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PAPER

Tree-ring based reconstruction of pre-monsoon temperatures variability in Pakistan's Western Himalayan since 1855 CE

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Keywords: dendroclimatology, *Abies pindrow*, temperature reconstruction, Western Himalayan, Pakistan

Supplementary material for this article is available online

Abstract

Understanding how forest tree species respond to past climate variability is essential for reconstructing the past climate and predicting future challenges, particularly in climate-sensitive mountain ecosystems like the Western Himalayan region. In this study, a new composite regional chronology (CRC) was developed from tree-ring samples of *Abies pindrow* collected from three different sites in the Western Himalayan region of Pakistan. The results of the correlation analysis revealed a significant negative relationship of CRC with pre-monsoon minimum, average, and maximum temperature, as well as a significant positive correlation with pre-monsoon rainfall. The CRC of *Abies pindrow* also showed a significant positive relationship with rainfall during the previous year's July, and November, and the current year April–September. In contrast, a significant negative correlation was noted with previous year's July temperature, while a significant positive correlation was found with August and September temperatures. Furthermore, a significant positive correlation of the CRC with January and February temperatures was observed. A marked negative correlation of the CRC was observed with the current year's May (−0.57), and June (−0.49) temperatures. Based on these correlations, we reconstructed a 166 year record of mean maximum pre-monsoon (May–June) temperature from the Western Himalayan region of Pakistan. The reconstruction accounted for 40.8% of the variance in the observed mean maximum temperature during the instrumental period (1956–2020 CE). The spatial correlation indicates a broad regional teleconnection across the Himalayan regions covering Pakistan, India, and Nepal. The interannual bands (2.43–3.57 years) of MTM spectral analysis and wavelet power spectrum revealed possible linkage with the Atlantic multidecadal oscillation. The superposed epoch analysis showed a substantial connection between the reconstructed temperature and the recorded volcanic eruptions. This study serves as a valuable resource for researchers exploring regional climate change dynamics, providing comprehensive insights into the intricate relationships between climate variations and tree growth in the Western Himalayas.

1. Introduction

A comprehensive understanding of regional climate change necessitates climate data spanning decades or even centuries [1]. However, the scarcity of long-term climate data poses a significant challenge. Insights into Earth's climate trajectory over the last 2000 years, commonly referred to as the 'Common

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Era', become feasible through paleoclimate reconstructions. Such reconstructions are crucial, since relatively short climate observations cannot capture such extended periods [2–7]. These reconstructions offer a nuanced understanding of climate fluctuations across timeframes ranging from interannual to millennium scales, shedding light on the climate's responsiveness and sensitivity to radiative forcing changes [3, 7–15].

Tree-ring, which serve as repositories of environmental signals, are frequently utilized in dendroclimatology to reconstruct climate conditions [16, 17]. Climate-particularly near the limits of a species' biological potential, significantly influences tree growth [18]. Tree-ring characteristics fluctuate annually in response to climate changes, making them reliable natural proxies of past environmental conditions [19, 20]. Numerous studies have examined these patterns on centennial to millennial scales [20–22]. Globally, mountain ecosystems, particularly in the Himalayas, are susceptible to adverse effects from climate change, with glaciers melting faster than the global average [23]. The Western Himalayan region of Pakistan [24], where populations are expanding at lower altitudes, provides an ideal location for dendroclimatological studies that may reveal the effects of human-induced climate change [25, 26]. The western Himalayas, specifically in Pakistan, is an optimal location for exploring dendroclimatic records [27]. Himalayan trees, with their age and high climatic sensitivity, have demonstrated dendroclimatic potential in global climate reconstruction over the past three decades [28–30].

In the Western Himalayas, *Abies pindrow* (Royle ex D. Don) is widely distributed and has been utilized in dendroclimatic reconstructions of the Indian subcontinent [31, 32]. Despite its high dendrochronological potential, limited dendroclimatological research has been conducted in the Western Himalayan region of Pakistan [1, 26]. Although, regional studies reported various reconstructions of different climate variables yet this is also important that the microclimates have a significant impact on forest ecosystems in the context of climate change [33–35]. Therefore, the reconstruction of this region is essential. The selection of *Abies pindrow* as the target species stems from its status as a climate-sensitive tree species in the moist temperate climate zone, making it ideal for growth analysis [36]. The study addresses a gap in existing research by thoroughly exploring *Abies pindrow* temperature growth response, potentially offering insights into historical climatic transitions. To substantiate this hypothesis, the study pursues two key objectives: 1. to analyze the correlation between the newly developed composite regional chronology (CRC) chronology of *Abies pindrow* and climate variable (temperature and rainfall). 2. To reconstruct past temperature fluctuation in the area of Western Himalayan belt of Pakistan, where no prior studies have been conducted, thereby enhancing our understanding of historical climatic variability in the region.

2. Materials and methods

2.1. Study area and climate data

For this study, three different forests, including Bara Gali (34° 04′N, 73° 21′E, 2617 m), Ayubia (34° 01′N, 73° 23′E, 2970 m), and Kuldana (33° 55′N, 73° 23′E, 2455 m) (figure 1) were sampled during June 2021. *Abies pindrow* species generally grow at elevations of about 2000 meters and above in the Western Himalayan region of Pakistan [37]. The sandy clay soils in this region exhibit a high concentration of organic matter [26, 38], and are characterized by a mild climate with cool summers and cold winters. June and July are the warmest months, whereas January and February are the coldest (figure 2). The recorded mean minimum and maximum temperatures in June are 13.3 °C, and 26.6 °C respectively. The average annual rainfall in this region is 1640 millimeters [39]. The Kakul Meteorological Observation Station (KMS) is located approximately 28.4 Km from the sampling sites (34° 11′E, 73° 15′N; altitude = 1308 m). The study area's forest is home to several dominant tree species such as *Quercus incana* (oak), *Aesculus indica* (chestnut), *Olea ferruginea* (Indian olive), *Pinus wallichiana* (blue pine), and *Pinus roxburghii* (chir pine) [40]

