



Tree-ring-based temperature reconstruction from the western Himalayan region in northern Pakistan since 1705 C.E.

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Abstract

The western Himalayan region in northern Pakistan is one of the most sensitive hotspots to climate change, due to the rapidly increasing population and delicate mountainous ecosystem. The relatively limited observed instrumental record impedes our understanding of long-term climate variability and their assessment. Using standard dendrochronological techniques, a 395-year (1620 to 2014 C.E.) tree-ring chronology of *Abies pindrow* (Royle) (Himalayan fir) was developed from the western Himalayan region in northern Pakistan. The results of the growth-climate relationship demonstrated that the radial growth of *Abies pindrow* was limited by minimum temperature. Using a robust reconstruction model, a 310-year (1705 to 2014 C.E.) minimum temperature was reconstructed from the western Himalayan region in northern Pakistan. The reconstructed minimum temperature accounts for 38% variance of the actual minimum temperature, and provides the evidences of Dalton minimum and modern maximum periods. The coldest years in the reconstruction were 1726, 1727, 1892, 1921, and 2001, whereas the hottest years were 1789, 1807, 1814, 1846, 2011, and 2013. Multi-taper method (MTM) spectral analysis showed a significant shorter quasi-cycles (2.3 to 3.5 years) and decadal cycles (11.5 to 17.5 years), suggesting a possible teleconnections with El Niño Southern Oscillation (ENSO), and Northern Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO) respectively.

Keywords Tree-ring · *Abies pindrow* · Growth-climate response · Temperature reconstruction · Western Himalayan · Northern Pakistan

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Introduction

The Himalayan mountainous region is one of the most vulnerable regions on the planet towards climate change and plays a pivotal role in influencing regional- to the large-scale circulation system. This mountainous system spreads over the east-southeast to west-northwest in an arc of 2400 km. The rapidly increasing temperature and their related environmental phenomenon are adversely affecting the Himalayan region. Studies showed that global warming reduces the glacier mass in the Himalayan region (Bolch et al. 2012; Rabatel et al. 2013). A regional-based temperature reconstruction dataset revealed that the Himalayan and Tibetan plateau have been warmed significantly at an unprecedented rate during the recent decades (Brohan et al. 2006; Diodato et al. 2012). In addition, the temperature of the high altitudinal region of Himalayan is increasing significantly than of the lower altitudinal region (Shrestha et al. 1999). The estimated short-term climate data from the western Himalayan region in northern Pakistan cannot elucidate comprehensive knowledge of the climate variability in long-term perspective. However, the climate proxy such as tree-ring with high-resolution natural archives can be used to fulfill this gap (Fritts 1976).

Tree-ring with high resolution and reliability and its sensitivity has the ability to store information of climate and is useful for the reconstruction of long-term climate variability (Fritts 1976; Speer 2010). A number of tree species have been reported for their utility in multiple aspects of tree-ring research from the Himalayan region (Bhattacharyya et al. 1988; Yadav et al. 1999; Shah et al. 2007; Cook et al. 2003, Sano et al. 2005; Thapa et al. 2015, Gaire et al. 2019); Hindu Kush (Khan et al. 2013); Karakoram (Ahmed et al. 2011; Cook et al. 2013; Esper et al. 2002; Zafar et al. 2015; Asad et al. 2016); and Tibetan Plateau (Yu et al. 2006; Li and Li 2017). These studies showed the influence of climate change on the regional to large scale. However, few tree-ring-based temperature reconstruction provided the evidence of increasing global warming over the Himalayas and Central Asia (IPCC 2007; Cook et al. 2013; PAGES 2k Consortium 2013; Zafar et al. 2015). Furthermore, tree-ring based temperature reconstruction from the altitudinal region of 2850 to 3296 m in northern Pakistan showed out-of-phase relationship with the Northern Hemisphere temperature (Zafar et al. 2015), while the reconstruction from the altitudinal region of 3550 to 3710 m indicated in-phase relationship with the Northern Hemisphere temperature (Asad et al. 2016). Indeed, these studies provide fruitful information about the climate of northern Pakistan. However, comparable to the adjacent region of Asian countries, Pakistan has very limited literature regarding climate reconstruction. In addition, the meteorological stations in northern Pakistan are scant and are located at lower elevations (Ahmed et al. 2011; Khan et al. 2013). In this scenario, tree-ring is the most reliable natural climate proxy, which can

be used for the reconstruction of past climate. In addition, to determine the geographical heterogeneity and to identify multiple climate signals in the tree-ring, further studies are highly needed.

The highland of the western Himalayan region in northern Pakistan boasts widespread conifer species and has great potential for dendroclimatic reconstruction. *Abies pindrow* (Royle) is abundantly distributed in the western Himalayan region. In the Indian subcontinent, this species has been widely used for dendroclimatic reconstruction (Bhattacharyya et al. 2001; Thapa et al. 2013; Ram and Borgaonkar 2014). In the light of these scientific evidences, it is obvious that *Abies pindrow* is highly valuable for dendroclimatic reconstruction. Prior to the current study, this species has not been used for the past climate reconstruction in northern Pakistan. Therefore, the present study was conducted with the following objectives: to (1) develop a new tree-ring width chronology of *Abies pindrow* from the uncovered region of Pakistan, (2) present growth-climate relationship, and (3) reconstruct past temperature for almost three centuries. It is intended that this study will enhance our understanding of long-term temperature variability from the western Himalayan region in northern Pakistan.

