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CLIMATE SIGNAL IN TREE-RING WIDTH CHRONOLOGIES OF *PINUS WALLICHIANA* FROM THE KARAKORAM MOUNTAINS IN NORTHERN PAKISTAN

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Abstract

In the study area, *Pinus wallichiana* one of the most dominant species at upper timberline, reaching age up to 700-years old was selected for the dendroclimatological study in the Karakoram region, northern Pakistan. In this paper, we demonstrated the relationship between its radial growth and climatic factors using two standard chronologies of *Pinus wallichiana*. Tree-ring width site chronologies showed a strong positive response to temperature ($p<0.05$) and weak response to precipitation and Palmer Drought Severity Index (PDSI). We found a significant positive correlation with March-May, June-August, April-September of the current growth season, and previous year October to current year September (annual) temperature. These findings confirm that the *Pinus wallichiana* growth is mainly limited to temperature rather than precipitation and PDSI, and suggest that this species (*Pinus wallichiana)* is potential for the climate reconstruction in the study area.

Key words: *Pinus wallichiana*, Tree rings, Dendroclimatology, Climate variations, Karakoram.

Introduction

The Hindu Kush-Karakoram-Himalaya (HKKH) mountain region is one of the world highest mountain system and considered as the "third pole" due to huge and highest amounts of perennial snow and glacier ice stored in its high elevation basins (Yao *et al.,* 2012). The climatic behavior of this region (HKKH) is not uniform due to different weather circulation systems. The Karakoram region is influenced by mid-latitude winter westerlies while bordering region (Himalayas) mainly affected by monsoon (Hewitt, 2014). High-resolution palaeoclimatic studies documenting long-term climatic variability is extremely limited. Most of the previous studies were mainly focused on short-term glacier fluctuations of the study area (Cogley, 2011; Iturrizaga, 2011; Bolch *et al.,* 2012; Gardelle *et al.,* 2013; Rankl *et al.,* 2014; Muhammad and Tian, 2016). Glaciers of the Karakoram region did not follow the global trends of retreating (Hewitt, 2005; Kaser *et al.,* 2010), mainly due to unique seasonality (lowering summer temperature and high winter precipitation: Hewitt, 2005; Kapnick *et al.,* 2014). The climate of the study area may also effect the tree growth, but the detailed knowledge about climate/growth relationship is extremely scarce. The study area contains mature natural forest without any disturbances and having a high potential for dendroclimatic studies (Ahmed *et al.*, 2011).

The high-resolution long-term climate records are very short in most regions. Since many studies have been focused on past climate variability, using the high resolved climate proxy of tree-ring data. For examples, tree-ring based climate reconstruction from Himalaya (Thapa *et al.,* 2014; Krusic *et al.,* 2015), Mongolia (Davi *et al.,* 2015), and Tibetan Plateau (Zhang *et al*., 2003; Bräuning & Mantwill, 2004; Zhu *et al.,* 2011; Zhang *et al.,* 2015). In the Karakoram region, a few studies are documented to analyze the impact of the climate on the tree growth (Ahmed, 1989; Esper *et al.,* 1995; Esper, 2000; Esper *et al.,* 2002; Ahmed & Naqvi, 2005; Esper *et al.,* 2007; Ahmed *et al.,* 2012; Ahmed *et al.,* 2013; Zafar *et al.,* 2015, Iqbal *et al.,* 2017). Despite of the high dendroclimatological potential, however, little is known about the relationship between the radial growth and climatic factors.

The objective of the present study was to develop a new tree-ring width chronology of *Pinus wallichiana* and to explore the associations between the tree-ring width and climatic factors.

Material and Methods

Sampling site: The Astore (35°.34N, 74°.79E) and Bagrot (36°.04N, 74°.65E) valleys are located in a per-humid area in the high-altitude northwestern Himalayan region of Pakistan (Fig. 1). The elevation ranging from valley bottom to the uppermost Nanga-Parbat massif is 1202 to 8126 m a.s.l. (Shroder *et al.,* 2000; Farhan *et al.,* 2014). In this region, precipitation varies along with the elevation (Kick, 1980), less than 135 mm year^{-1} precipitation occurred at lower elevations (1454 m) to more than 720 mm year^{-1} at higher elevations (4120 m) (Mayer *et al.,* 2010). In summer, the mountains of this region are under the influence of the South-Asian summer monsoon, while during the winter season mid-latitude westerly circulation nourishes these mountains (Kick, 1980; Owen *et al.,* 2002; Kapnick *et al.,* 2014). According to the meteorological record of Astore at the valley floor (74° 54' E, 35° 22' N, 2167 m a.s.l. from 1955-2013), the total mean annual precipitation is 488 mm, and the annual mean temperature is 9.78°C. The monthly mean temperature ranges from -2.33°C (January) to 20.80°C (July; Fig. 2). At Burzil station (4,030 m a.s.l.), the mean annual temperature decreases to −2.9°C with an increase of precipitation up to 870 mm per year (Farhan *et al.,* 2014).