2.2. Laboratory methods and statistical analyses

2.2.1. Formation of CRC and response function analysis

A total of 63 cores/wood samples were collected from *Abies pindrow* tree species utilizing an increment borer. Due to excessive moisture contents around 14-wooden samples were damaged and therefore not used in this study. The remaining 49 cores samples were dried at room temperature. Each core sample was carefully mounted onto a grooved wooden holder using Anchor German glue. The mounted cores samples were then dried thoroughly and subsequently polished with progressively fine sandpaper (from 80 to 1000 grit), following standard dendrochronological approaches [41]. The Ring margins of collected cores samples were identified, and ring-width measurements were determined at a resolution

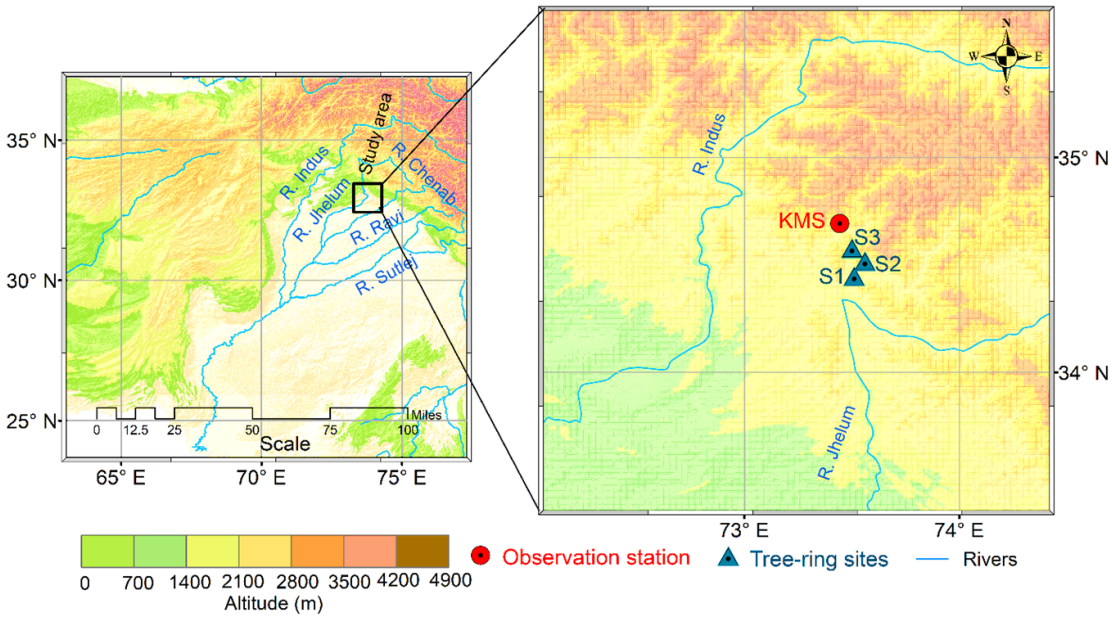


Figure 1. Study area Map showing the sampling sites (S1–S3), and Kakul meteorological observation station (KMS).

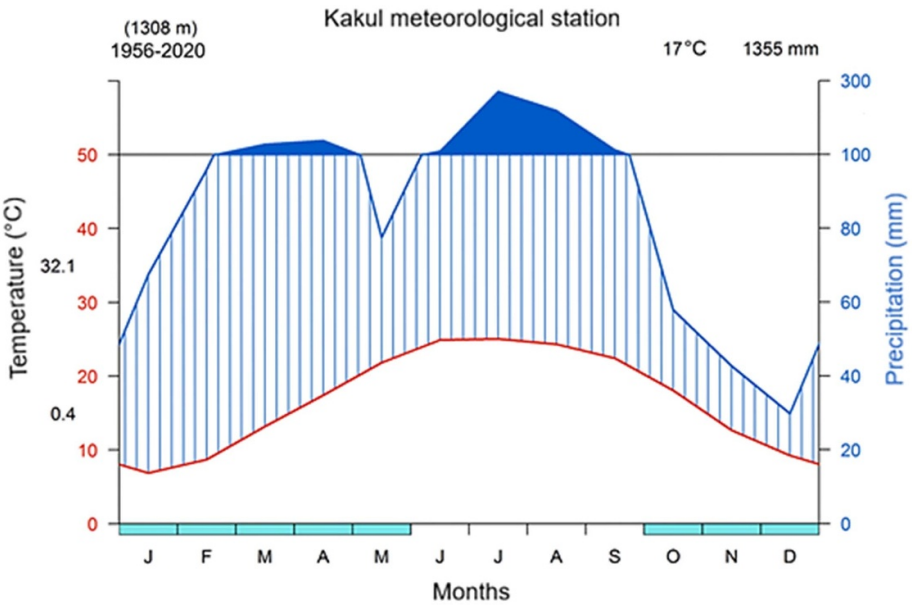


Figure 2. Walter-Lieth climate diagram of the Kakul meteorological observation station (KMS) for the period 1956–2020 CE.

of 2400 dpi through WinDENDRO software in conjunction with the STD4800 scanner. To check the quality of cross-dating the tree-ring index was checked through COFECHA program. During developing of tree-ring width chronology (TRWC) process we applied negative exponential curve fits to exclude non-climate trend undesirable tree growth such as age and stand dynamics. Since the sampling sites were very closed to each other (≈20 Km distance), and showed relatively high correlation, we merged the site tree-ring index into one file (table 1) to developed a CRC [42–45]. The tree-ring index data were processed and transformed into standardized CRC using the dplR package in R [46]. An expressed population signal (EPS $>$ 0.85) indicates patterns at the broader population level and helps to determine the appropriate sample size for dendroclimatological studies. To ensure the credibility of the reconstruction model, the CRC was truncated at 1854 based on the EPS threshold limit [47]. Pearson's correlation coefficient analysis between the CRC and mean monthly minimum, average, and maximum temperatures,

Table 1. Sampling sites information of *Abies pindrow* species and their statistical characteristics from the Western Himalayan region of Pakistan.