Materials and methods

Study area (Table 1)

The study area (Harban valley, 35°25'N and 73°40'E) is located in the western Himalayan region of northern Pakistan at an elevation ranging from 3100 to 3250 m (Fig. 1). The area is bordered by the Wakhan Corridor to the north, KP province to the west, China to the east, and India to the south. The climate of this region is mainly influenced by westerlies wind (also known as western disturbances or winter monsoon) during winter and to some extent by the Indian summer monsoon (Khan et al. 2019). Based on the climate data of the nearest climate stations (i.e., Chilas ≈ 30 years and Gilgit ≈ 60 years of climate records), June to August are the hottest months, and November to February are the coldest months (Fig. 2). The recorded average temperatures were 20.3°C (Chilas) and 18.8°C (Gilgit), whereas the average precipitations were 197 mm and 177.1 mm respectively. In both stations, the highest precipitations have been recorded from March to May (Pakistan Meteorological Department Karachi, Pakistan 2016).

Selection of species and sample collection

Abies pindrow, a native conifer species of the Himalayan region, is distributed from central Nepal to northeast China and India (Bhandari et al. 2020). It generally grows in the moist

Table 1 Site information and statistical characteristic of *Abies pindrow* (Royle) (Himalayan fir) chronology from the western Himalayan region in northern Pakistan

Site name	Harban valley of Indus Kohistan
Latitude (N)	35°25'
Longitude (E)	73°40'
Elevation range (m)	3100 to 3250 m
Chronology length	1620 to 2014 C.E.
Samples (cores/trees)	Total = 51/33, rejected = 13/7, used in final analysis = 38/26
Common period	1760–2004
Mean sensitivity	0.186
Correlation with master	0.622
Mean correlation between all series	0.367
Mean correlation within tree	0.495
Mean correlation between trees	0.365
First order autocorrelation	0.823
Standard deviation	0.617
Expression population signal (EPS)	0.921
Signal-to-noise ratio (SNR)	11.585
Explained variance in first eigenvector (%)	40

and cold region at an elevation of 2000 to 3300 m, and reaches a diameter of 2 to 2.5 m and heights of 40 to 60 m (Farjon 2010; Xiang et al. 2013). In northern Pakistan, *Abies pindrow* is widely distributed from dry to moist temperate areas (Ahmed 1989; Ahmed et al. 2010, b). Trees with higher monetary value are usually harvested in northern Pakistan. However, because of the low market value, *Abies pindrow* was undisturbed by the local community, comparable to other conifer species like *Cedrus deodara*, *Pinus wallichiana*, and

Picea smithiana. In the sampling site, *Abies pindrow* was the dominant tree species. Using standard dendrochronological techniques, core/wood samples were extracted from the *Abies pindrow* through increment borers (diameter, 5.15 mm) (Stokes and Smiley 1968; Fritts 1976; Speer 2010; Ahmed 2014). In general, two cores were extracted from the older tree, and only one core was extracted from the younger tree (less than 150 years). A total of 51 core samples from 33 trees were collected for analysis (Fig. 3).

Fig. 1 Locations of *Abies pindrow* (Royle) sampling site (red rectangular) and meteorological stations (lime triangles) from the western Himalayan region in northern Pakistan

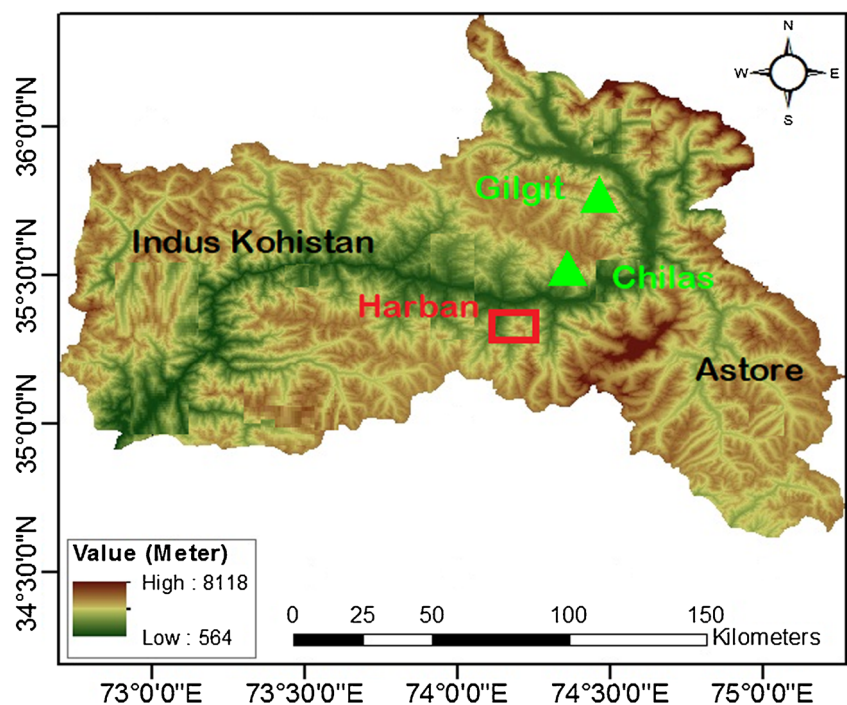
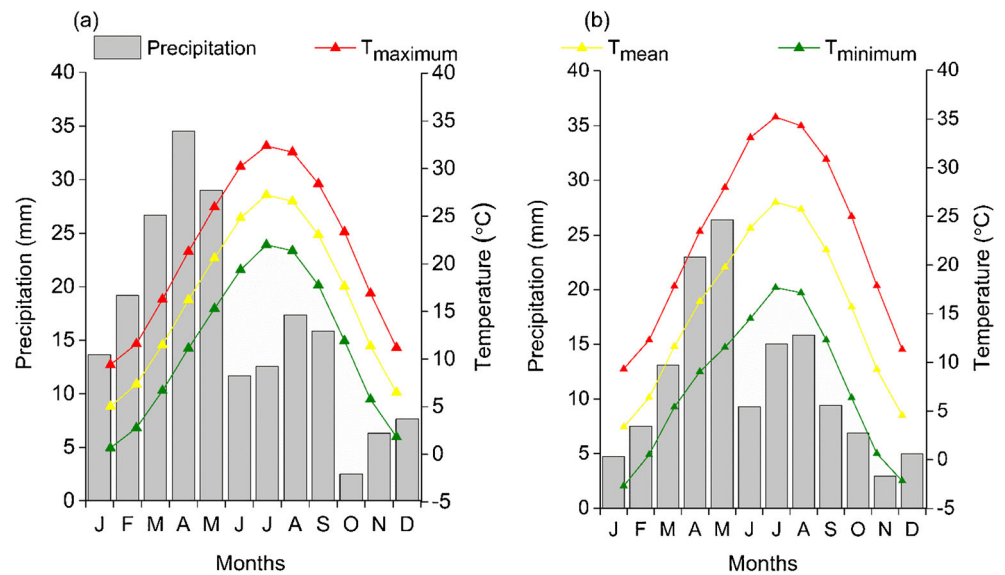


