/w12082140>.
- Harris, I., Osborn, T.J., Jones, P., Lister, D., 2020. Version 4 of the CRU TS Monthly High-Resolution Gridded Multivariate Climate Dataset. *Sci Data* 7, 109. <https://doi.org/10.1038/s41597-020-0453-3>.
- Hartl, C., Schneider, L., Riechelmann, D.F.C., Kuhl, E., Kochbeck, M., Klippel, L., Büntgen, U., Esper, J., 2022. The temperature sensitivity along elevational gradients is more stable in maximum latewood density than tree-ring width. *Dendrochronologia* 73, 125958.
- Holmes, J.A., Cook, E.R., Yang, B., 2009. Climate change over the past 2000 years in Western China. *Quat Int* 194 (1–2), 91–107. <https://doi.org/10.1016/j.quaint.2007.10.013>.
- Ivanova, T.P., Trifonov, V.G., 2005. Neotectonics and Mantle Earthquakes in the Pamir-Hindu Kush Region. *Geotectonics* 39 (1), 56–68.
- Keller, J., Lamprecht, R., 1995. Road dust as an indicator for air pollution transport and deposition: An application of SPOT imagery. *Remote Sensing Environment* 54, 1–12.
- Klesse, S., DeRose, R.J., Guiterman, C.H., et al., 2018. Sampling bias overestimates climate change impacts on forest growth in the southwestern United States. *Nat Commun* 9, 5336. <https://doi.org/10.1038/s41467-018-07800-y>.
- Körner, C., 2003. Carbon limitation in trees. *Journal of Ecology* 91, 4–17.
- Körner, C., 2007. The use of 'altitude' in ecological research. *Trends Ecol. Evol.* 22 (11), 569–574. <https://doi.org/10.1016/j.tree.2007.09.006/>.
- Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift* 15, 259–263.
- Kuteminskiy, V.Y., Leontyeva, R.S., 1966. *Soils of Tajikistan*. Irfon Press, Dushanbe, pp. 1–324.
- LaMarche, V.C., 1974. Paleoclimatic Inferences from Long Tree-Ring Records. *Science* 183 (4129), 1043–1048. <https://doi.org/10.1126/science.183.4129.1043>.
- Leal, S., Melvin, T.M., Grabner, M., Wimmer, R., Briffa, K.R., 2007. Treering growth variability in the Austrian Alps: the influence of site, altitude, tree species and climate. *Boreas* 36, 426–440.
- Lei, Y., Liu, Y., Song, H., et al., 2014. A wetness index derived from tree-rings in the Mt. Yishan area of China since 1755 AD and its agricultural implications. *Chin Sci Bull* 59, 3449–3456.
- Leonelli, G., Pelfini, M., Battipaglia, G., et al., 2009. Site-aspect influence on climate sensitivity over time of a high-altitude *Pinus cembra* tree-ring network. *Climatic Change* 96, 185–201.
- Liang, E., Shao, X., Eckstein, D., Huang, L., Liu, X., 2006. Topography- and species-dependent growth responses of *Sabina przewalskii* and *Picea crassifolia* to climate on the northeast Tibetan Plateau. *Forest Ecology and Management* 236 (2–3), 268–277.
- Liang, E., Wang, Y., Xu, Y., et al., 2010. Growth variation in *Abies georgei* var. *smithii* along altitudinal gradients in the Sygera Mountains, southeastern Tibetan Plateau. *Trees* 24, 363–373. <https://doi.org/10.1007/s00468-009-0406-0>.
- Liu, L.-S., Shao, X.-M., Liang, E.-Y., 2006. Climate Signals from Tree Ring Chronologies of the Upper and Lower Treelines in the Dulan Region of the Northeastern Qinghai-Tibetan Plateau. *Journal of Integrative Plant Biology* 48, 278–285. <https://doi.org/10.1111/j.1744-7909.2006.00158.x>.
- Lydolph, P.E., 1977. *Climates of the Soviet Union*. Elsevier, Amsterdam Oxford, p. 443.
- Lyu, L., Deng, X., Zhang, Q.-B., 2016. Elevation Pattern in Growth Coherency on the Southeastern Tibetan Plateau. *PLoS ONE* 11 (9), e0163201.
- Mack-Cynon, D., 1993. Satellite data on dust storms in Tajikistan. In: *Soviet-American Experiment on Arid Aerosol. Hydrometeoroidat*, St.Petersburg, pp. 25–26.
- Maksimov, E.B., Grebenyuk, A.K., 1972. Variability of natural environment of high-altitude zone of Zeravshan Range for the last 800 years. *Izvestiya USSR Academy of Sciences Geographic series* 2, 105 in Russian.
- Mukhamedshin, R.D., Sarbaev, S.K., 1988. *Champion of longevity*. Alma-Ata, Kaynar in Russian.
- Mukhamedshin, K.D., Talancev, N.K., 1982. *Juniperus forests (forest, light forest, scrubs)*. Lesnaia promyshlennost Press, Moskva 1–185 in Russian.