Statistical items	Bara Gali	Ayubia	Kuldana	CRC
Latitude (N)	34° 04'N	34° 01'N	33° 55'N	—
Longitude (E)	73° 21'E	73° 23'E	73° 23'E	—
Altitude ranges (m)	2300-2617	2740-2970	2150-2455	—
Core samples/trees	15/10	24/14	10/10	49/34
Chronology span	1773-2020	1773-2020	1799-2020	1773-2020
Series-inter correlation	0.499	0.566	0.491	0.531
Rbar between trees	0.374	0.363	0.341	0.38
Standard deviation	0.338	0.353	0.250	0.293
Mean sensitivity	0.253	0.270	0.231	0.301
Signal to noise ratio (SNR)	8.593	10.731	11.658	11.908
Variance in first Eigen vector (%)	75.3	78.1	79.8	77.6
First year where EPS > 0.85 (no of trees)	1854 (3)	1854 (3)	1875 (3)	1854 (5)
Cross correlation	0.378**	0.831**	0.222**	

Table 2. Statistical characteristics of (a) leave-one-out cross-validation, and (b) split calibration-validation methods for the pre-monsoon temperature reconstruction from the Western Himalayan region, Pakistan.

(a)

r	r^2	Adjacent r	*F*	Sign-test	RE	Durbin–Waston statistic
−0.639	0.408	0.435	33.671**	$41^{+}/25^{-}$**	0.351	1.901

(b)

	Calibration (1955–1989)	Validation (1990–2020)	Calibration (1955–1989)	Validation (1990–2020)	Full calibration (1955–2020)
r	−0.648	−0.627	−0.667	−0.551	−0.639
R^2	0.419	0.393	0.573	0.304	0.408
R^2_{adj}		0.387		0.297	0.435
DW		1.881		1.721	1.901
F value		27.445**		25.168*	33.671**
RE		0.316		0.278	
CE		0.252		0.223	
Sign test		$24^{+}/7$ **		$21^{+}/9^{-}$ *	
First-order sign test		$19^{+}/11^{-}$ *		$21^{+}/8^{-}$ *	

R^2_{adj} = R^2 adjusted, DW = Durbin–Watson, RE= reduction of error, CE = Coefficient of efficiency.

as well as precipitation was performed from the previous year's July to the current year October by utilizing DENDROCLIM2002. To obtain more robust results, we also calculated the correlation coefficient between the CRC and CRU TS 4.05 gridded data.

2.2.2. Pre-monsoon (May–June) temperature reconstruction and validation

Based on strongest correlation between CRC and pre-monsoon (May–June) mean maximum temperature, a 166 year (1854–2020 CE) pre-monsoon temperature series was reconstructed. The reconstruction accounted for 40.8% of the variance ($r = -0.639$) in the observed temperature over the common period of 1955–2020 CE. To ensure the credibility of the reconstruction model, we determined both leave-one-out cross validation statistics and split calibration and verification tests. Statistical metrics, including the reduction of error (RE), coefficient of efficiency (CE), and root mean square error (RMSE) were applied for validation purposes [19, 48]. To gauge the consistency between actual and reconstruction data, differences in the first-order values of both datasets were correlated. In addition, the actual and reconstructed temperature datasets were subjected to a sign rank test and a paired *t*-test to analyze their variations. The positive values RE and CE demonstrate the validity of reconstruction model. The Durbin–Watson statistics (1.901) further supports the reliability of the reconstruction (table 2).

2.2.3. Assessment of temporal patterns, spatial representativeness, and climate forcing

We determined the thresholds for cold and hot years by utilizing the values at the 10th and 90th percentiles of the reconstructed temperature, respectively. To uncover potential significant periodic patterns, MTM spectral analysis was determined via utilizing Multi-Taper Method [2, 49]. The validation of observed periodicities in our data was carried out through wavelet analysis [50]. To check the spatial representativeness of our reconstruction at both local and large scale a spatial correlation analysis between the reconstructed temperature and KNMI climatic explorer graded temperature were performed (https://climexp.knmi.nl/start.cgi). The impact of intense volcanic eruptions (VEI $\geqslant$5) on pre-monsoon temperature variability in the Western Himalayan region was determined through superposed epoch analysis (SEA) [51]. To determine the regional to large-scale linkages, we compared our reconstructed temperature with existing reconstruction records from the Western Himalayan region of Pakistan and Northern Hemisphere temperature reconstruction records.

3. Results

3.1. Characteristics of CRC chronology and response function analysis

We developed a 248 year (1773–2020 CE) CRC from tree-ring samples of *Abies pindrow* collected from three different sites in the Western Himalayan region of Pakistan (figure 3). An EPS value surpassing the 0.85 benchmark (EPS $>$ 0.85) indicates that the chronology represents the population signal from 1854 CE onward. The developed CRC demonstrates high mean sensitivity (MS) (0.301), standard deviation (0.272), inter-series correlation (0.531), auto-correlation (0.674), and signal to noise ratio (SNR) (11.908). These metrics affirm the effective cross-dating of our collected samples and validate the chronology's suitability for a dendroclimatic study. The statistics of TRWC of *Abies pindrow* were shown in table 1.

The response function analysis demonstrated that the TRWC of Bara Gali showed a significant positive correlation with the current year's June–July rainfall (figure 4). In contrast, it revealed a significant negative correlation with the previous year's September and the current year's January–February, and June-July minimum temperatures. Similarly, it showed a significant negative correlation with April-July and September maximum temperatures, and with June–July CRU TS 4.05 maximum temperatures. The Bara Gali TRWC also demonstrated a significant positive correlation with previous year's September mean maximum temperature.

