***Pak. J. Bot.*, 53(3): 1091-1099, 2021.** **DOI: http://dx.doi.org/10.30848/PJB2021-3(20)**

DENDROCHRONOLOGICAL INVESTIGATION OF SELECTED CONIFERS FROM KARAKORAM-HIMALAYA, NORTHERN PAKISTAN

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Abstract

Tree ring investigations at the high altitude mountains of the Karakoram-Himalaya, northern Pakistan have received limited attention concerning the climate-tree growth relationship studies. To test the climate-growth relationship, we developed four tree-ring width (TRW) standard chronologies represented by *Pinus wallichiana* and *Picea smithiana* from four sites in the Bagrot (BGR), Astore (AST), Phaphorash (PPR), and Naltar (NLT) valleys in northern Pakistan, respectively. These chronologies spanned 585, 514, 330, and 470 years, respectively. The tree growth was sensitive to spring precipitation and summer temperature, such as AST and PPR chronologies were sensitive to summer temperature. TRW chronologies of BGR and NLT were sensitive to spring precipitation and drought. Principal Component 1 (PC1) chronology was sensitive to spring temperature and showed an overall weak correlation with Palmer Drought Severity Index (PDSI). These multi-sites based study revealed variable climate-growth response, highlighting the heterogeneity in micro-climate on a local scale.

Key words: *Pinus wallichiana, Picea smithiana,* Temperature, Precipitation, PDSI, Climate-tree growth relationship..

Introduction

Global warming has increased the intensity and frequency of climatic extremes (Meinshausen *et al.,*., 2009). To understand the changes in past climate, long term climatic records are necessary. Due to annual resolution, precise dating, and widespread distribution, dendrochronological methods are being widely used to investigate the changes in past climate (Fritts, 1976; Speer, 2010, Asad *et al*., 2017a, b). The annual rate of warming in the northwestern Himalaya is 1.1°C/100 years, which is abnormally higher than the global rate of 0.7°C/100 years (Bhutiyani, 2016). Similarly, Karakoram region has experienced substantial warming about 1.12°C since the mid-twentieth century, and 1.94°C since the mid-nineteenth century (Asad *et al*., 2017a). In the context of global climate change and greenhouse gas emissions, forests are regarded as an important natural resource for mitigation of climate change (Field, 2014). However, climate change impact substantially affects forest ecosystem functions and species distribution, thus endangering the loss of forest ecosystem services and socio-economic well-being (Mayor *et al*., 2017). However, the scarcity of long term instrumental climatic records and accessibility limits our understanding of climate-growth relationships on the forested slopes of Karakoram-Himalaya.

Dendrochronological investigations provide an opportunity to explore the climate-growth relationship, as tree rings afford a finer resolution of inter-intra annual and interdecadal variations with better spatial representativeness (Fritts, 1976). In Pakistan, tree rings based studies reported so far have established the climatic potential of the coniferous species at high mountains (Ahmed, 2014; Ahmed & Naqvi, 2005; Ahmed *et al*., 2011; Esper, 2000). A handful of studies analyzed the impact of the climate on tree growth (Iqbal *et al*., 2017; Zafar *et al*., 2015). Recently, Asad *et al.*, (2017b) study at the upper timberline ecotones in Karakoram mountains suggested temperature to be sensitive to tree growth. The finding by Zafar *et al.*, (2015), however, elaborated precipitation sensitivity to tree growth. The spring precipitation had a direct relationship with tree growth in the nearby mountains of Jammu and Kashmir (India) (Singh *et al*., 2017). Whereas, towards lower elevation limits, PDSI was correlated significantly with the TRWs of *Abies pindrow* and *Picea smithiana* (Ram, 2012). Due to prior climate-growth relationship studies showed variable climate-growth response, dendroclimatic studies in Karakoram-Himalaya are still required to ascertain the climate-growth relationship effectively. Therefore, we developed three chronologies of *Pinus wallichiana* (blue pine) and one chronology of *Picea smithiana* (Spruce) by applying standard dendrochronological techniques (Speer, 2010). Our objective is to investigate the relationship between the climatic factors (temperature, precipitation and drought) and tree growth. This will improve our understanding of climate-growth relationships across the four sampled sites in the Karakoram-Himalaya region.

Materials and Methods

Study area and climate: The four study sites AST (74° 47'E, 35° 2'N), BGR (74° 33'E, 36° 03'N), NLT (74° 10'E, 36° 08'N), and PPR (74° 47'E, 35° 59'N) representing northern Karakoram-Himalayan mountains, were sampled (Fig. 1). The sites were carefully selected, where the forested slopes were least disturbed and steep enough to capture climate sensitivity. The elevation ranges from valley bottoms (1202 m) to the highest massifs; Nanga Parbat (8126 m) in Himalaya and Rakaposhi peak (7788 m) in the Karakoram (Phillips *et al*., 2000; Mayer *et al*., 2010). Generally, the bottoms of valley are typically dry or expressing aridity as compared to highly elevated humid montane systems, for example, less than 135 mm/year precipitation occurred at lower (1454 m) elevations to more than 720 mm/year at higher (4120 m) elevations (Mayer *et al*., 2010; Treydte *et al*., 2006). The meteorological stations of Astore (74° 51' E, 35° 21'N, at 2167 m a.s.l. from 1955-2013) and Gilgit (74° 19' E, 35° 55'N, at 1462 m a.s.l. from 1955-2013) at the valley floors (Fig. 2a, b) show 493 mm and 138 mm of total mean annual precipitation, respectively. This indicates that the precipitation levels could go as high as 870 mm with a decrease in temperature -2.9°C per year with respect to increasing elevation levels (4,030 m a.s.l.) (Farhan *et al*., 2014). The annual mean temperature for Astore is 9.8°C and for Gilgit is 16°C, while the monthly mean temperature ranges from -2.3°C (January) to 20.8°C (July) for Astore whereas 3.6°C (January) to 27.3°C (July) for Gilgit. The meteorological stations at valley floors show a significantly increasing trend in temperature while insignificant decreasing and the increasing trend can be noticed for precipitation in Astore and Gilgit valley floors, respectively (Fig. 2c, d).