Fig. 2 Climograph for Chilas (a) and Gilgit (b) stations including monthly variation in precipitation (gray bars), monthly maximum temperature (red lines with arrows), monthly mean temperature (yellow lines with arrows), and mean monthly minimum temperature (green lines with arrows) from the western Himalayan region in northern Pakistan



Sample preparation and chronology development

After collection, the wood samples were packed in drinking plastic straw to avoid breakage. The samples were air-dried and mounted on pre-fabricated wooden frames. The wood samples were polished through fine sandpapers (100–1000 grades size). The skeleton plot technique was used for cross-dating (Speer 2010), and each sample was measured through

the Velmex tree-ring measuring machine connected with a computer and J2X software (Voortech 2020). Samples with double and complacent rings (13 cores from 7 trees) were eliminated out to attain accurate cross-dating. All the tree-ring width series were merged in a single file and the result of the cross-dating was checked through COFECHA software (Holmes et al. 1986). To develop a standardized tree-ring width chronology, and to remove the unwanted growth trends (noises) such as age and stand dynamics, the cross-dated raw ring widths index was de-trended by fitting a negative exponential curve using ARSTAN software (Cook and Kairiukstis 1990). Various statistics including mean sensitivity, standard deviation, autocorrelation, signal-to-noise ratio (SNR), expressed population signal (EPS), and rbar were calculated to estimate the quality of the developed tree-ring width chronology (Fritts 1976; Wigley et al. 1984; Briffa 1995).

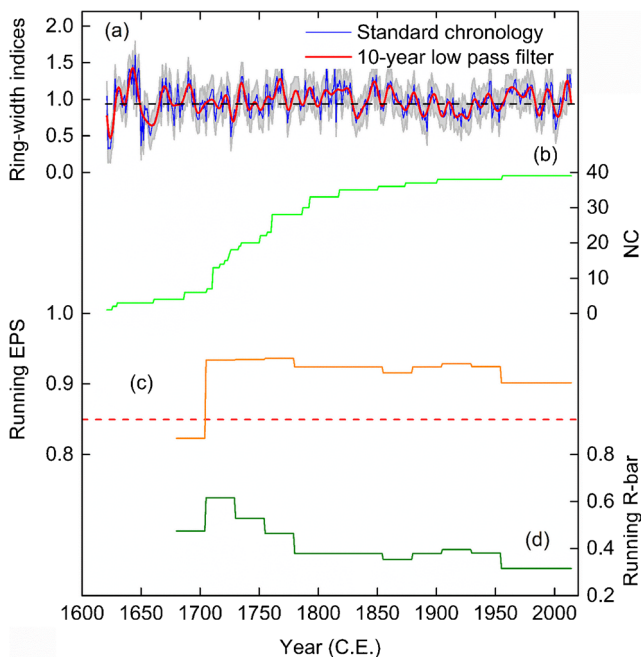


Fig. 3 (a) Standard tree-rings width chronology of *Abies pindrow* with 10-year low pass filter. (b) Number of core samples (NC) in the chronology. (c) Running EPS. (d) Running R-bar. The black dash in the panel represents the mean (0.98) value of the tree-ring width chronology, whereas the red dash line shows threshold limit (0.85) of the expression population signal (EPS). The shaded area demonstrates standard error of the regression

Growth-climate relationship analysis

To assess the growth-climate relationship, Pearson's correlation was determined between tree-ring chronology and meteorological data through DENDROCLIM 2002 software (Biondi and Waikul 2004). The meteorological station of Chilas region (35°25'N, 74°06'E, elevation = 1250 m asl) was the nearest (about 25 km) to our tree-ring sampling site. However, based on the number of missing data and short-term climate record (i.e., 30 years), we decided to use Gilgit station data (35°55'N, 74°20'E, elevation = 1460 m asl), with long-term climate record (60 years, aerial distance ≈ 55 km). In high altitudinal regions, the growth of conifer species mostly depends on microclimate. However, it varies from species to species and from site to site. To determine accurate growth months, and to find out the influence of the previous year climate on the current year's growth of *Abies pindrow*,

Pearson's correlation between tree-ring width chronology and climate variables was performed from the previous year March to the current year October. The climate variables include maximum, minimum, and mean temperature, and precipitation. Among these climate variables, a strong significant correlation ($r = 0.615$, $p < 0.001$) was found between tree-ring width chronology and from August to October mean minimum temperature. The precipitation from August to October showed a significant negative correlation ($r = -0.30$, $p < 0.001$). This indicates that from August to October minimum temperature was the key climatic factor for the radial growth of *Abies pindrow*, whereas precipitation of these months inhibits the radial growth. Therefore, minimum temperature and precipitation were used for further analysis.

