Growth response of conifer trees from high-altitude region of Western Himalaya

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Tree-ring width index chronologies of some species (*Abies pindrow* and *Picea smithiana*) of Western Himalaya are sensitive to the moisture availability and amount of soil moisture of the region. The first principal component among the site chronologies explaining 61.2% of the common variance is strongly correlated with Palmer Drought Severity Index during summer season (May–July). Whereas increased temperature of the region had significant adverse effect on tree growth. The moisture availability, especially in the growing season is found more conducive in developing the annual tree-ring width compared to rainfall during the season. Moreover, the increasing temperature and vapour pressure during November and December of the previous year might play an important role for early snow melt over region, which maintains enough soil moisture favouring trees growth during subsequent growing season of the trees as well as in physiological processes.

Keywords: Conifer trees, growth response, high-altitude region, ring-width index, soil moisture.

CONIFERS tree-ring samples of the Western Himalaya have been collected and analysed by several researchers[1–9] in relation to the changing climate scenario. They have further reconstructed rainfall and temperature back to several centuries to establish the proxy climatic records. The precipitation reconstruction of several hundred years back during March to July was revealed by Singh *et al.*[8], using tree-ring chronologies of different species from Satluj basin, Kinnaur, Himachal Pradesh. Yadav[9] has shown long-term climatic reconstruction of precipitation and temperature using millennium-long tree-ring chronologies of several conifers species from the Western Himalaya.

The temperature of the Western Himalaya has been reconstructed back to several centuries using tree-ring data from remote areas situated even far from the meteorological stations[1,5,10]. Most of the studies are restricted to replicate the signature of precipitation and temperature in ring-width.

Ram and co-workers[11–15], as well as Borgaonkar *et al.*[16] have shown significant positive relationship between teak tree-ring width index chronologies prepared from Central and peninsular India and moisture index as well as Palmer Drought Severity Index (PDSI). Further, the chronologies were used to estimate the moisture index over Central India back to AD 1866. However, over the Western Himalaya, due to limitations of climatic variables and scarcity of weather records near the tree-ring sampling sites, tree growth climate/relationship is not well understood. Thus, for better understanding of tree growth–climate relationship of the region, the gridded data near sampling sites might be useful in the absence of observed data for improving understanding of tree growth/climate relationship and also to get the accuracy of local climate effect on tree growth so that the influence of local and regional climate on tree growth could be understood properly. However, in this communication, the gridded monthly rainfall, mean temperature, PDSI and vapour pressure of the region nearest to sampling sites have been used for better understanding of tree growth–climate relationship over Western Himalaya, India.

Tree-ring width data of different species have been downloaded from the website, http://www.ncdc.noaa.gov/paleo/treering.html/. Tree-ring width data from the two sites at Gulmarg and Khillanmarg[10] and one site at Pahalgam[1,17] in Jammu and Kashmir have been used in this study. Moreover, tree-ring width data of junipers from high-altitude region of Karakoram[18] have also been used (Figure 1). All tree core samples in the present analysis are from trees growing at high elevation ranging from 2700 to 3750 m amsl, where meteorological observatories are not available near the sampling sites.

Tree-ring analysis of fir (*Abies pindrow*) and spruce (*Picea smithiana*) from three different sites of the Western Himalaya have been carried out in the present analysis. All the ring-width measurements were checked for missing rings and dating errors for individual sites using the program COFECHA[19]. Mean correlation of 13 radii of *P. smithiana* and 8 radii of *A. pindrow* with their respective master series at Pahalgam as computed by COFECHA is 0.52 and 0.54 respectively. Similarly, mean correlation of all radii with master series of their respective sites is 0.47

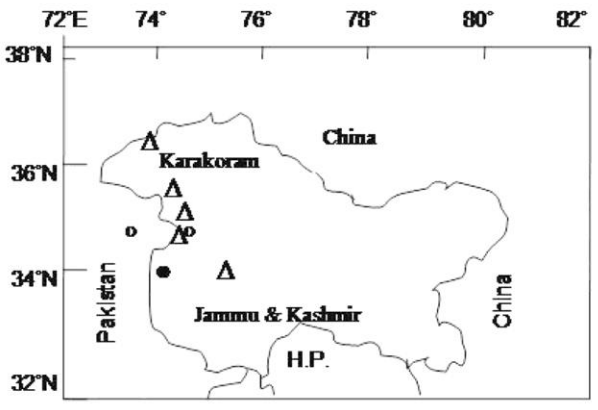

Figure 1. Location of tree-ring sites (Δ) over Western Himalaya; grid point climate data (O) and Palmer Drought Severity Index (PDSI) (•).