- Mukhamedshin, K.D., 1978. The most long-lived tree species of Middle Asia as the object of dendrochronological investigations. *Materials of the All-Union Meeting Scientific Conference on the Subject of Dendrochronology and Dendroclimatology (in Russian)*.
- Najia, H.R., Taherpoura, M., 2019. The effect of simulated dust storm on wood development and leaf stomata in *Quercus brantii* L. *Desert* 24–1, 43–49.
- Nazarov, B.I., Abdullaev, S.F., Maslov, V.A., 2016. Dynamic processes during dust incursions in Central Asia. *Dushanbe, Irfon*.
- 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.
- Opala, M., Niedźwiedz, T., Rahmonov, O., Owczarek, P., Malarzewski, L., 2017. Towards improving the Central Asian dendrochronological network - new data from Tajikistan, Pamir-Alay. *Dendrochronologia* 41, 10–23.
- Opala-Owczarek, M., 2019. Warm-season temperature reconstruction from high-elevation juniper tree rings over the past millennium in the Pamir region. *Palaeogeography, Palaeoclimatology, Palaeoecology* 532, 109248.
- Opala-Owczarek, M., Niedźwiedz, T., 2019. Last 1100 yr of precipitation variability in western central Asia as revealed by tree-ring data from the Pamir-Alay. *Quat. Res.* 91 (1), 81–95. <https://doi.org/10.1017/qua.2018.21>.
- Opala-Owczarek, M., Owczarek, P., Rahmonov, O., Niedźwiedz, T., 2018b. The first dendrochronological dating of timber from Tajikistan – potential for developing millennial tree-ring record. *Tree-Ring Res.* 74 (2), 50–62. <https://doi.org/10.3959/1536-1098.74.1.50>.
- Opala-Owczarek, M., Owczarek, P., 2019. Dry and humid periods reconstructed from tree rings in the former territory of Sogdiana (Central Asia) and their socio-economic consequences over the last millennium. In: Yang, L.E., Bork, H.R., Fang, X., Mischke, S. (Eds.), *Socio-environmental Dynamics Along the Historical Silk Road*. Springer.
- Opala-Owczarek, M., Błaś, M., Owczarek, P., Sobik, M., Godek, M., 2018a. A dendroclimatology study of east- and west-facing slopes in mountainous areas subjected to strong air pollution (the Sudetes, Central Europe). *Physical Geography* 40 (3), 186–208. <https://doi.org/10.1080/02723646.2018.1547872>.
- Owczarek, P., Opala-Owczarek, M., Rahmonov, O., Mendecki, M., 2017. 100 years of earthquakes in the Pamir region as recorded in juniper wood: a case study of Tajikistan. *J. Asian Earth Sci.* 138, 173–185.
- Owczarek, P., Opala-Owczarek, M., Rahmonov, O., Razzokov, A., Jary, Z., Niedźwiedz, T., 2018. Relationships between loess and the Silk Road reflected by environmental change and its implications for human societies in the area of ancient Panjikent, central Asia. *Quat Res* 89 (3), 691–701.
- Panthi, S., Brauning, A., Zhu, Z.-K., Fan, Z.-X., 2018. Growth response of *Abies georgei* to climate increases with elevation in the central Hengduan Mountains, southwestern China. *Dendrochronologia* 47, 1–9.
- Panthi, S., Fan, Z.-X., van der Sleen, P., Zuidema, P.A., 2020. Long-term physiological and growth responses of Himalayan fir to environmental change are mediated by mean climate. *Glob Change Biol.* 26, 1778–1794.
- Qi, Z., Liu, H., Wu, X., Hao, Q., 2015. Climate-driven speedup of alpine treeline forest growth in the Tianshan Mountains, Northwestern China. *Global Change Biology* 21, 816–826. <https://doi.org/10.1111/gcb.12703>.
- Qin, C., Yang, B., Melvin, T.M., Fan, Z., Zhao, Y., et al., 2013. Radial Growth of Qilian Juniper on the Northeast Tibetan Plateau and Potential Climate Associations. *PLoS ONE* 8 (11), e79362.
- Rahmonov, O., Rahmonov, M., Opala-Owczarek, M., Owczarek, P., Niedźwiedz, T., Myga-Piatek, U., 2017. Ecological and cultural importance of juniper ecosystem in the area of Zeravshan valley (Tajikistan) on the background of environmental condition and anthropogenic hazards. *Geogr Pol* 90 (4), 441–461.
- Regent Instruments Inc, 2006. *WinDENDRO: Manual*. Regent Instruments Inc., Quebec, Canada.
- Romanov, N.N., 1960. *Dust storms in Central Asia*. Tashkent, 198.
- Sadikov Ch, 2012. *The juniperus forests of catchment of Iskander river (Tajikistan)*. Lambert Academic Publishing, Saarbrücken, Germany, pp. 1–150.
- Salzer, M.W., Larson, E.R., Bunn, A., Hughes, M., 2014. Changing climate response in near-treeline bristlecone pine with elevation and aspect. *Environ Res Lett* 9, 114007.