Reconstruction methodology

Based on growth-climate relationship, it was found that the for temperature reconstruction of August to October, minimum temperature was theoretically possible. Therefore, a reconstruction model between the standard tree-ring width chronology and August to October mean minimum temperature was developed as follows:

$$T_{ASO} = 11.235 \text{ STD} + 25.023$$

where T_{ASO} is the mean minimum temperature from August to October and STD is the standard chronology (Fritts 1976; Speer 2010). The reconstruction model was statistically significant ($n = 60$, $r = 0.615$, $R^2 = 37.9\%$, $R^2_{\text{adj}} = 36.8\%$, $F = 35.325$, $p < 0.001$). The correlation between the standard tree-ring width chronology and from August to October minimum temperature during the common calibration period of 60 years (1955 to 2014 C.E.) was statistically significant ($r = 0.615$, $p < 0.001$). The predicted variable (minimum temperature) accounted for 38% variance (37% after being adjusted for loss of the degree of freedom, $F = 35.325$ and $p < 0.001$) in the actual data during calibration period. The positive value of reduction of error (RE), obtained by the leave-one-out cross-validation technique (Michaelsen 1987), demonstrated the stability of our reconstruction model (Table 2). To check the autocorrelation of our reconstructed minimum temperature, we used the Durbin-Watson (DW)

statistic. For the reliability of response and predicted variables, the reconstructed and actual temperatures were tested through an F-test. Based on the stability and effectiveness of the reconstruction model, August to October minimum temperature reconstruction was truncated at the point of commonly used expression population signal (EPS) threshold limit ($\text{EPS} \geq 0.85$). Spectral analysis was determined by the multi-taper method (MTM) (Mann and Lees 1996).

Results

Tree-ring width chronology of *Abies pindrow* and growth-climate response

We developed a 395-year (1620 to 2014 C.E.) standard tree-ring width chronology of *Abies pindrow* from the western Himalayan region in northern Pakistan. Based on the EPS threshold limit ($\text{EPS} < 0.85$), the chronology is reliable to represent the respective population after 1705 C.E. The chronology generally shows high mean sensitivity and standard deviation. The average correlation with master chronology was 0.573, while the mean ring width was 1.62 mm. Autocorrelation, which indicates the dependence of the current year growth on the previous year, was considered reliable for the reconstruction of the past temperature. The high mean inter-series correlation (0.315 to 0.616) demonstrated that the tree-ring width chronology of *Abies pindrow* has a strong climate signal.

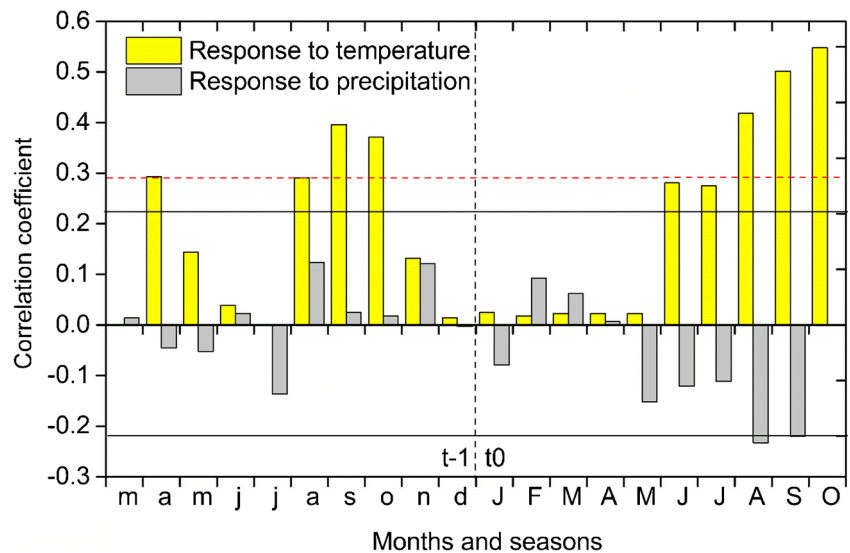
The growth-climate relationship of *Abies pindrow* was assessed by the correlation coefficient between tree-ring width chronology and climate variables for 60 years (Fig. 4). The correlation coefficient ± 0.23 was significant at $p < 0.05$ for 60 years. The results revealed that the tree-ring width chronology has a negative relationship with precipitation of the current year August and September. Furthermore, the chronology showed a significant positive correlation with the minimum temperature of the previous year April and from August to October, and the current year minimum temperature from June to October (Fig. 4). The tree-ring index revealed a marked relationship with August to October minimum temperature ($r = 0.615$, $p < 0.001$). Therefore, we choose these months for reconstruction.