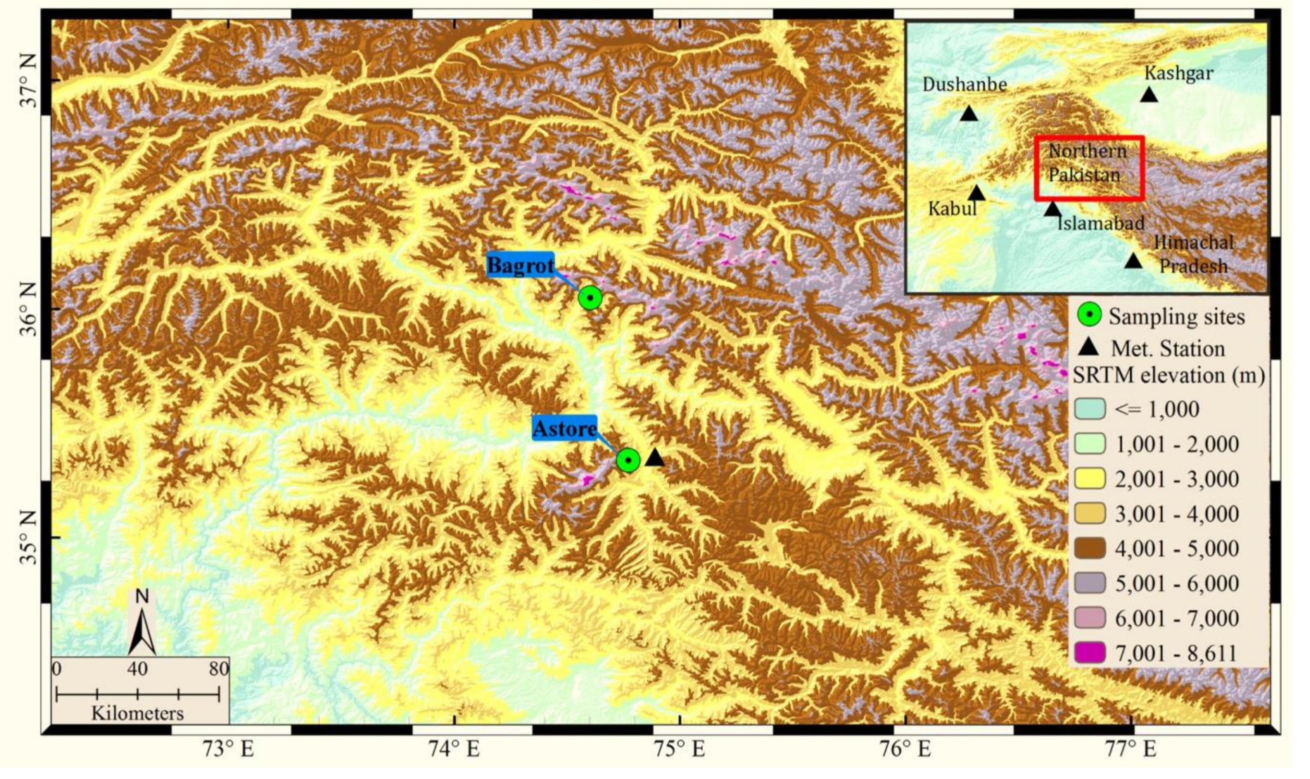

Fig. 1. Tree-ring sampling site and location of the Astore meteorological station in the Karakoram, northern Pakistan.

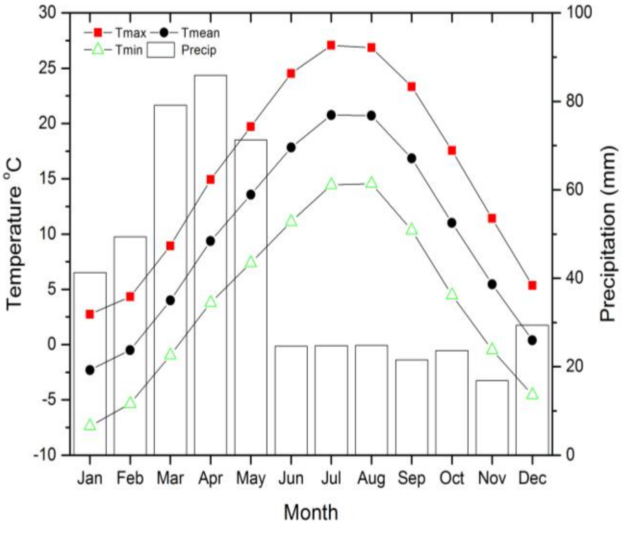

Fig. 2. Climate diagram of the Astore instrumental records from the period of 1955-2013.

Tree-ring data and chronology development: *Pinus wallichiana* is more extensive and dominant species at timberline, having a wide range of tolerance in the Karakoram region of northern Pakistan. The increment cores were extracted from healthy trees from Bagrot and Astore valley, between 3005 and 3423 ma.s.l. with no human interference and fire disturbance. A total of 109 tree cores were extracted from 78 living *P. wallichiana* (Bagrot 44/26, and Astore 63/52) at 1.37 meters above the ground level (breast height; Table 1). The tree cores were dried, fixed on the wooden slot, and fine-sanded for visual cross-dating following by standard dendrochronological techniques (Stokes & Smiley, 1968; Fritts, 1976). The crossdated series with the calendar year were measured at a resolution of 0.01 mm using LINTAB 6 Measuring System, and then the Computer program COFECHA (Holmes, 1983) was used to validate the results of the crossdating.