Tree ring data and chronology development: *Pinus wallichiiana* for BGR, AST, and PHP and *Picea smithiana* for NLT were sampled in July and August of the year 2016. Both species are native to Karakoram-Himalaya and essential constituents of the timberline ecosystem. The blue pine is well adapted to precipitation range 300-1500 mm/year and spruce from 1000-2500 mm/year, while both species have the same temperature range -20 to 35°C (Sheikh, 1993). The climatic sensitivity of these species is well reported in Karakoram-Himalaya (Ahmed *et al*., 2011; Zafar *et al*., 2015; Asad *et al*., 2017a, b). The increment cores were taken from healthy trees (two cores per tree) at breast height (1.37 meter) and their position was determined using a global positioning system (GPS). Tree cores were air-dried, mounted on wooden frames, and sanded with sanding papers of variable coarseness to achieve shiner look for visual cross-dating (Fritts, 1976; Speer, 2010). Subsequently, LINTAB 6 measuring system with a resolution of 0.01 mm was used to count and measure TRW. For cross-dating, TSAPWin software was used for TRW comparisons; in that way, an exact year of tree-ring formation was sorted out for each core. Meanwhile, COFECHA computer program was used for validation of cross-dating (Holmes, 1983).

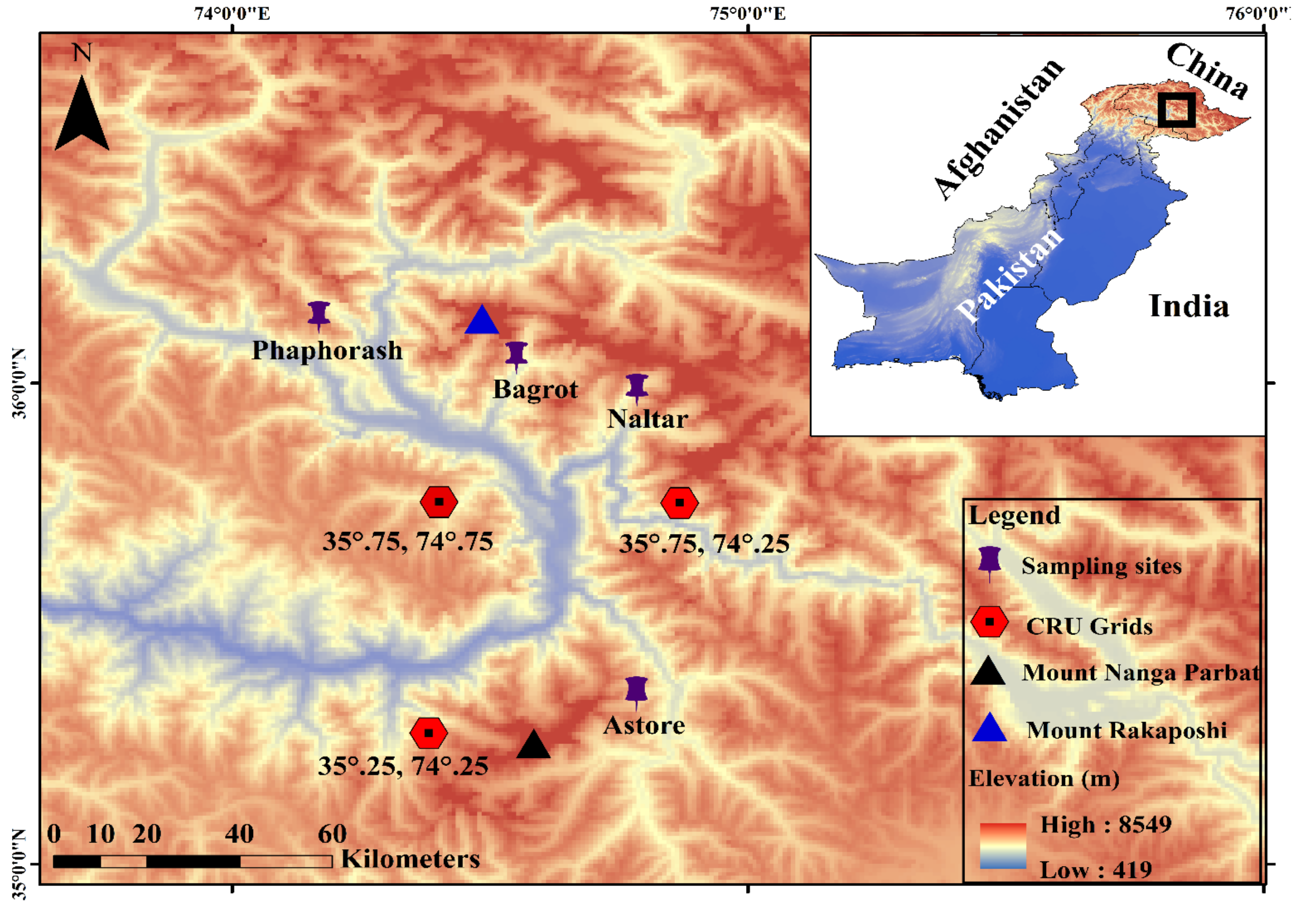

Fig. 1. Study area map showing the location of the sampling sites in Karakoram-Himalaya (northern Pakistan).