Table 2 Leave-one-out cross-validation statistics for the reconstructed August to October mean minimum temperature from the western Himalayan region in northern Pakistan

r	r^2	Adjacent r	F	Sign test	RE	PMT	Durbin-Watson statistic
0.615	0.379	0.368	35.325	32+/27	0.382	3.713	1.404

RE reduction of error, PMT product mean test

Fig. 4 Correlation coefficients between tree-ring width index and meteorological data of Gilgit including mean minimum temperature (yellow vertical bars) and total monthly precipitation (gray vertical bars). The correlations were computed from the previous year March to the current year October over the common period of 60 years (1955 to 2014 C.E.). The horizontal black solid lines represent a significant level at 95% confidence limit, whereas the horizontal red dashed line indicates a significant level at 99% confidence limit through time

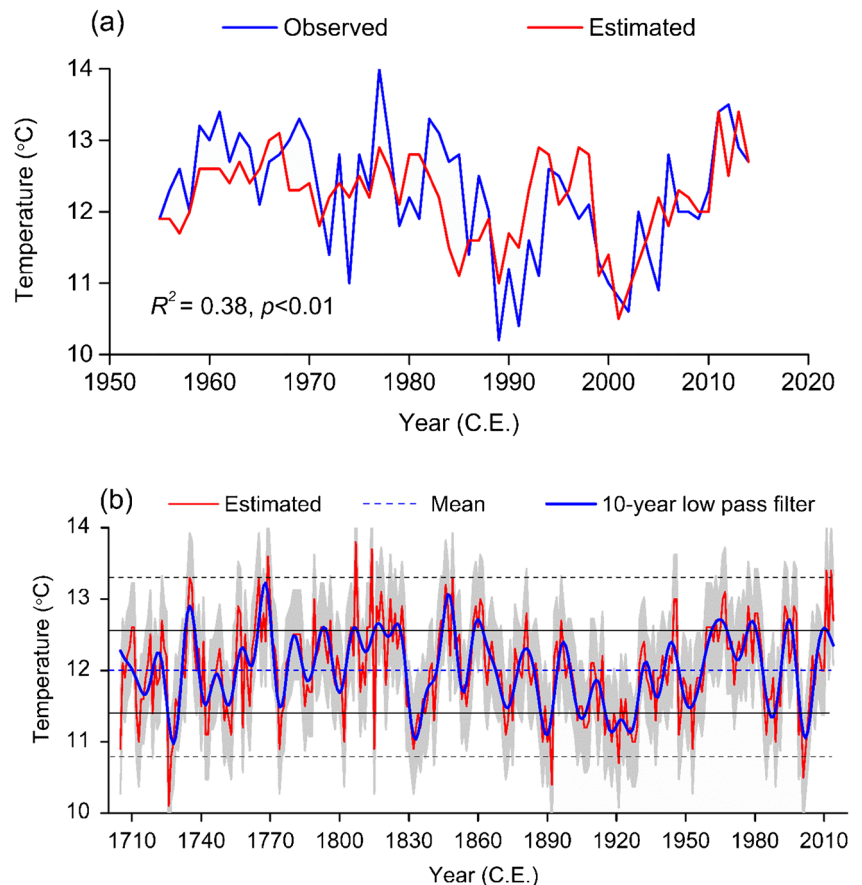


Temperature variations from 1705 to 2014 C.E. for the western Himalayan region

Based on transfer function, a 310-year (1705 to 2014 C.E.) mean minimum temperature from August to October (ASO) was reconstructed for the western Himalayan region in northern Pakistan (Fig. 5(b)). The estimated temperature was

superimposed on the observed temperature curve, except for few extremely high or low years (Fig. 5(a)) having a mean value of 12.02 with a 0.62 standard deviation (σ). The reconstructed series showed 14 coldest periods (temperature $<12.02^{\circ}\text{C}$), and 11 hottest periods (temperature $>12.02^{\circ}\text{C}$) with the most prominent historical decreasing temperature trend of Dalton minimum, and slightly increasing temperature

Fig. 5 (a) Observed and estimated mean minimum temperature of August to October from the western Himalayan region in northern Pakistan, over the common calibration period of 60 years (1955 to 2014 C.E.). (b) Estimated temperature (red thin line) with 10-year low pass filter (blue thick line) for the period of 310 years (1705–2014 C.E.). The central horizontal blue dashed line represents the long-term mean temperature (12.02°C), the inner solid horizontal black lines show the border of 1 standard deviation (11.40°C and 12.64°C), and the outermost dashed horizontal red lines represent the border of 2 standard deviation (10.78°C and 13.26°C)



trend of modern maximum. Over the past 310 years, the coldest periods were 1712 to 1716, 1726 to 1733, 1742 to 1746, 1749 to 1754, 1784 to 1788, 1829 to 1839, 1884 to 1892, 1801 to 1908, 1915 to 1929, 1933 to 1939, 1947 to 1958, 1984 to 1991, and 1999 to 2004, whereas the hottest periods were 1762 to 1773, 1777 to 1783, 1789 to 1796, 1803 to 1808, 1821 to 1828, 1845 to 1852, 1857 to 1863, 1893 to 1897, 1959 to 1983, 1992 to 1998, and 2007 to 2014. In the present study, the recorded extremely hottest years (mean temperature greater than $+2\sigma$, i.e., 13.26) were 1789, 1807, 1814, 1846, 2011, and 2013, while the coldest years (mean temperature less than -2σ , i.e., 10.79) were 1726, 1727, 1892, 1921, and 2001.

MTM spectral analysis

The spectral analysis of the reconstructed minimum temperature from the western Himalayan region in northern Pakistan revealed both shorter (2.3 to 3.5 years) and decadal (11.9 to 17.5 years) frequency cycles (Fig. 6).