The TRWC of the Ayubia sampling site showed a significant positive correlation with current-year April-July rainfall (figure 4). In contrast, it revealed a significant negative correlation with the previous year's July and September minimum temperatures, as well as the current year's June and July minimum temperatures. The TRWC revealed a significant positive correlation with the current year's January minimum temperatures. In addition, it demonstrated a significant positive correlation with the current year's January average temperature, and a significant negative correlation with the current year's April and June-July average temperatures. Furthermore, the TRWC showed a significant negative correlation with the current year's January, April–July, and September maximum temperature, as well as with the current year's June CRU TS 4.05 maximum temperature.

The TRWC of the Kuldana sampling site revealed a significant positive correlation with the previous year's July rainfall and the current year's April–July rainfall (figure 4). It also showed a significant positive correlation with the previous year's September and the current year's January minimum temperatures. In contrast, it demonstrated a significant negative correlation with the current year's June-July minimum temperatures. In addition, the TRWC showed a significant negative correlation with the current year's February, April, and June–July average temperatures. Similarly, it revealed a significant negative correlation with the previous year's September and the current year's April–July and September maximum temperatures. The TRWC of the Kuldana site also showed a significant negative correlation with the current year's May–July CRU TS 4.05 maximum temperatures.

The CRC developed from tree-ring data of the three sampling sites revealed a significant positive correlation with current-year March–August rainfall, whereas it showed a significant negative correlation with the previous year's August and the current year's April–June minimum temperatures (figure 4). In addition, the CRC demonstrated a significant negative correlation with the previous year's September and the current year's March and May average temperatures, while showing a significant positive correlation with the current year's January average temperature. The CRC also revealed a significant negative correlation with the current year's April–May maximum temperatures and a significant positive correlation with the previous year's August maximum temperature. Furthermore, it showed a significant negative correlation with the current year's May–June CRU TS 4.05 maximum temperatures.

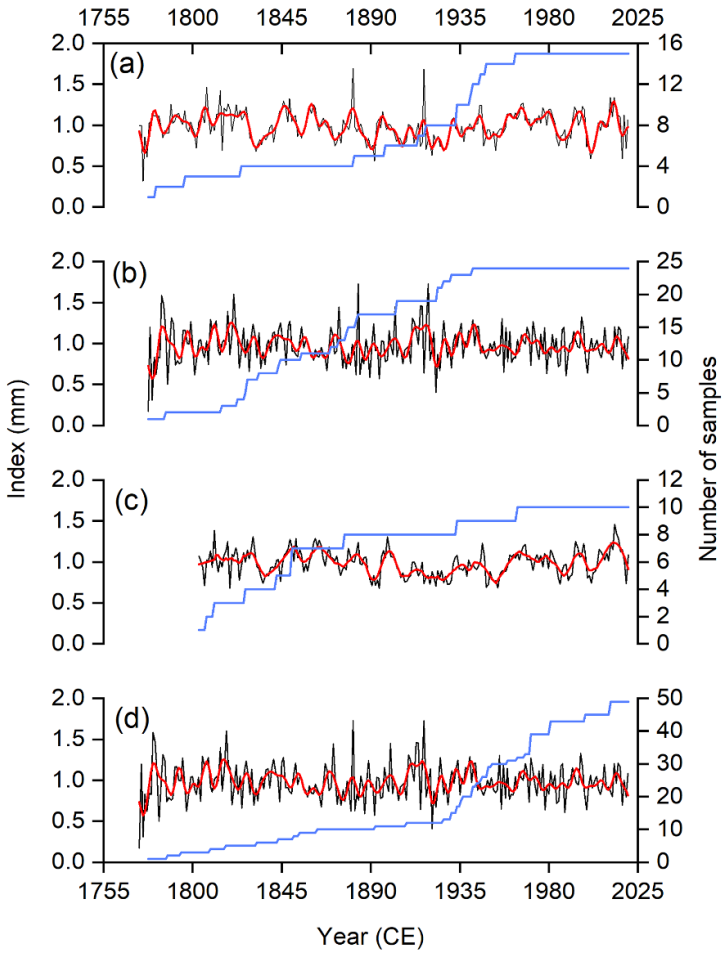


Figure 3. Tree ring width chronology (TRWC) from (a) Bara Gali, (b) Ayubi, (c) Kuldana, and (d) the composite regional chronology (CRC) of the study area. The thick bold red lines represent the 15 year low-pass filter, while the thick bold blue lines indicate sample size. The EPS threshold for the CRC is 1854 (EPS > 0.85).

3.2. Temperature reconstruction and validation

Based on growth-climate response analysis, we developed a reconstruction model for pre-monsoon mean maximum temperature and CRC index as follows:

$$\text{Mean MJ}_{\text{Tmax}} = -5.63\,(\text{CRC}) + 36.02$$
$$\left(n = 66, r = -0.639, R^2 = 40.8\%, R^2{}_{\text{adj}} = 39.9\%, F = 33.671, p < 0.001\right).$$

The reconstructed pre-monsoon mean maximum temperature shows positive value of RE (0.316), and CE (0.252), highlighting the validity of the reconstruction model. The RMSE value for the model was 0.379, while the *Durbin–Watson Statistic* was 1.901. We reconstructed pre-monsoon mean maximum temperature for the past 166 year (1855–2020 CE) (figure 5). The reconstructed temperature accounted for 40.8% of the variance in the actual pre-monsoon mean maximum temperature. Statistical tests, including the sign rank test and paired *t*-test, confirmed minimal differences between actual and reconstructed temperatures, as supported by elevated *p*-values. Details of the reconstruction, calibration, regression, and statistical tests are provided in supplementary table 1. A notable correlation ($r = 0.74$, $p < 0.0001$) was found between the first-order differences of the real and reconstructed temperatures series.