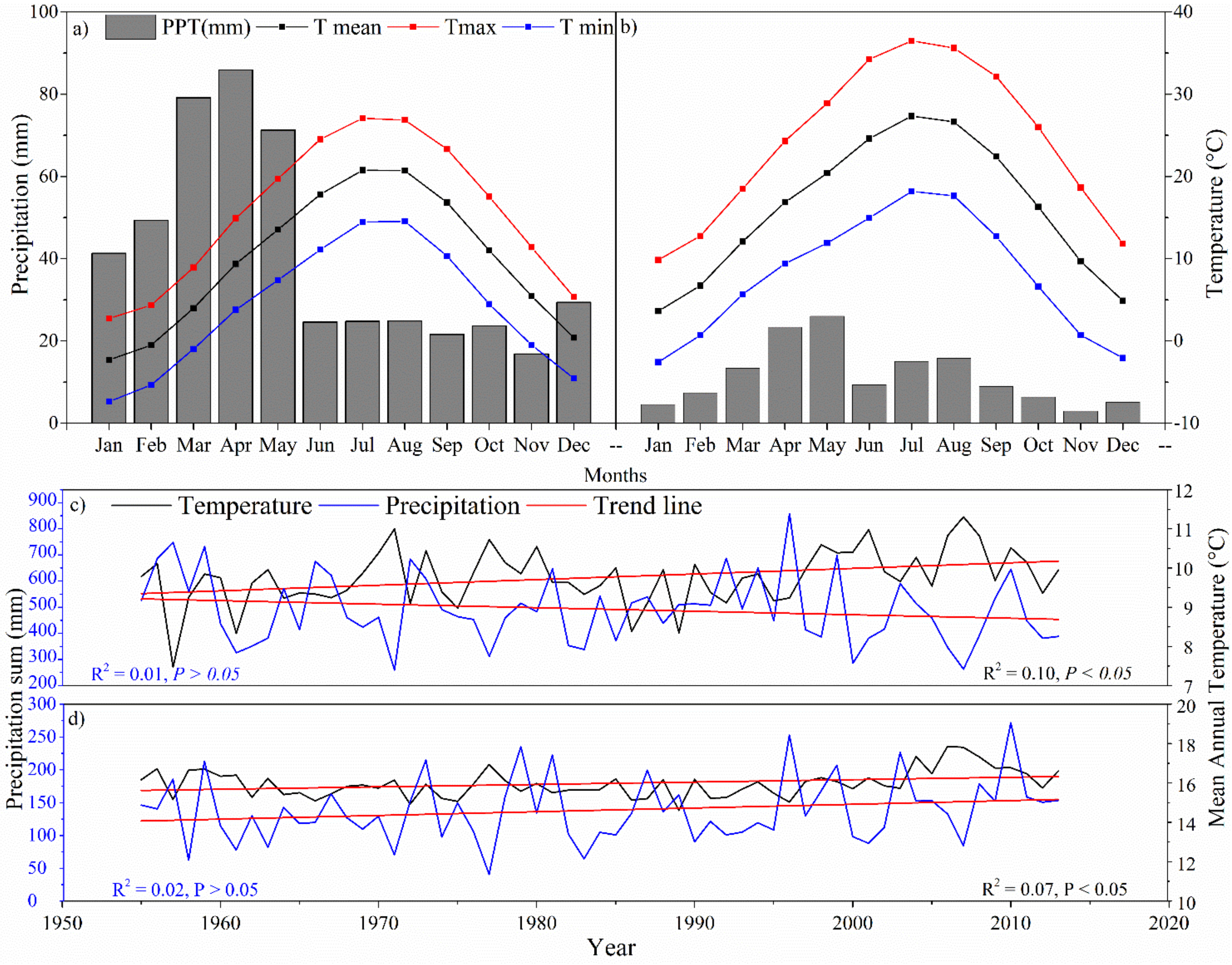

Fig. 2. The climate data of Astore (2167 m) (a) and Gilgit (1462 m) (b) meteorological stations at valley floors for the period (1955-2013). Temperature and precipitation trend derived from respective meteorological stations in the Astore valley (c) and Gilgit valley (d) for the period (1955-2013).

To remove biological growth trends and to preserve the climatic signals, computer program ARSTAN was used (Cook, 1985). Interactive detrending and standardization by using 60 years cubic smoothing spline on raw measurement series of each site were performed (Cook *et al*., 1990). We obtained standard chronologies for each site in the ARSTAN output file. The statistical data of each site chronologies are shown in Table 1. Moreover, we performed Principal Component Analysis (PCA) over the shared period of chronologies (1740-2016) to evaluate the regional growth controlling variables. The PC1 with an eigenvalue higher than 1 (Guttman, 1954) and variance explained 60% was used for further analyses.