Discussion

Chronology development and growth-climate relationships

In this study, a new tree-ring width chronology of *Abies pindrow* over the past 395 years (1620 to 2014 C.E.) was developed from the western Himalayan region in northern Pakistan. *Abies pindrow* has a great dendrochronological potential and has been widely reported in the Himalayan region of the Indian subcontinent (Bhattacharyya et al. 2001;

Chaudhary et al. 2013, Thapa et al. 2013; Ram and Borgaonkar 2014). In Pakistan, reconstruction of the past climate through tree-ring of *Abies pindrow* has not been explored yet, as the tree-ring research of this species was only limited to age, growth rate, and chronology assessment (Ahmed 1989; Khan et al. 2018; Iqbal et al. 2020). In this study, we determined that *Abies pindrow* growing in the western Himalayan region in northern Pakistan has a potential for the reconstruction of the past climate. The statistical characteristics of our tree-ring width chronology were comparable to other studies of *Abies pindrow* reported from various sites of the Himalayan region (Bhattacharyya et al. 2001; Ahmed et al. 2010, b, 2011; Chaudhary et al. 2013; Thapa et al. 2013). However, the ultimate reasons for the statistical variations in chronology of this study are altitude and microclimate of different regions. Altitude controls the microclimate of an area, which significantly influences the radial growth of trees. In this study, the moderate mean sensitivity, high standard deviation, and reliable EPS, and Rbar statistics, showed that the radial growth of *Abies pindrow* was significantly limited by the regional climate (Cook and Kairiukstis 1990; Luckman 1997; Speer 2010; Zhang et al. 2017). In addition, the tree-ring width chronology of *Abies pindrow* developed in the present study also showed similar statistical characteristics with the tree-ring chronologies of different species reported from northern Pakistan (Zafar et al. 2015; Asad et al. 2016; Esper 2000; Tyredte et al. 2006; Cook et al. 2013; Rao et al. 2018). This indicates that the climate of northern Pakistan has similar influences on the radial growth of multiple tree species.

The results of the grow-climate relationship demonstrated that minimum temperature especially during late-growing season (August to October) is the key limiting factor for the radial growth of *Abies pindrow*. The tree-ring width chronology showed relatively high correlations with mean minimum temperature from August to October. Studies showed that the active growth period of the Himalayan conifer starts in March and continues until October (Chowdhury 1939; FRI information series-18 1976; Zhang et al. 2014). These evidences suggested that climate during August to October months is crucial for the radial growth of *Abies pindrow*. According to Borgaonkar et al. (2018), in the Himalayan region, formation of earlywood in the conifer species is active in March and continues until May or June, whereas the latewood formation continues throughout October. In some parts of Pakistan, the radial growth of conifer also starts in early March (Ahmed 1989). However, it varies from site to site and from species to species even on the same site. It is obvious that the western Himalayan region in northern Pakistan received high snowfall from December to March. At the high altitude and glaciated area of this region, the glacier remained until late summer. In such conditions, minimum temperature played a crucial role as it creates moist condition with air

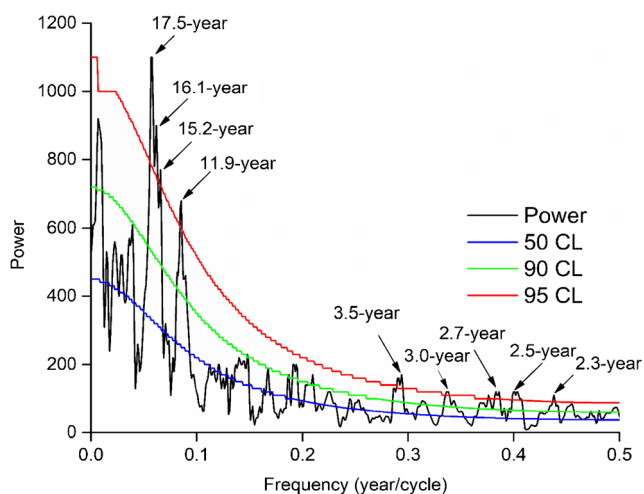


Fig. 6 Multi-taper method (MTM) power spectra of the reconstructed mean minimum temperature of August to October from the western Himalayan region in northern Pakistan. The peak above the red solid line indicates a significance level at 95% confidence limit

circulation and thus supports the growth of conifer species. However, the abrupt increment in temperature during pre-monsoon creates soil moisture stress, which ultimately limit the radial growth of some of the trees in different parts of the Himalayas (Pant et al. 2000; Yadav et al. 2004, b; Zafar et al. 2015). The marked relationship between tree-ring width chronology and minimum temperature might be due to this reason. Generally, trees growing at high altitudinal region are mostly sensitive to temperature rather than to precipitation. Such trees are receiving sufficient water through the melting of glaciers, and thus perform normal physiological functions. Previous studies reported that in normal conditions, the conifer needles typically reach peak photosynthetic potential in the next growing season; therefore, the climate of the previous year has a significant influence on the radial growth in the current year (Fritts 1976; Zafar et al. 2015). Similar to these studies, the radial growth of *Abies pindrow* in the present study also showed a significant positive correlation with the mean minimum temperature of the previous year April, and from August to October. The lowest correlation (particularly negative) between tree-ring width chronology and precipitation might be due to the absence of seasonality in precipitation at the western Himalayan region in northern Pakistan or availability of the sufficient soil moisture for the growth. However, this point needs further research.

Temperature reconstruction

The western Himalayan region in northern Pakistan plays a vital role in the supply of fresh water in Pakistan. The glaciated high mountainous region in northern Pakistan feeds more than 70% of water to the eastern and western rivers of Pakistan. Due to the abrupt rising of temperature associated with global warming, the glaciers of the Himalayan region are under severe threat. In the Himalayan region, the increasing temperature accelerates the glacier mass melting, which supplies more water to the surrounding rivers, but in unpredictable manner. If rising of temperature continues in the same rate, in the near future the water supply in the Himalayan mountainous region of northern Pakistan will be altered. A recent water assessment report demonstrated that 36% of the glacier mass in the Himalayan and Hindu Kush regions will melt by the twenty-first century even if the temperature raises below 1.5°C (Wester et al. 2019). If the temperature in these regions raises by 2°C, around half of the glacier mass will melt (Virk et al. 2020). It is evident that winter temperature in the Himalayan region has been rising with 0.65°C, which is 0.44°C higher than the average raise of global temperature (Jain 2018). More precisely, rising of temperature in winter is more alarming for the western Himalayan region in northern Pakistan. Therefore, proper planning and knowledge of long-term temperature are important in this region.