Detrending and standardization of the raw measurement series were achieved utilizing the Computer program ARSTAN (Cook, 1985). The raw series were detrended to remove the biological growth trends and to conserve as much of low-frequency signal as possible (Cook, 1985). We detrended and standardized the individual ring width series fitted by Negative Exponential Curves, and a 90-year cubic smoothing spline function (only two cores for Bagrot chronology) (Cook & Kairiukstis, 1990). The tree-ring index was averaged series to get one mean chronological series of each site.

We calculated several statistical descriptors for the Bagrot and Astore chronologies (Table 1). Mean Inter-series correlation is a measure of the accuracy and quality of dating, while Mean sensitivity (MS) is a measure of year-to-year variability in the tree growth series (Fritts, 1976; Speer, 2010). The variance explained by the First Principal Component (PC1) and Expressed Population Signal (EPS; threshold of >0.85) with a 50 years epoch and 25 years lag was used to determine at what point the number of cores were enough to present a reliable part of the tree-ring chronologies (e.g. Cook & Kairiukstis, 1990). To evaluate the growth controlling variables between the individual sites, the First Principal Components of tree-ring data were obtained through the Principal Component analyses (PCA) over the shared period of the chronologies (1519–2013). The tree ring series exhibiting higher loading in the First Principal Component (PC1) are assembled into the PC1 chronology.

Table 1. Site characteristics and summary statistics for the TRW chronologies.

Chronology site	**Bagrot**	**Astore**
Species	*P. wallichiana*	*P. wallichiana*
Lat (N)	36°04	35°34
Long (E)	74°65	74°79
Elevation range (m)	3005-3402	3305-3423
Cores/trees	44/26	63/52
Time Span	1487–2013	1519–2013
Series Inter-correlation	0.63	0.57
Standard-deviation	0.17	0.21
Mean sensitivity (MS)	0.14	0.13
Mean-correlation among all series	0.47	0.20
Mean-correlation within a tree	0.45	0.38
Signal to noise ratio (SNR)	16.15	8.92
Expressed-population-signal (EPS)	0.94	0.90