Climate data: To test the climate-growth relationship, we performed correlations between gridded Climate Research Unit (CRU) data and TRW chronologies of all sites, including PC1 chronology. In the Karakoram-Himalaya, meteorological stations with long and homogenous data records are few and restricted to valley floors (Fig. 2). Therefore, we used CRU TS 4.01 gridded data (Harris & Jones, 2017) with a 0.5° spatial resolution using KNMI climate explorer (http://climexp.knmi.nl), which was more consistent with the period covered by the meteorological station at Astore valley floor (Fig. 2a). Three nearest grids to the sampling sites were selected, and climate data was downloaded.

The strong correlations (p<0.01) were observed between CRU gridded and meteorological station data for all months. Pearson correlations were performed between the standard chronologies and monthly and seasonal; winter (December-February), spring (March-May), summer (June-August), and autumn (September-November) climate records to identify the dominant climatic factor controlling radial growth.

Results

Tree-ring width data (TRW) assessment: Four standard chronologies were developed using coniferous blue pine trees from AST, BGR, and PPR and spruce from NLT in the Karakoram-Himalayan mountains of Pakistan (Fig. 3). The BGR represented the oldest chronology 585-years, and it was shortened to 526-years until the threshold Expressed Population Signal (EPS) value was > 0.85. The mean TRW of BGR chronology was 0.98 with a standard deviation (SD) of ± 0.23 around the mean value (Fig. 3a). The AST chronology spanned 514-years, and it was shortened to 456-years to achieve the EPS value of > 0.85

(Fig. 3b). The mean TRW was 0.98 with SD ± 0.20. The PPR chronology represented the growing record of 330-years which was shortened to 276-years to attain EPS threshold value > 0.85 (Fig. 3c). The mean TRW was 0.99 with SD ± 0.15. NLT chronology of spruce spanning 470-years was reduced to 341-years to achieve the EPS value > 0.85 (Fig. 3d). The mean TRW for NLT was 0.99 having SD ± 0.14. All chronologies showed an overall positive growth tendency as the TRWs, in majority, were consistently near to or > 1. TRWs, which were < 1 in each chronology, were not consistent (at least 9 consecutive years with an average of < 0.7) to suggest a decline in growth trends (Li & Zhang, 2017).

A significant and strong association was found between BGR and NLT, and AST and PPR chronologies for a common period 1740-2016 (EPS > 0.85), respectively. The correlations grew stronger for progressively younger chronologies, particularly between 1850-2016 for BGR and NLT, and 1950-2016 for AST and PPR (Table 2).

Climate-tree growth assessment: The reliable mean sensitivity which is the year to year ring width variability to climate parameters and higher EPS values > 0.85 for our study sites indicated a coherent stand-level signal (Table 1). Consequently, we examined the influence of climatic parameters on tree growth and correlation analysis was performed between the climate data and individual, and PC1 chronologies from 1955 to 2016 (Figs. 4 & 5).

Spring precipitation sensitivity: The chronologies of blue pine from BGR and spruce from the NLT region revealed negative correlations with temperature (Fig. 5a, b). BGR chronology revealed a significantly negative correlation with the temperatures of the previous year August, September, October, and current year March, April, and May. The seasonal influence of climate on trees growth has also been explored. BGR chronology showed a significant and negative correlation (r = -0.36, $p<0.05$) with the spring mean temperature. Spring and summer precipitation exhibited significantly positive (r = 0.35, $p<0.05$) and negative (r = -0.26, $p<0.05$) correlations with tree growth at BGR, respectively. A significant and positive correlation (r = 0.31, $p<0.05$) was found between the spring PDSI and tree growth of BGR (Fig. 5a).

NLT, regardless of species difference (spruce), tree growth also negatively correlated with temperature. The temperatures of the previous year July, August, October, and current-year April have shown negative correlations with tree growth at NLT. Whereas, the maximum temperature of the summer season showed a significant and positive correlation (r = 0.29, $p<0.05$). Like BGR, tree growth at NLT also showed a significant and negative correlation (r = -0.26, $p<0.05$) with the spring mean temperature. Summer precipitation showed significantly negative association (r = -0.26, $p<0.05$) with tree growth of NLT (Fig. 5b).

Table 1. Summary statistics and sites description for the TRW chronologies.

Sites	**Astore (AST)**	**Bagrot (BGR)**	**Naltar (NLT)**	**Phaphorash (PPR)**
Species	***Pinus wallichiana***	***Pinus wallichiana***	***Picea smithiana***	***Pinus wallichiana***
Latitude (N)	35° 2'	36° 03'	36° 08'	35° 59'
Longitude (E)	74° 47'	74° 33'	74° 10'	74° 47'
Elevation range (m)	3374-3504	3020-3250	3096-3277	3252-3491
Cores/Trees	61/31	61/32	65/33	63/32
Chronology span	1502-2016 AD	1431-2016 AD	1546-2016 AD	1686-2016 AD
Series-inter correlation	0.65	0.65	0.65	0.61
Mean R_{BAR}	0.50	0.56	0.45	0.44
R_{BAR} within a tree	0.82	0.88	0.77	0.66
R_{BAR} between trees	0.46	0.53	0.45	0.40
Standard deviation	0.20	0.21	0.20	0.22
Mean sensitivity	0.20	0.26	0.18	0.16
Signal to noise ratio (SNR)	15.39	17.29	11.24	13.91
EPS > 0.85 since	1560 (0.97)	1490 (0.95)	1675 (0.96)	1740 (0.97)
Missing rings (%)	0.12	0.26	0.03	0.02

Table 2. Correlations between site chronologies from older to younger common periods at significance $p<0.001$ (***), $p<0.01$ (**), and $p<0.05$ (*) levels. Values without asterisks are insignificant at all significance levels.