3.3. Characteristics of reconstructed temperatures

The reconstructed and actual pre-monsoon mean maximum temperature series showed considerable year-to year variability (figure 5). The long-term reconstructed pre-monsoon temperature mean is 30.62 with a standard deviation of 1.08. The reconstruction demonstrated relatively stable conditions during mid-19 to early 20th century with slight fluctuations. A prominent cooling phase is observed in the mid of 20th century, followed by a clear warming phase from the 20th century onward as observed in actual temperature (figure 5). The reconstruction temperature demonstrated twenty-one cooler years (1871,

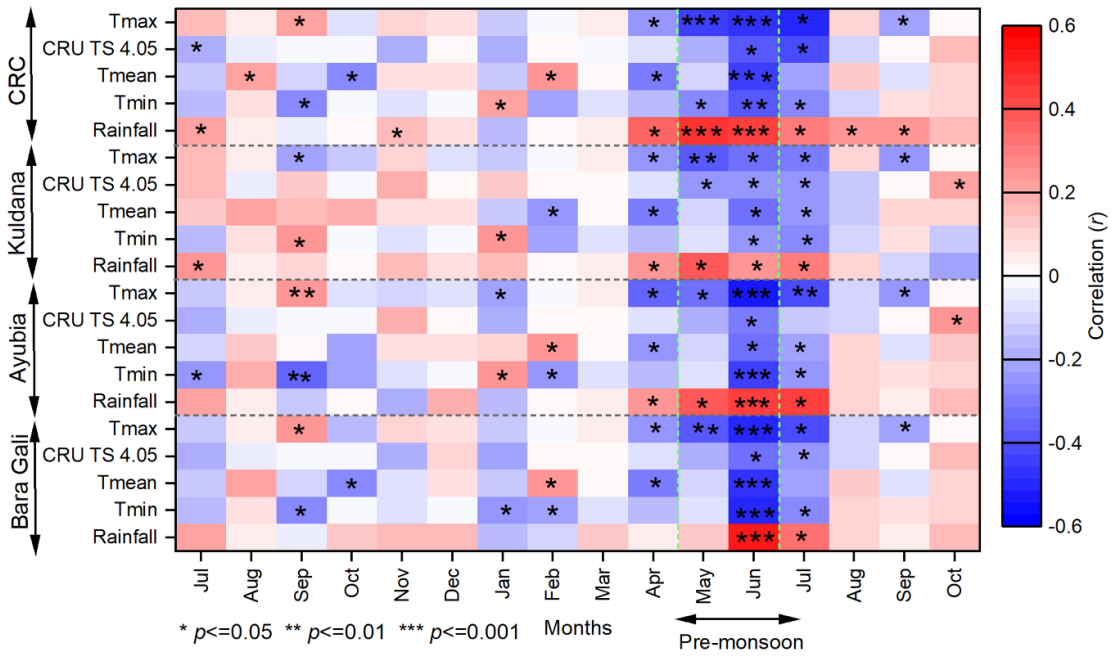


Figure 4. Heat map representing the response of TRWC of *Abies pindrow* from Bara Gali, Ayubia, and Kuldana, along with the composite regional chronology (CRC), to mean monthly maximum, average, and minimum temperatures, as well as rainfall in the study area. Correlation coefficients were calculated from the previous June to the current September.

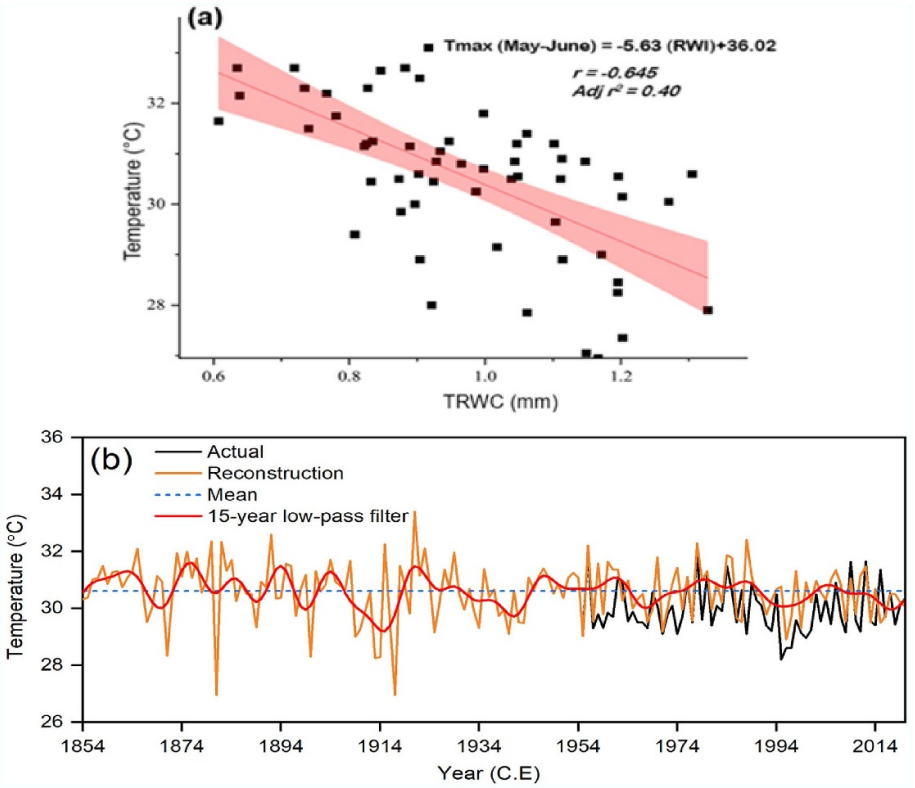


Figure 5. (a) Regression of actual mean May–June temperature with tree-ring width (TRW) of *Abies pindrow* (b) reconstructed mean May–June temperature. The black line in (b) represents the actual temperature, the blue line shows the mean of May–June temperature reconstruction, whereas the red bold line reveals 15-year low-pass filter.