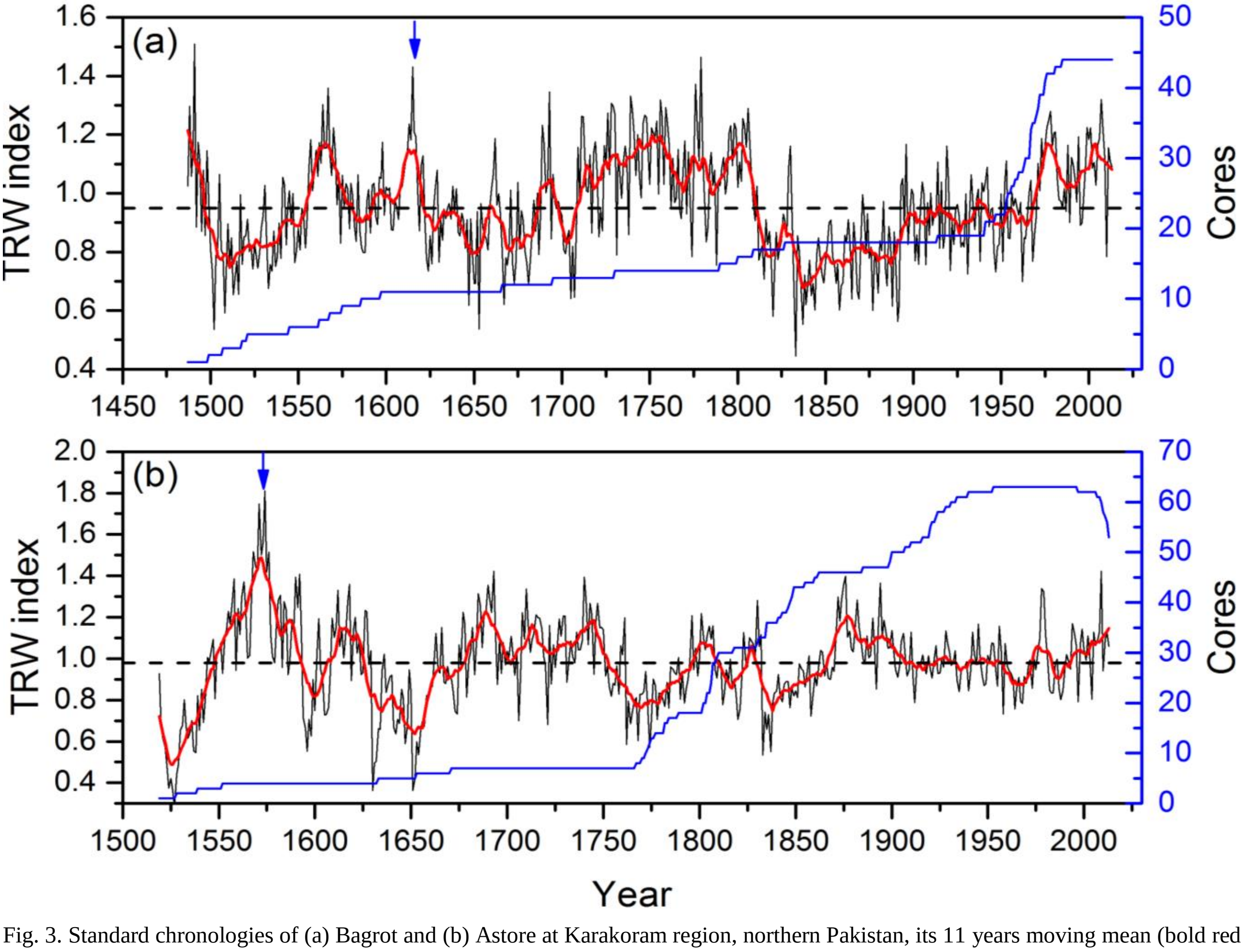

Fig. 3. Standard chronologies of (a) Bagrot and (b) Astore at Karakoram region, northern Pakistan, its 11 years moving mean (bold red curve), long-mean (horizontal dashed line), and vertical blue arrow represent the year elsewhere which the EPS>0.85.

Climate-growth relationship: To investigate the relationship between tree-ring indices and climate, we correlated tree-ring width (TRW) data with climate factors for the period 1955 to 2013. Climate records were obtained from Astore weather station (detail above), which comprises monthly mean (Tmean), mean maximum (Tmax), and mean minimum temperatures (Tmin), and monthly and annual sum precipitation. We computed drought growth relationship with Palmer-Severity Index (PDSI; from 1955-2012) of the adjacent gridded data from 36.25°N, 74.75°E (Dai *et al.,* 2004) to tree ring sampling sites. The instrumental records of Karakoram region are accessible since 1955 AD, hence the climate records are reliable after 1955 AD. Considering the previous year climate may also have an influence on radial growth (Fritts, 1976), Pearson correlation was performed with climate records from September of the previous year to October of the current year. We also performed spatial correlation between the PC1 chronology and temperature variation using CRU Ts 3.23 gridded data sets which has a 0.5^0 spatial resolution (the period from 1955 to 2013; Fig. 6), to assess it's spatial representatively. The analysis was accomplished utilizing the KNMI climate explorer (http://climexp.knmi.nl).