Pair of sites	**Correlation coefficient (r) during common time periods**		
	1740-2016	**1850-2016**	**1950-2016**
BGR and NLT	0.71***	0.80***	0.80***
AST and PPR	0.69***	0.65***	0.70***
BGR and PPR	0.29**	0.20**	0.09
AST and NLT	0.43***	0.31***	0.19
AST and BGR	0.36***	0.30***	0.18
PHP and NLT	0.33***	0.18*	0.08

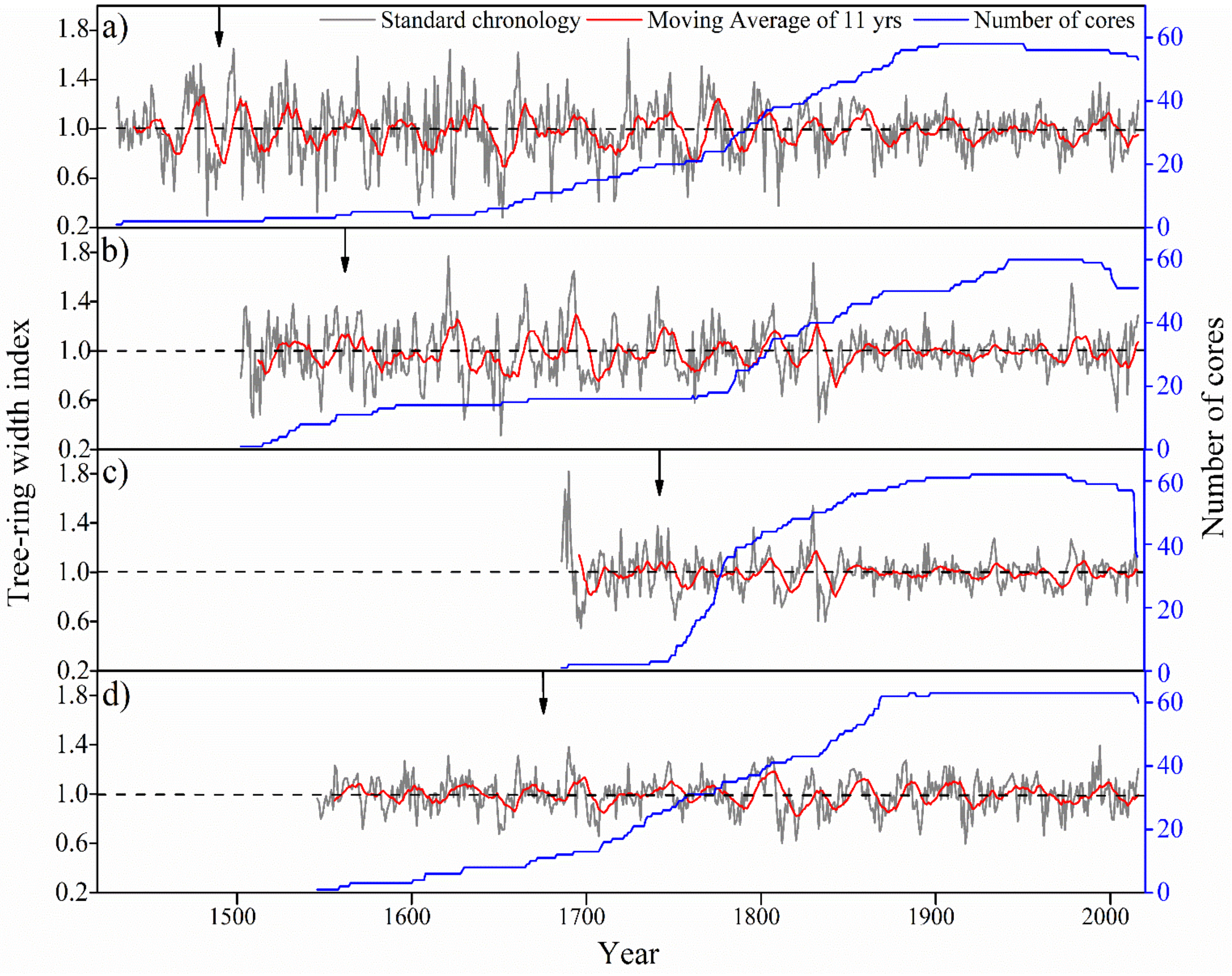

Fig. 3. Standard chronologies of (a) BGR), (b) AST, (c) PPR, and (d) NLT, from Karakoram-Himalaya region, northern Pakistan, their 11 years moving mean (red curve), long-mean (horizontal dashed line), and vertical black arrow represent the year elsewhere with the EPS > 0.85.