The characteristics and variance explained by our reconstruction were consistent with the previous tree-ring-based temperature reconstruction from the northwestern Himalayan region of India (Bhattacharyya et al. 2001; Chaudhary et al. 2013) and the western Himalayan region of Nepal (Thapa et al. 2015). Similar to our study, some researchers also presented tree-ring-based late summer temperature reconstruction from the Himalayan region of the Indian subcontinent (Chaudhary et al. 2013; Borgaonkar et al. 2018). These studies provide further evidence of stability and reliability to our reconstruction. Our study also revealed the evidence of the Dalton minimum period (Tambora eruption of 1815) (Cole-Dai et al. 2009) and cooling period of Krakatau eruption (occured in 1883). The Dalton minimum period coincides with a period having cooler temperature around the globe. This decrease in temperature was attributed to the massive volcanic eruption of the Tambora mountain in Indonesia. Due to this notable decreasing trend in temperature, most parts of the Northern Hemisphere experienced heavy snowfall; therefore, this period was considered the period without summer. The Indonesian volcano Krakatoa which erupted in 1883 cooled the sea surface temperature and suppressed it for decades afterward. Our reconstruction also indicates the modern maximum period of temperature; however, it was not prominent as the above said periods. The physical mechanism, which explains how these periods affect the Himalayan climate in northern Pakistan, is unknown and needs further research.

Studies evident that mountainous ecosystems are the most delicate ecosystems and are very sensitive to climate change (Diaz et al. 2003; Borgaonkar et al. 2018). Therefore, change in temperature in the mountainous ecosystems directly or indirectly affects the natural resources and their related livelihood. Our study showed a prominent decreasing trend of temperature from 1810 to 1990 C.E. However, in recent decades the temperature trend is slightly increasing. Some studies from the central and western Himalayan regions provided evidence of increasing temperature (Shrestha et al. 1999; Liu and Chen 2000; Pant et al. 2003; Bhutiyani et al. 2007). This notable warming trend was not observed in our reconstruction; however, the slightly increasing trend in temperature during the late twentieth century indicates that the western Himalayan region in northern Pakistan is getting warm.

MTM power spectral analysis and teleconnections

The significant ($p < 0.01$) shorter spectral cycles (2.3 to 3.5 years) of our reconstruction demonstrated that the climate of the western Himalayan region is influenced by El Nino-Southern Oscillation (ENSO) (Allan et al. 1996; Allan 2000; Bridgman and Oliver 2006; Ruibo et al. 2016). The decadal spectral cycles (11.9 to 17.5 years) showed a possible teleconnection with Northern Atlantic Oscillation (NAO) or

Atlantic Multidecadal Oscillation (AMO). Similar results were also noted in the temperature reconstructions from the western Himalayan region of India (Singh and Yadav 2013) and the Tibet mountain of China (Wang et al. 2008). These results indicated that the western Himalayan region in northern Pakistan was influenced by regional- to broader-scale climate circulation. However, concerning this point, no estimated records are available for the western Himalayan region in northern Pakistan. Therefore, we recommend further research on this aspect to identify the mechanism on how ENSO or AMO influences the climate in the Himalayan region.

Comparison with regional studies of Pakistan

To assess the regional-scale temperature trend, we compared our reconstructed August to October (ASO) minimum temperature from the western Himalayan region in northern Pakistan with summer (JJA) (Zafar et al. 2015), and April to July (AMJJ) (Asad et al. 2016) minimum temperature (Fig. 7), from the Karakoram region in northern Pakistan. On the inter-annual scale, our reconstructed August to October minimum temperature showed a low correlation with the previous reconstructed minimum temperature of northern Pakistan (Zafar et al. 2015; Asad et al. 2016). After a 10-year low pass filter, the correlation of our reconstructed minimum temperature was significantly increased, i.e., $r = 0.569$, $p < 0.001$ (Zafar et al. 2015) and $r = 0.271$, $p < 0.01$ (Asad et al. 2016). These correlations indicate that the influence of climate in northern Pakistan was consistent on decadal scales. Our reconstruction also showed agreement with some warm and cool periods (the shaded line) with previous studies conducted in northern Pakistan (Fig. 7). For example, the pronounced cooling period

of Maunder minimum (before the 1700 century) reported in the tree-ring study of Asad et al. (2016) was also observed in our study. However, because of the short proxy, limited record of this study, the whole period was not recorded properly. Similarly, the Dalton minimum (Tambora 1815) period and cooling period of Krakatau (1883) of this study were also observed in the reconstruction of Asad et al. (2016). These evidences were not clear in the reconstruction of Zafar et al. (2015). This might be due to differences in elevations of the selected study sites, and the use of different approaches for the reconstruction. Furthermore, for the determination of climate signal in the tree-ring samples, aspect also owns a significant role. Zafar et al. (2015) collected tree-ring samples from the north aspect of the Karakoram region in northern Pakistan. Asad et al. (2016) did not discussed the aspect of their sampling site. According to Esper (2000), in the Karakoram range of northern Pakistan, the moist temperate *Pinus* and *Picea* species are mostly growing on the north slope, whereas the dry-temperate *Juniperus* is growing on the south slope. The strong correlation between our reconstruction and Zafar et al.'s (2015) reconstruction may be due to the same aspect of the sampling sites. Additionally, *Abies pindrow* has a wide ecological amplitude and is distributed from moist (Ahmed 1989) to dry zones of Pakistan (Khan et al. 2016; Ahmed et al. 2011). Our sampling site was also located on the dry site of the western Himalayan region in northern Pakistan (Khan et al. 2016; Saqib et al. 2006).