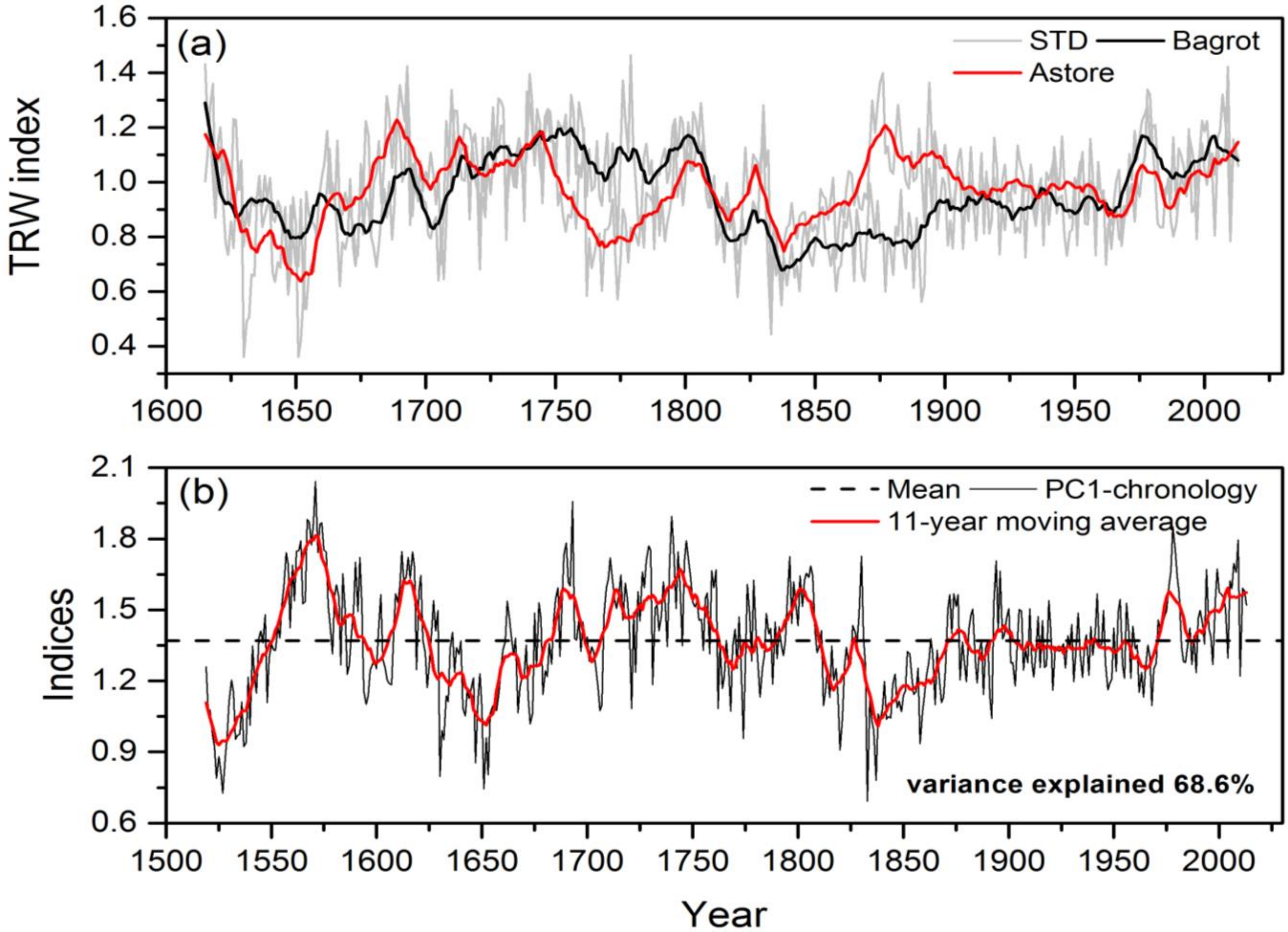

Fig. 4. (a) Comparison of Astore and Bagrot chronology (reliable chronologies part; EPS>0.85) during the common period of AD 1615 to 2013 (b) PC1 chronology.

Results and Discussion

TRW chronologies and their statistics: Two standard tree-ring chronologies (527 years and 495 years) of *P. wallichiana* were developed for the Karakoram region, northern Pakistan (Fig. 3). The Bagrot chronology (BC) included 44 cores from 26 trees (Table 1). The reliable chronology was shortened, when the EPS values of the BC was higher than the standard threshold of 0.85 after AD 1615. This designates the mark to which the precise sample chronology represents a hypothetically reliable chronology (Wigley *et al*., 1984). Generally, the BC chronology shows a long visible trend (consider the reliable part of the chronology), and it is stable from AD 1615 to 1700, growing trend from AD 1710 to 1800 and showed a quick decline 1810s followed by increasing trend from AD 1880 to 2013 (Fig. 3a).

The Astore chronology (AC) was composed of a large number of cores (63) from 52 trees (Table 1). The oldest studied tree (*P. wallichiana*) contained 495 tree rings. But the reliable chronology was shortened, when the EPS reached a threshold of 0.85 after AD 1570 to have at least 23 cores (Fig. 3b). The statistical characteristics of both chronologies over the period common to all trees (1850–2013) (Table 1) revealed the reliable cross-dating and common climatic signal. The chronologies statistics of the present study is relatively consistent with others past studies on the northern Pakistan (Ahmed *et al.*, 2012; Ahmed *et al.,* 2013; Zafar *et al.,* 2015), but lower than the values from neighboring regions such as, western Himalaya and Tibetan Plateau (Bhattacharyya *et al.*, 2006; Zhu *et al.,* 2008; Zhu *et al.,* 2009; Zhang *et al.,* 2011; Dawadi *et al.,* 2013; Liang *et al.,* 2014; Zhang *et al.,* 2015; Liang *et al.,* 2016). Generally, mean sensitivity (MS) and series inter-correlation (Rbar) are sites depend on subalpine-temperate regions and have lower MS and Rbar as compared with arid sites (Gou *et al.,* 2008; Liang *et al.,* 2009; Shao *et al.,* 2010). However, a low mean sensitivity does not essentially mean that there is no climatic signal revealed by the year-to-year variability in ring width (Wilson & Topham 2004). The statistics of the present chronologies suggests that the *P. wallichiana* is one of the potential species for use in dendroclimatological studies particularly, for climate reconstruction.

We found significant (r=0.37, p<0.001) correlation between Bagrot and Astore chronology over the common period of AD 1615 to 2013 (reliable chronologies part; EPS>0.85). Comparatively, the AC is little short and it reveals relatively flat trend (Fig. 4). The magnitude of AC was lower than BC during the period AD 1745 to 1800 and grew into higher magnitude during AD 1815 to 1916 (Fig. 4a). Since AD 1950, the magnitude of both chronologies was relatively consistent and showing a similar trend of viability, followed by contrasting pattern during the last decade. To investigate the regional trend of the study area, Principal components (PC1) were extracted from two sites chronologies (see "Methods" for detail; Fig. 4b). The eigenvalue higher than one was used (Guttman, 1954), and variance explained 68.6%. The PC1 chronology was selected for further analysis in the common period AD 1519 to 2013.