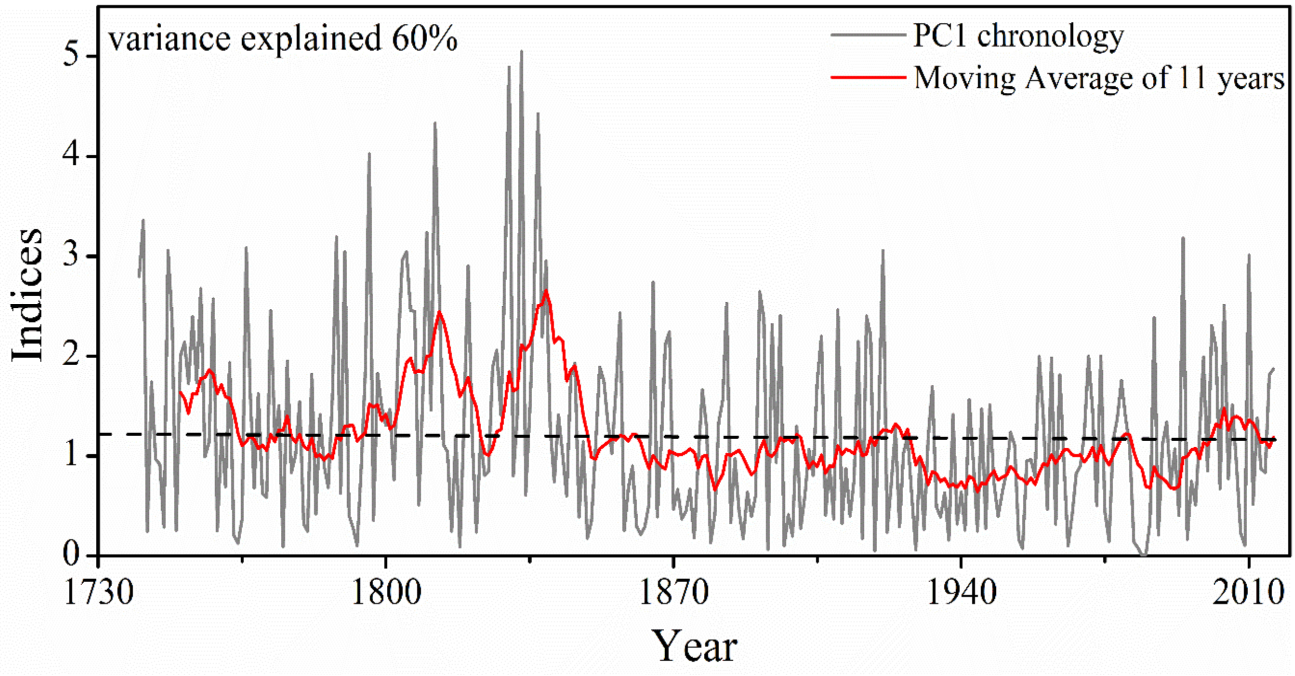

Fig. 4. Principal component 1 (PC1) chronology from the common period 1740-2016 for Karakoram-Himalaya.