Influence of volcanic eruption on Himalayan climate

A number of tree-ring studies supported the influence of volcanic eruptions on tree-ring and its association with strong

Fig. 7 Graphical comparison between the reconstructed minimum temperature from August to October of this study and the tree-ring-based minimum temperature from northern Pakistan (Zafar et al. 2015, Asad et al. 2016). The gray shaded area represents similarities in temperature of this study and previous studies of northern Pakistan

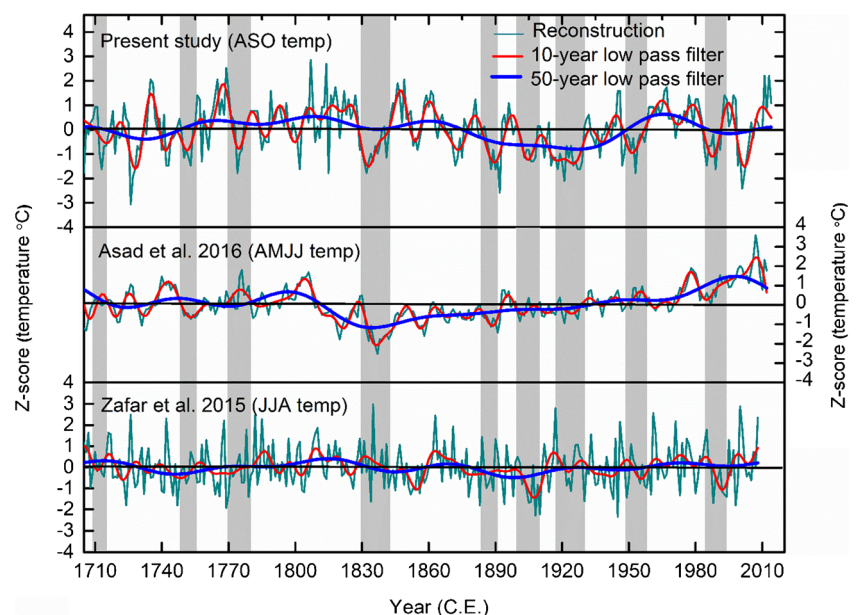


Table 3 Largest explosive volcanic eruption events and low temperature from the western Himalayan region in northern Pakistan since 1705 to 2014 C.E.

Volcano region	Years and month	Anomaly value (°C)
Tarumai, Japan	August, 1739	-0.14
Katla, Iceland	October, 1755)	-0.16
Laki, Iceland	June, 1783	-0.78
St Helens, USA	May, 1980	-0.34
Tambora, Indonesia	April, 1815	-2.1
Cosiguina, Nicaragua	June, 1835	-1.65
Komagatake, Japan	September, 1856	-0.13
Krakatau, west of Java	August, 1883	-0.35
Tarawera, New Zealand	June, 1886	-0.69
Mt. Pelée, Martinique	May, 1902	-0.73
Taal, Philippines and Katmai, USA	June, 1911	-0.42
Novarupta (Katmai), Alaska	June, 1912	-1.51
Kelat, Indonesia	May, 1954	-0.75
Bezymianny, Russian	March, 1956	-0.39
Augustine, USA	Jan, 1976	-0.21
Bezymianny, Russian	Feb, 1979	-0.17
Pinatubo, Philippines	June, 1991	-1.17

cooling events including the eruption of Tambora and Krakatau (LaMarch and Hirschboeck 1984; Briffa et al. 1998; D'Arrigo and Jacoby 1999; Gervais and MacDonald 2001; Borgaonkar et al. 2018). Compared to volcanic eruptions, our study indicated that there is no systematic relationship between tree-ring-based minimum temperature reconstruction and the volcanic eruption or forcing data of Simkin and Siebert (1994). However, some clear low values were observed in 19 different events and each event follows the volcanic eruption. The mean anomaly of a particular year is -0.69°C below the mean temperature (12.02°C) (Table 3). This indicates that the major volcanic eruptions in the tropical and extra-tropical regions of the world can cause temperature anomaly (generally cooling effect) in the Himalayan region in the same or years following the eruptions.

Conclusions

We developed a 395-year (1620 to 2014 C.E.) long tree-ring width chronology of *Abies pindrow* (Himalayan fir) from the western Himalayan region in northern Pakistan. It was noted that the radial growth of *Abies pindrow* in the western Himalayan region was mainly limited by mean minimum temperature. By using a robust reconstruction model, a 310-year (1705 to 2014 C.E.) long mean minimum temperature was reconstructed, which showed the evidences of Dalton and Krakatau decreasing temperature trends and slightly increasing temperature trend of modern maximum. The spectral analysis revealed some shorter and decadal spectral cycles, which indicates that the climate of western Himalayan in northern

Pakistan was influenced by broad-scale climate circulation. On decadal scale, our reconstruction corresponds well to previous temperature reconstructions from northern Pakistan. However, some discrepancies were found in the marked cooling and warming trends. To overcome this problem and to determine the spatio-temporal variation in the climate in the northern Pakistan, we recommend further in-depth study focusing on multiple tree species, sites, elevations, and aspects.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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