1881, 1886, 1900, 1909, 1910, 1913, 1914, 1916, 1917, 1925, 1933, 1934, 1940, 1943, 1955, 1971, 1980, 1991, 1996, and 2011), and fifteen warmer years (1865, 1873, 1875, 1880, 1882, 1887, 1892, 1915, 1921, 1923, 1929, 1978, 1988, 1999, and 2017) in the temperature records.

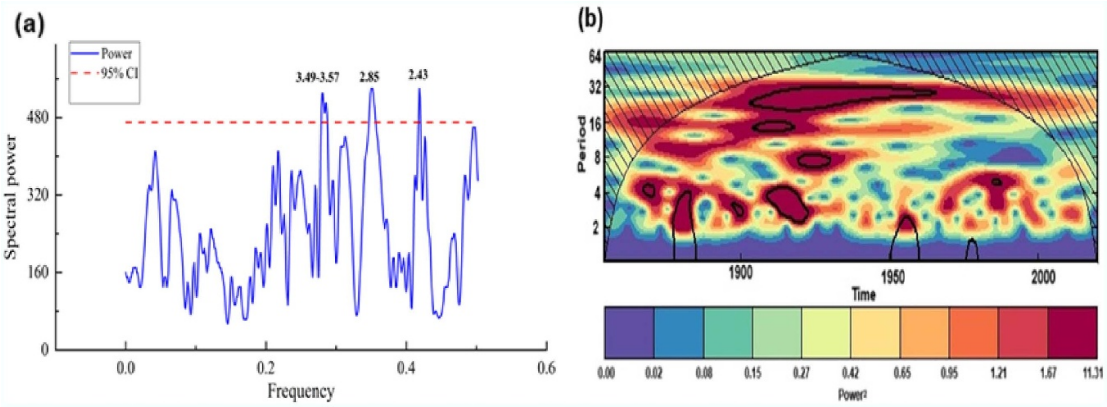


Figure 6. (a) MTM power spectral analysis for the reconstructed mean maximum May–June temperature and (b) Wavelet power spectrum of the reconstructed mean maximum May–June temperature, with significant periods ($p < 0.05$) denoted by black lines.

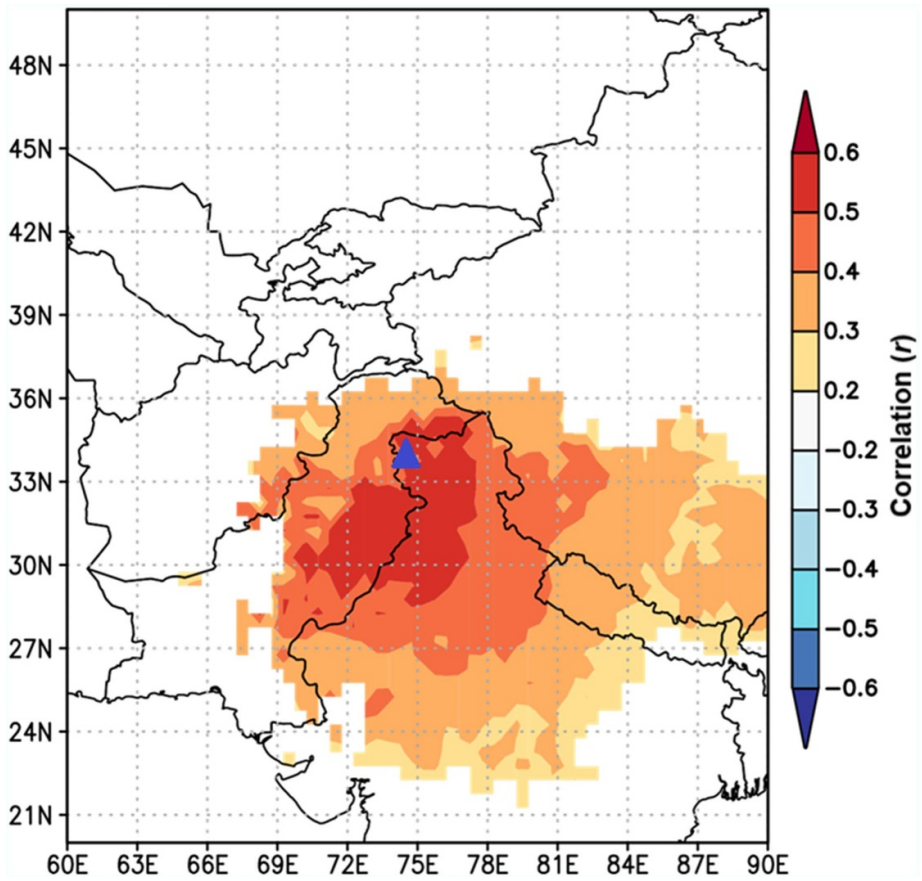


Figure 7. Spatial field correlation maps between reconstructed mean maximum May–June temperature with gridded mean maximum for the common period 1956–2020 CE. The blue triangle represents the tree-ring sampling location.

The MTM spectral analysis revealed significant interannual bands (*i.e.* 2.43–3.57 years) (figure 6(a)). These interannual bands were further validated by wavelet analysis (figure 6(b)). The spatial fields correlation map between the reconstructed and gridded (CRU TS 4.01) pre-monsoon temperatures reveals a significant positive correlation ($p < 0.01$) over large geographical regions (24–36° N, 68–90° E) (figure 7). This spatial relationship extends from the Western Himalayan region of Pakistan to most part of Kashmir, India and Nepal.