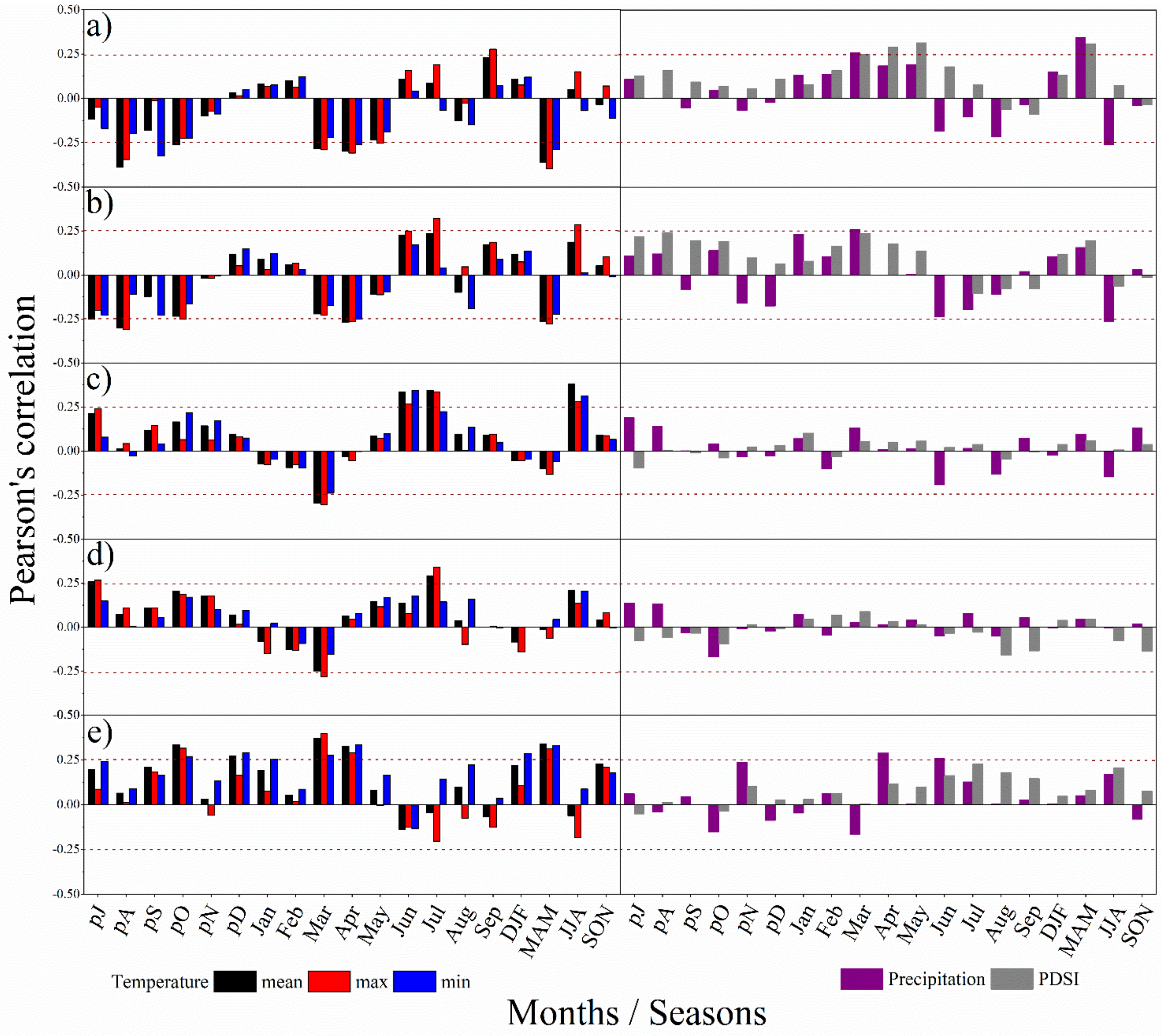

Fig. 5. The correlation of (a) BGR, (b) NLT, (c) AST, (d) PPR, and (e) PC1 chronologies at 95% confidence levels (horizontal dashed lines) with climate factors using CRU TS 4.01 data from 1955 to 2016. On the left side: (Black, Red, and Blue bars show mean, maximum, and minimum temperature, respectively). On the right side: (Purple and Grey bars show Precipitation and PDSI, respectively). The climate data arranged from prior year July (pJ) to current year September (Sep) and seasonal data, (for example, DJF, MAM, JJA, and SON represents winter, spring, summer, and autumn season, respectively).

Summer temperature sensitivity: AST chronology of blue pine showed a significant and negative correlation with the temperature of the current year March and insignificantly associated with the spring temperature (Fig. 5c). It, however, revealed a significant and positive correlation (r = 0.38, $p<0.05$) with the summer temperature. The tree growth at PPR correlated negatively (r = -0.28, $p<0.05$) with current year March maximum temperature, whereas the significant and positive relationship was observed for the temperatures of the previous and current year July. No significant correlations were noticed at PPR between tree growth and temperature for all seasons (Fig. 5d). The AST and PPR chronologies did not show any significant relationship with precipitation and PDSI (Fig. 5c, d).

Regional-scale temperature sensitivity: Since PC1 chronology (1740-2016) is the representative of all sites, climate data from previously used CRU grids were averaged and correlations were performed with PC1 chronology from 1955 to 2016. The PC1 chronology showed a positive and significant correlation with the temperatures of the previous year October and December, and the current year January and April (Fig. 5e). The winter minimum temperature was positively associated with PC1 (r = 0.29, $p<0.05$). PC1 also showed significant and positive relationship with mean (r = 0.34, $p<0.05$), maximum (r = 0.31, $p<0.05$), and minimum (r = 0.33, $p<0.05$) spring temperatures. Positive relationship was observed with the precipitation of current year April (r = 0.29, $p<05$) and June (r = 0.26, p<0.05), however, PC1 did not show any significant correlation with PDSI (Fig. 5e).

Presence of missing rings: During crossdating, missing ring years across all the investigated chronologies were studied (Fig. 6). This allowed us to match the missing ring years with respect to the low moisture/dry episodes or years reported by other studies from the surrounding regions. BGR contained the maximum number of missing rings between (1782-1820, 1848-1987), followed by AST (1632-1679, 1997-2010). The NLT and PPR had a missing ring year 2007 and 2010 in common with BGR and AST, respectively.

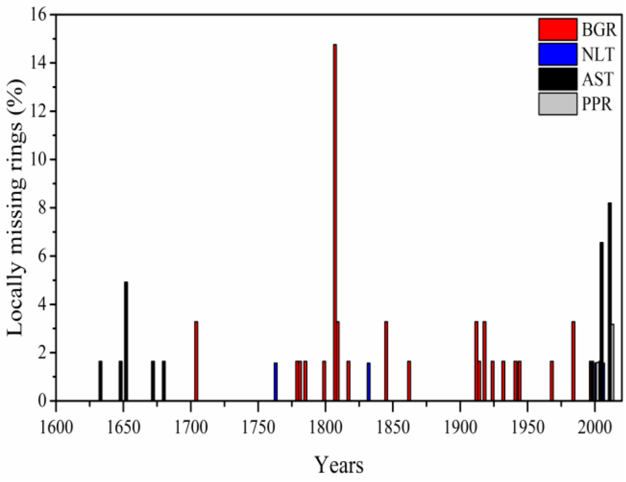

Fig. 6. Percentage of locally missing rings for all the chronologies over the period (1632-2010).

Discussion

Chronologies sensitivity to temperature and precipitation: Precipitation of the spring season and current year March showed a significant positive correlation with the TRW of BGR and NLT respectively. The observed data at the valley floor showed maximum spring precipitation (46%) from 1955 to 2013 (Fig. 2b). This was similar to the direct relationship of ring width chronologies with spring precipitation in the mountains of Jammu and Kashmir (northwestern Himalayas) (Singh *et al*., 2017). BGR also showed a positive association with the PDSI of the spring season (Fig. 5a). This indicated that precipitation sensitiveness could be because of an overall warming of the region (Asad *et al*., 2017b; Cook *et al*., 2013)˒ resulting in excessive evapotranspiration or drought stress, also reported from neighboring regions (Cook *et al*., 2010 - High Asia; Singh *et al*., 2017 - Northwest Himalaya; Ren *et al*., 2019 - Tibetan Plateau).