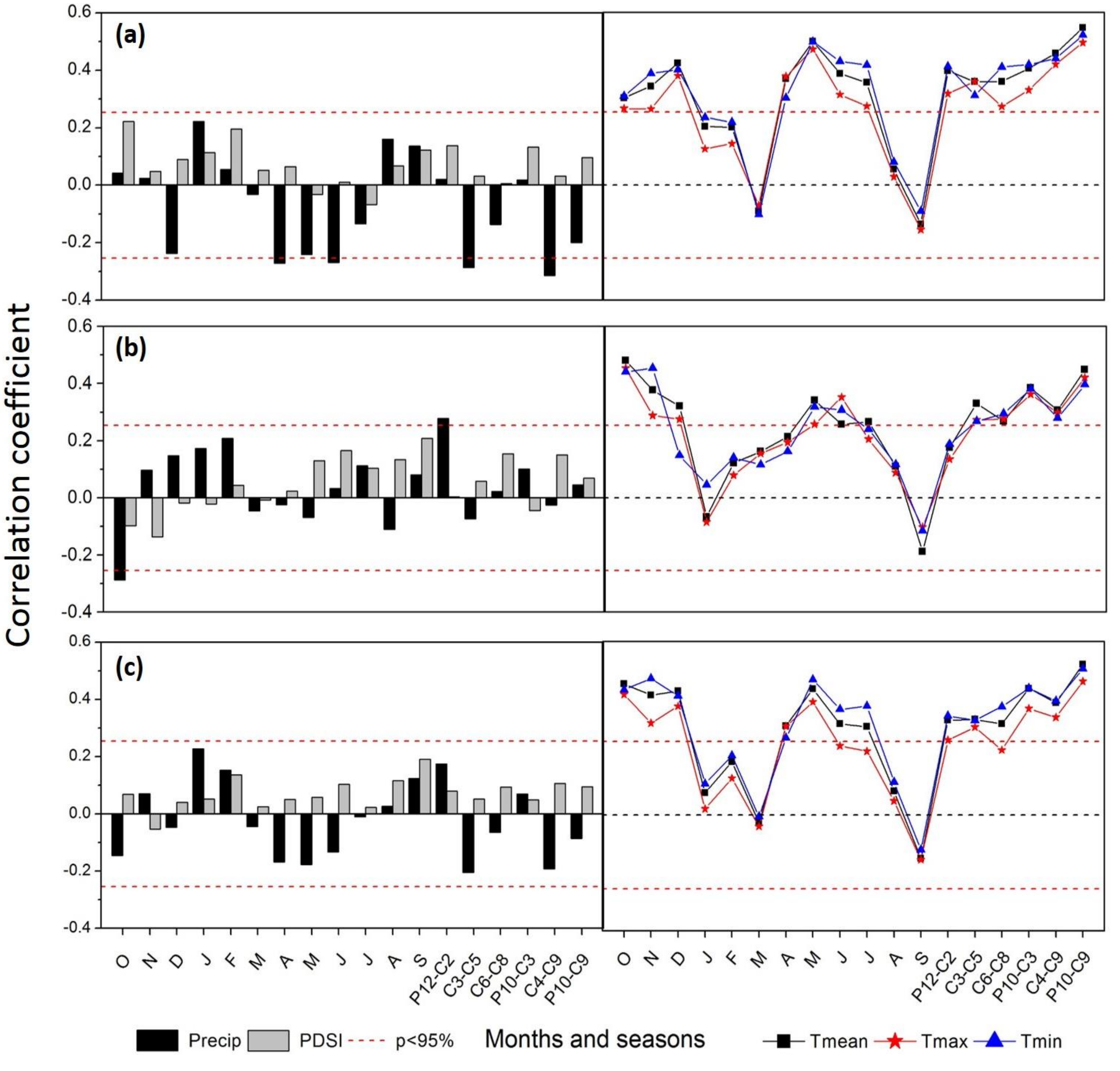

Fig. 5. The correlation of (a) Bagrot, (b) Astore, (c) and PC1 chronology with climate factors from prior year October to current year September and seasonal data assembled, using data of Astore meteorological station from 1955 to 2013. P12-C2: previous December to current February, C3-C5: current March to May, C6-C8: current June to July, P10-C3: previous October to current March, C4-C9: current April to September, P10-C9: previous October to current September.

Climate-growth assessment: The correlation analysis showed that the *P. wallichiana* TRW chronologies were positively correlated with temperatures (Fig. 5). Significant ($p<0.05$) and relatively high correlations are found with current year April, May, Jun, July, and previous October, November, and December. TRW chronologies are weakly associated with precipitation and PDSI. Only current year April, June, April-September, March-May (Fig. 5a), and previous year October (Fig. 5b) precipitation exhibited a significantly ($p<0.05$) negative correlations with tree growth. After testing different combinations of months (seasons), TRW chronologies yielded the highest correlation coefficient in March to May, June to August, April to September, and previous year October to current year September (annual) temperatures.

To determine the regional climate signal of the Karakoram region, we analyze the relationship between the PC1 chronology with climate variables. A significant positive relationship ($p<0.05$) with temperatures and weak correlation with PDSI and precipitation was found (Fig. 5c). Generally, TRW chronologies showed common climatic signal (temperature), the BC and PC1 chronology explained relatively strong correlation than AC, whereas seasonal (as above) and annual temperatures showed higher correlation coefficients with tree growth than for single months. This indicates that the seasonal and annual temperature is the essential limiting climate factor for the tree growth in the Karakoram region. A similar positive effect of temperature on radial growth for this region had also been reported by Esper *et al.* (2002), Ahmed *et al.*

(2010), and Asad *et al.* (2016), and in nearby region reported by Bräuning (2006), Liang *et al.* (2008), and Lv and Zhang (2013). However, our findings are in contrast to an earlier study by Zafar *et al.* (2015). They reported that the tree growth was negatively correlated to summer (JJA) temperature, which was remarkable for the tree-line sites (e.g. Asad *et al.*, 2016). We found positive correlations between temperature and tree-ring width, whereas tree growth at upper timberline mostly responded positively to summer temperature (Körner, 1998). The distinction refers to the difference with Zafar *et al.* (2015) and may be due to the particular sampling site elevations, and/or character of species associated with an ecological and physiological appearance in deciding climate association with tree growth (Fang *et al.*, 2009, Cook *et al.*, 2001).