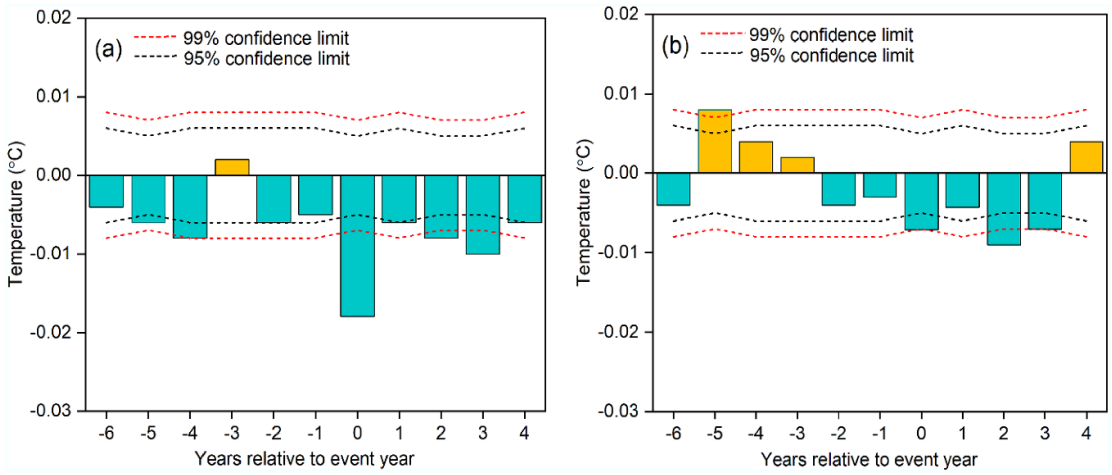


Figure 8. Superposed epoch analysis (SEA) between major volcanic eruptions (VEI $\geqslant 4$) and estimated pre-monsoon temperatures for the eruption year (year 0) (a), followed by the year after the eruption (year 1) (b).

3.4. Assessment of temporal patterns and climate forcing

To determine the spatial temporal pattern of the reconstructed pre-monsoon temperature at regional to large scales, we compared our reconstruction with existing records from the Western Himalayan and upper Indus Basin regions of Pakistan [37, 52], as well as the Northern Hemisphere [53, 54] (supplementary figure 1). The *Z*-scores analysis demonstrated a significant positive correlation with the late summer temperature reconstruction of the Western Himalayan region of Pakistan [37] ($r = 0.231$, $p < 0.05$), and summer temperature of the upper Indus Basin, Pakistan [52] ($r = 0.277$, $p < 0.05$). Our reconstruction also showed a correlation with annual temperature [53] ($r = 0.151$, $p < 0.05$), and mid-latitude summer temperatures ($r = 0.192$, $p < 0.05$) of the Northern Hemisphere. Although, these correlations are relatively weak and some divergences are observed in the late 20th century. This may be associated with regional climatic response. However, broadly consistent cooling and warming patterns are evident during the late 19th and early 20th centuries in all series (supplementary figure 1). The warming phase of mid-20th century is also evident in all series and was prominent in the reconstruction records of [37, 52], and [53].

Cooling phases in temperature are generally associated with the major volcanic eruption and can substantially influence tree growth thereby resulting valuable insight into the timing, intensity and broader impact on the regional climate system. The impact of volcanic eruption on our regional pre-monsoon reconstructed temperature was evaluated by utilizing SEA, which determine cooling anomalies in the year in which eruption occurred (year 0), and the subsequent year (year +1) (figure 8). Our reconstructed temperature captures a total of 11 major volcanic eruption events (supplementary table 1). Notably, the cooling year such as 1886, 1916, 1933, 1980, 1991, and 2011 correspond to large volcanic eruption as recorded in New Zealand, Azul, Kharimkotan, St. Helens, USA, Pinatubo, Philippines, and Puyehue-Cordon Caulle respectively. Our reconstructed temperature consistently showed cooled anomalies in the years following these eruptions. For instance, the massive volcanic eruption of 1991 (VEI = 6) observed in Pinatubo, Philippines is clearly reflected in our reconstruction. The reconstructed temperature for 1991 is 30.4°C, followed by a further decline to 29.8 °C in 1992, attributed to anomalies of −0.23 °C and −0.87 °C compared to the long-term mean (30.65 °C) (supplementary table 1).

4. Discussion

4.1. CRC and response function analysis

We developed a 248 year (1773–2020 CE) CRC from three stand of *Abies pindrow* in the Western Himalayan region, Pakistan. The statistical characteristics of our CRC are aligned with those reported in previous dendroclimatological studies from the Western Himalaya [18, 30, 36, 55, 56]. The commendable MS and robust inter-series correlation, alongside fair EPS and SNR values, suggest that regional climate exert a substantial influence on the radial growth of *Abies pindrow* [41, 57, 58]. Temperatures at high altitudes profoundly influence radial growth due to hindrances in root development and cambium functionality. In addition, low soil temperature can further inhibits root growth and water uptake

[59]. Research indicates that xylem formation is primarily influence by surrounding temperature, with a threshold of approximately 5 °C–6 °C marking the onset of cambial reactivation and xylem activity [60, 61]. Night temperatures, in particular, play a more pivotal role in xylem cell lignification than daytime temperatures [62] and also regulate cambial activity by pursuing the tracheids' division and growth during growth seasons [63]. These physiological responses may explain the estimated negative correlation between the CRC and temperature in the Western Himalayan region of Pakistan.

Several studies from tropical zones [64–67], and boreal woodlands [68, 69] have reported an inverse relationship between radial growth and temperature. The CRC of this study also reveals a significant negative correlation with temperature and a significant positive correlation with rainfall. This growth-climate pattern may be attributed to escalating temperatures, leading to heightened evapotranspiration and autotrophic respiration, thereby reducing plant air–water potentials [70, 71]. One possible explanation for the negative correlation between CRC and temperatures may probably due to the relatively lower elevation of sampled sites compared to other dendroclimatological study in Pakistan [52]. Studies evident that tree growing at lower elevations often shows negative correlation with temperature, and positive correlation with rainfall [72]. In addition, rising temperatures may extend the growth season, resulting in positive growth correlations of trees with winter temperature, as reported in other study [73]. The aforementioned physiological mechanisms [65, 70, 71, 74] might deter plants from assimilating more carbon. Therefore, altitudinal variation in growth responses of this species may be determine in future studies.