Similarly, NLT representing *Picea smithiana*, which was well adapted to moist conditions (Sheikh, 1993; Ahmed *et al*., 2006) was sensitive to precipitation in the current year March. The sensitivity of BGR and NLT to drought is in contrast to the previous study conducted in the same region by Asad *et al.,* (2017a). Our finding nevertheless, supports common knowledge, such as drought-stress towards lower-mid elevations due to excessive evapotranspiration (Büntgen *et al*., 2007; Tranquillini, 1964). The tree growth sensitivity to spring precipitation could be the result of cooler early growth periods (Farhan *et al*., 2014; Fowler, 2006) that could possibly delay the snowmelt and reduce the number of growing days (Vaganov *et al*., 1999). The low temperature during winters and early growth periods could induce a variety of physiological stresses or initiating sink limitation activities (Dolezal *et al*., 2019). In the later stages of growth periods, high temperature favors excessive evapotranspiration or occurrence of droughts (Ren *et al*., 2019). Contrary to spring precipitation, the negative association of summer precipitation with BGR and NLT chronologies (Fig. 5a, b) suggests local snow melting during summertime warming offsets moisture availability constraints for tree growth (Bader *et al*., 2017).

The TRW chronologies of AST and PPR representing comparatively higher elevation ranges are temperature sensitive. The AST showed a positive correlation with the summer temperature (Fig. 5c), and PPR chronology has also correlated significantly with the July temperature of the previous and current year (Fig. 5d). The above findings contradicted Zafar *et al*., (2015) study in the Karakoram region, in which summer temperature was negatively associated with tree growth. At the upper timberline ecotones, low minimum temperatures could favor the occurrence of frequent freezing events and curtail xylogenesis rates during growth periods (Li *et al*., 2017; Shen *et al*., 2014; Zhang *et al*., 2018 - Tibetan Plateau treelines). AST and PPR did not show a significant association with the precipitation and PDSI. This may be due to more precipitation at higher elevations in the region (Farhan *et al*., 2014), which eliminates precipitation as an impediment to tree growth (Dolezal *et al*., 2019; Tewari *et al*., 2018) unless considered with low temperatures.

The positive relationship of PC1 chronology with winter and spring temperature highlighted the role of temperature in determining tree growth on a regional scale (Fig. 5e). Moreover, PC1 chronology also showed sensitivity towards precipitation in the current year (April and June) months, giving the slight evidence of moisture limitation due to low temperature in the late spring (April) and high temperature in the summers (June).

Locally missing rings and drought: The growth of BGR is mediated primarily by moisture limitation or drought as suggested by the presence of more locally missing rings (Fig. 5a & 6). This was also observed in *Betula utilis* and *Pinus roxburghii* in central Himalayas (Liang *et al*., 2014, 2019; Sigdel *et al*., 2018) and *Cederus deodara* in the northwestern Himalayas (Singh *et al*., 2017). Moreover, PPR and BGR chronologies had a locally missing ring in 1998 and 2002, respectively (Fig. 6). That realistically captured the occurrence of one of the worst droughts in the history of Pakistan during (1998-2002) (Ahmed *et al*., 2016; Xie *et al*., 2013). Most of the missing rings in this study were observed during dry or low moisture episodes (1630-1632, 1651-1653, 1833-1837) in northwestern Karakoram region (Asad *et al*., 2017a) and in northwest Indian Himalaya (1830-1834, 1848-1849, 1859-1876, 1887-1901, 1933-1953, 1964-1973) (Ram, 2012). The BGR and NLT chronologies representing different species had a locally missing ring in the year 2007. Similarly, AST and PPR showed a locally missing ring in the year 2010 (Fig. 6). This similarity in expression between the sites BGR and NLT, and AST and PPR confirmed their strong mutual correlations (Table 2) and also signifying the evidence of moisture limitations at high and low elevation levels, respectively.

Conclusion

The TRW chronologies derived from the Karakoram-Himalayan mountains were sensitive to a variety of climatic parameters. Tree growth was mediated by drought or moisture stress during the spring season at mid-elevations. The summer temperature mediated tree growth at treeline ecotones. PC1 suggested the sensitivity of tree growth to both temperature and precipitation on a regional scale. These findings suggest that tree growth is limited to variable climate factors, which may be related to different sites of the Karakoram-Himalayan region, northern Pakistan. Since our study is based on tree growth-climate relationships, further tree-ring network studies should consider non-climatic variables (e.g. elevation, slope, aspect) to precisely examine the climate-growth relationship.

Acknowledgment

This work was funded by the National Natural Science Foundation of China (No. 41771240), West Light Foundation of the Chinese Academy of Sciences to Haifeng Zhu, CAS Special Project on International Cooperation along the Belt and Road Initiative (No. 131C11KYSB20160061), and a joint project between NSFC and ICIMOD (No.4161101318). Munawar Ali was supported by the University of Chinese Academy of Sciences Scholarship for International Masters students.

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(Received for publication 6 June 2019)