The meteorological station record for the Karakoram region reveals a continuous increase of precipitation along the elevation gradient (e.g. Fowler & Archer, 2006; Hewitt, 2014). High precipitation could compensate drought stress caused by higher evapotranspiration due to warming, resulting in a significant positive relationship between tree-ring and temperature. Generally, the low winter temperature limits the growth of high elevation conifer species, due to low soil temperature initiating reduced the root activity (Korner, 1998). This reveals the temperature is a crucial factor for the radial growth and provides a physiological background for the climate reconstruction.

Pointer years: In the present study, the extreme tree-ring width responses were examined over the period AD 1519 to 2013 using the PC1 chronology. Extreme radial growth events were defined as positive and negative pointer years (Čejková & Kolář, 2009), based on its mean (0.0) and standard deviation (STDV 0.23) value. Values higher and below than ±1.5 were considered for positive and negative extreme pointer years respectively (Fig. 7a). Over the past 495 years, 28 negative and 33 positive pointers were identified (shown in Table 2). The rate of positive pointer years was more frequent than the negative pointer year particularly, during the 20th-century and first decade of the 21st century (AD 1978, 1979, and 2009). No negative pointer was identified during this epoch (as above). Given that temperature was found to be the most sensitive climate factor for the tree growth (*P. wallichiana*) in the study area. Positive pointer years corresponded well with higher temperature and weakly coincided with precipitation (Fig. 7b), suggesting that recent warming was favorable for tree growth in the Karakoram region. Esper *et al.* (1995) reported 52 negatives and 50 positive pointer-year during the period AD 1741-1990, which reflected climate variation (particularly temperature). However, most positive pointer year of this study corresponds well with the favorable growing condition of the Karakoram (Pakistan), whereas tree-ring width reflects temperature variation (Esper, 2000; Esper *et al.*, 2001).

Table 2. Number of extreme negative and positive pointer year.

Negative pointer-year	Positive pointer-year
1522-1529, 1533-1535	1557, 1562-1564
1537-1538, 1540	1567-1576, 1592
1630-1632, 1647	1612, 1615, 1617
1651-1653, 1673	1689-1690, 1693
1774, 1820, 1833	1711, 1729-1730
1836-1837, 1858	1740-1741, 1743
	1747, 1796, 1830
	1978-1979, 2009

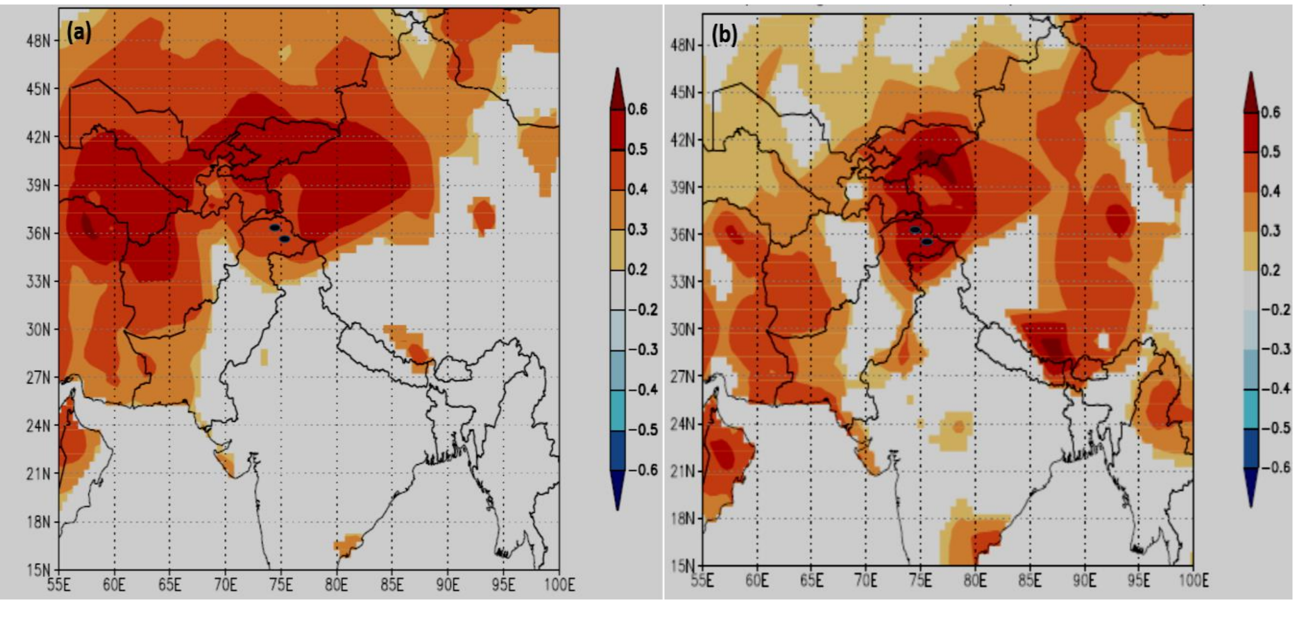

Fig. 6. Spatial correlation of growing season (a) April-September and (b) annual (previous October to current September) mean temperature with the PC1 chronology for the period 1955-2013. The black spot represents the sampling site. The correlation increased towards northwest direction and gradually decreased from the east direction. Significant (p<0.01) correlation covered the Karakoram region of Pakistan, Kunlun mountain, West Tian-Shan, Pamir, Tarimu-Basin, central and east Himalayan reign. Insignificant correlations found with lower Indus Basin in central-southern Pakistan and Indian continent.