4.2. Characteristics of reconstructed temperature

This study represents the first tree-ring based temperature reconstruction from the Muree area of the Western Himalayan region of Pakistan. A study from the Indus Kohistan region of Western Himalayas has explored late summer (August–October) temperature reconstruction. The mid-20th century cooling, and late 20th century onward warming phases of our study are consistent with the finding of [37]. The warming phase observed in the late 20th century has been attributed to socioeconomic impacts [75, 76]. This increasing phase in our temperature reconstruction has also been reported in both actual and paleoclimatic reconstruction records across the across the Northern Hemisphere [77, 78]. Tree-ring based temperature reconstruction studies from the Northern area of Pakistan have demonstrated discrepancies in summer temperature trends compared to Northern Hemispheric temperature records [79, 80]. The reconstruction reveals out of phase [79], and in phase [80] relationship. The observed may be associated to differences in reconstruction approaches and sampling sites. Zafar *et al* [79] study was based on negative correlation of tree-ring data and temperature, whereas Asad *et al* [80] used a positive correlation approach for reconstruction. The negative correlation of tree-ring chronology and temperature indicates that radial growth of tree is primarily limited by soil moisture condition. Similarly, a soil moisture reconstruction from the western Himalayan region demonstrated that soil moisture is a significant climatic variable during the growing season (Rauf *et al* [1]). The negative correlation of our CRC with temperature may be attributed to moisture stress. However, it is noteworthy to highlight that our pre-monsoon temperature reconstruction did not showed a significant relationship with Northern Pakistan reconstruction records [79, 80]. In contrast, a significant positive relation was observed between our pre-monsoon temperature reconstruction and soil moisture reconstruction record [1]. This indicates that temperature variability in the study area is substantially influenced by hydroclimatic condition and moisture availability.

4.3. Assessment of temporal patterns and climate forcing

Comparative regional analyses have pinpointed the years 1889, 1913, 1914, 1917, 1924, 1933, 1934, and 2011 as cold periods, aligning with the broader Western Himalayan region in Northern Pakistan [37]. The identified cold period of the 19 century is consistent with tree-ring reconstruction conducted in the North-Western Himalayan region of Srinagar, Kashmir [18]. Our pre-monsoon temperature reconstruction reveals a significant correlation with temperature reconstructions from the Western Himalayan and upper Indus Basin regions of Pakistan [37, 52]. In addition, the mid-20th century cooling and late 20th century onward warming trends are consistent with Northern Hemisphere temperature records [53, 54]. This indicates that our pre-monsoon temperature reconstruction captures a robust regional to Hemispheric climate signal, reflecting the influence of large-scale climatic drivers.

The interannual periodicity bands identified in the MTM spectral analysis and wavelet power spectrum generally reflect the influence of Atlantic multidecadal oscillation (AMO) on regional climate [81]. Study evident that unusual warming in the Atlantic Ocean has caused substantial temperature variability in Northern Hemisphere including Pakistan [82]. A correlation between MXD based temperature reconstruction from the upper Indus Basin of Pakistan and the AMO demonstrated that the AMO has

a substantial influence on Pakistan's climate [52]. This indicates that the observed interannual bands in our study may be attributed to the influence of the AMO on Western Himalayan temperature; however, further in-depth studies on this aspect are needed.

Numerous dendroclimatological studies have confirmed the influence of volcanic activity on tree-ring width and associated temperature drops, particularly following major eruptions [52, 83–87]. In addition, some studies illustrated that massive volcanic eruptions are commonly associated with narrow rings and reduced temperatures [83, 88]. Unlike other studies, our study also shows consistent linkage between massive volcanic eruptions and reduced temperature [52, 89]. Nevertheless, eleven specific instances in our reconstruction revealed noticeable temperature anomalies following massive volcanic events. The year 1991 corresponds to the massive volcanic eruption (VEI = 6) of Mount Pinatubo in the Philippines. Similarly, reduced temperature observed in 1886, 1916, 1933, 1980, and 2011 coincide with massive volcanic eruption recorded in different regions of the world. The post- eruption effect persist for 2–4 years in our pre-monsoon temperature reconstruction [90]. Overall, the results of this study highlight that temperature variability in the Western Himalaya of Pakistan is influence by multiple drive forces, which warrant further investigation in future studies.

5. Conclusions

In this study, a 248 year CRC of *Abies pindrow* was developed from three sites in the Western Himalayan region of Pakistan. The CRC exhibits a significant negative correlation with pre-monsoon temperature and a positive correlation with rainfall. By integrating the tree-ring data of *Abies pindrow* with the observed temperature and rainfall records from the Kakul meteorological station, we reconstructed 166 year (1854–2020 CE) pre-monsoon (May–June) temperature variability in the Western Himalayan region, Pakistan. The reconstructed temperature reveals a prominent cooling phase during the mid of 20th century, followed by a warming phase from the late 20th century onward. These observed phases are consistent with temperature reconstructions from Northern Pakistan and broader Northern Hemisphere. Interannual variability bands identified through MTM spectral analysis and wavelet power spectra suggests that pre-monsoon temperature variability in the region may be linked to large-scale climate circulation such as the AMO. SEA further indicates post-eruption cooling associated with major volcanic eruptions events. In light of these findings, temperature variability in the Western Himalayan region of Pakistan appears to be substantially influenced by multiple drive forces. However, more comprehensive studies incorporating various tree species and tree ring proxies from diverse locations is essential for understanding regional to large scale climate dynamic in the Western Himalayan. *Abies pindrow* proves to be highly sensitive to temperature variability, and we recommend that relevant stakeholders implement strategies to protect it.

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Data availability statement

The data cannot be made publicly available upon publication because no suitable repository exists for hosting data in this field of study. The data that support the findings of this study are available upon reasonable request from the authors.

Supplementary data available at https://doi.org/10.1088/2515-7620/ae718e/data1.

Conflict of interest

There are no conflicting interests listed by the authors.

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