- Saulnier, M., Corona, C., Stoffel, M., Guibal, F., Edouard, J.-L., 2019. Climate-growth relationships in a *Larix decidua* Mill. network in the French Alps. *Sci Total Environ* 664, 554–566. <https://doi.org/10.1016/j.scitotenv.2019.01.404>.
- Schurr, B., Ratschbacher, L., Sippl, C.H., Gloguen, R., Yuan, X., Mechie, J., 2014. Seismotectonics of the Pamir. *Tectonics* 33, 1501–1518. <https://doi.org/10.1002/2014TC003576>.
- Seim, A., Tulyaganov, T., Omurova, G., Nikolay, L., Botman, E., Linderholm, H.W., 2016. Dendroclimatology potential of three juniper species from the Turkestan range, northwestern Pamir-Alay Mountains, Uzbekistan. *Trees* 30, 733–748. <https://doi.org/10.1007/s00468-015-1316-y>.
- Sidor, C.G., Popa, I., Vlad, R., Cherubini, P., 2015. Different tree-ring responses of Norway spruce to air temperature across an altitudinal gradient in the Eastern Carpathians (Romania). *Trees* 29, 985–997. <https://doi.org/10.1007/s00468-015-1178-3>.
- Solomina, O., 2002. Dendrogeomorphology: research requirements. *Dendrochronologia* 20 (1–2), 233–245.
- Stokes, M.A., Smiley, T.L., 1968. *An Introduction to Tree-ring Dating*. University of Arizona Press, Tucson, p. 73.
- TIBCO Software Inc., 2017. *Statistica (data analysis software system)*, version 13. Statistica Electronic Manual.
- Valor, G.B., López, D.J.M.G., 2017. *OGIMET – Professional Information about Meteorological Conditions in the World* (Accessed July 01, 2018). <http://www.ogimet.com/>.
- Vinnichenko, G.P., Tadzhibekov, M., 2010. The relief evolution of Pamir and Hissar-Alay in the Phanerozoic. *Doklady Akademii Nauk Respubliki Tadzhikistan* 53 (11), 879–883 in Russian.
- Vlasov, N.G., Dyakov, Y.A., Cherev, E.S., 1991. *Geological Map of the Tajik SSR and Adjacent Territories, 1:500,000*. Vsesojuznoi Geological Institute, Leningrad, Saint Petersburg.
- Wang, Y., Liu, X., Herzschuh, U., 2010. Asynchronous evolution of the Indian and East Asian Summer Monsoon indicated by Holocene moisture patterns in monsoonal central Asia. *Earth Sci Rev* 103, 135–153.
- Williams, M.W., Konovalov, V.G., 2008. *Central Asia Temperature and Precipitation Data, 1879–2003*. USA National Snow and Ice Data Center, Boulder CO.
- Yadav, R.R., 2009. Tree ring imprints of long-term changes in climate in western Himalaya, India. *J Biosci* 34, 699–707. <https://doi.org/10.1007/s12038-009-0058-7>.
- Yadav, R.R., Singh, J., Dubey, B., Mishra, K.G., 2006. A 1584-year ring-width chronology of juniper from Lahul, Himachal Pradesh: prospects of developing millennia long climate records. *Current Science* 90, 1122–1126.
- Yang, B., He, M., Melvin, T.M., Zhao, Y., Briffa, K.R., 2013. Climate Control on Tree Growth at the Upper and Lower Treelines: A Case Study in the Qilian Mountains, Tibetan Plateau. *PLoS ONE* 8 (7), e69065.
- Yang, M., Yu, Y., Zhang, H., Wang, Q., Gan, M., Yu, R., 2020. Tree ring based drought variability in Northwest Tajikistan since 1895 AD. *J. Arid Land* 12, 413–422. <https://doi.org/10.1007/s40333-020-0062-1>.
- Yin, Z.Y., Li, M., Zhang, Y., Shao, X., 2016. Growth–climate relationships along an elevation gradient on a southeast-facing mountain slope in the semi-arid eastern Qaidam Basin, northeastern Tibetan Plateau. *Trees* 30, 1095–1109. <https://doi.org/10.1007/s00468-015-1348-3>.

- Zapryagaeva, V.I., 1976. Forest resources of Pamir-Alay Range. Nauka Press, Leningrad 1–593 in Russian.
- Zhang, W.T., Jiang, Y., Dong, M.Y., Kang, M.Y., Yang, H.C., 2012. Relationship between the radial growth of *Picea meyeri* and climate along elevations of the Luyashan Mountain in North-Central China. For. Ecol. Manage. 265, 142–149. <https://doi.org/10.1016/j.foreco.2011.10.017/>.
- Zhang, Q.-B., Qiu, H., 2007. A millennium-long tree-ring chronology of *Sabina przewalskii* on northeastern Qinghai-Tibetan Plateau. Dendrochronologia 24, 91–95.
- Zhirnova, D.F., Belokopytova, L.V., Barabantsova, A.E., Babushkina, E.A., Vaganov, E.A., 2020. What prevails in climatic response of *Pinus sylvestris* in-between its range limits in mountains: slope aspect or elevation? Int J Biometeorol 64, 333–344. <https://doi.org/10.1007/s00484-019-01811-0>.