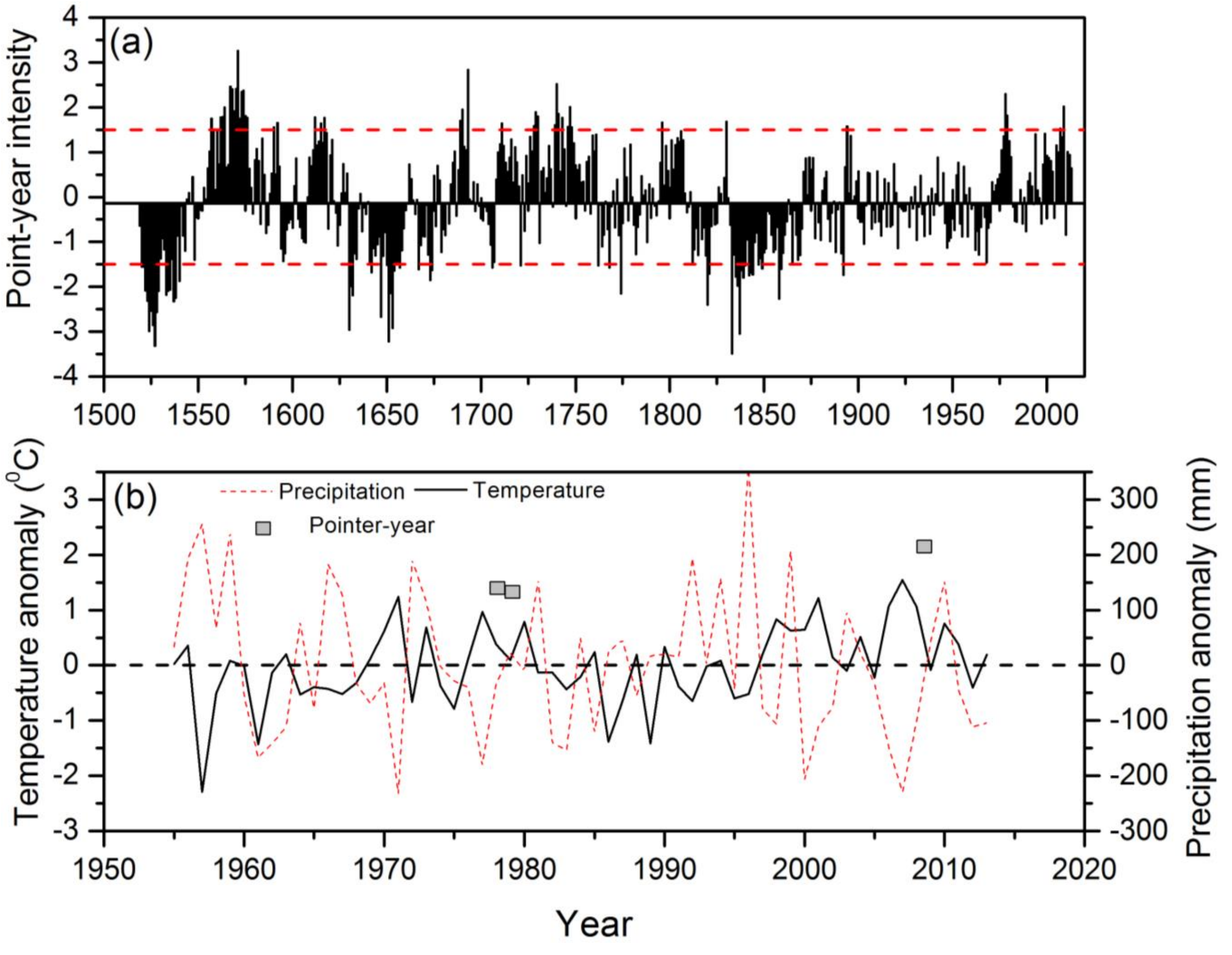

Fig. 7. (a) Pointer year indices values of the PC1 chronology of the Karakoram region, northern Pakistan. The horizontal red dashed lines (±1.5) shows upper and lower limits of pointer years, (b) pointer years corresponds well with an extreme annual temperature of Astore station.

Conclusions

We developed two new tree-ring chronologies of *P. wallichiana* from nearly located upper timberline of the Karakoram region, northern Pakistan. The relationship between the climate and TRW revealed the growing season (March-May, June-August, April-September of the current year) and mean annual (previous year October to current year September) temperature had a significant influence on the radial growth of *P. wallichiana*. TRW chronologies are weakly correlated with precipitation and PDSI. Additionally, the PC1 chronology is significantly positively associated with temperature and insignificantly correlated with precipitation and PDSI. This indicated that the tree-growth in the region is sensitive to temperature rather than precipitation and PDSI. The favorable growing condition was more frequent during the 20th century, indicating that the warming of the 20th century was positive for tree-growth in the study area. However, more detail studies representing more sites are necessary to minimize the uncertainties and for better understanding the relationships between radial growth and climatic variations in the Karakoram region.

Acknowledgments

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