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(Khillanmarg, 10 radii of *A. pindrow*), and 0.54 (Gulmarg, 13 radii of *A. pindrow*). Such high correlation at high-altitude reveals good dating control among the ring-width data and representing the common signal in the ring-width data, i.e. climate.

Tree-ring index chronology was prepared using the ARSTAN program[20] by removing growth trends. Two-step detrending methods were applied to raw ring-width measurement series of each tree core sample for each site. First, a linear or negative exponential growth curve was used to remove age-related growth trend. Then the detrended series were again filtered with a spline of 35 years length with 50% frequency response cut-off to remove the varying proportions of the low-frequency variations in all the series. The spline length was selected to maximize the correlation among the site chronologies. Tree-ring indices were prepared for each series by taking the ratio of the measurements and fitted values in each year; the indices were then prewhitend using an auto-regressive model selected on the basis of the minimum Aaike criterion. All the series from individual site were combined to prepare mean chronology using biweight robust estimation[20]. In spite of long distance and different slope orientations, these chronologies are significantly correlated each other in the range 0.29–0.49 for the common period 1781–1980. This strong coherency between these chronologies justifies merging all samples to prepare a regional chronology.

Based on the strong relationship, we have merged ring-width measurement series of precisely cross-dated samples from three sites. There are total 44 cores from 44 trees. Datings of growth ring sequences were re-examined using the dating quality control program COFECHA[19]. The results from COFECHA confirmed cross-dating and revealed mean correlation (0.42) for 44 core samples. The high correlation establishes the excellent cross-matching of the tree-ring width patterns and strongly indicates the presence of the common climate forcing signal in the data of tree-ring width.

To prepare a regional tree-ring chronology compatible with the regional climatic signal, similar derending method has been performed to raw ring-width data after merging from three sites (Gulmarg, Khillanmarg and Pahalgam). The detailed statistics of regional tree-ring index chronology using ARSTAN is shown in Table 1. Generally, high mean sensitivity (MS), standard deviation (SD), expressed population signal (EPS) and signal-to-noise ratio (SNR) indicates the strong environmental influence on tree growth[21]. Table 1 shows that MS increased but SD, common variance, EPS and SNR decreased slightly in residual chronology. The results show that standard chronology is a better environmental indicator than residual chronology due to persistent of lag-1 auto-correlation (0.44; Table 1) in the series. Therefore, we focused on standard chronology in tree-growth environment relationship analysis.

Table 1. Statistics of the regional tree-ring index chronology

Chronology timespan	1604–1982
Mean sensitivity	0.093 (0.114)
Standard deviation	0.117 (0.104)
Lag-1 autocorrelation	0.444 (–0.021)
Common period analysis	1776–1980
Common variance	0.224 (0.219)
Signal-to-noise ratio	6.36 (6.16)
Expressed population signal	0.864 (0.860)

Values within parenthesis are with autoregressive modelling.

Similarly, mean correlation of all 31 radii of 26 juniper trees from a valley (valley 1), 38 radii of 24 trees very close to valley 1, 37 radii of 28 juniper trees from another valley (valley 2) and 25 radii of 20 Turkestan juniper trees located in valley 2 of the Karakoram range[18] with master series of their respective sites computed using COFECHA is 0.634, 0.521, 0.670 and 0.461 respectively. Similar detrending method has been performed for each site to prepare the tree ring-width index chronology as mentioned above.

Statistics of the chronologies (not shown) reveals the reliability for dendroclimatic potential[18,22]. Based on the relationship among the site chronologies of Karakoram region, which ranges from 0.31 to 0.64 during 1593–1993, a regional chronology has been prepared by taking the mean chronology of all the sites from Karakoram range. This was compared with a regional tree-ring chronology prepared from Kashmir valley to see the long-term variations in ring-width patterns over Western Himalaya (Figure 2). Time series of the chronology from two distinct locations (Kashmir and Karakoram) has been shown during 1609–1982 (Figure 2 *a*). The smoothed line in Figure 2 *b* shows the 30 year cubic smoothing spline fit. Principal component analysis for the common period has been performed for further analysis between regional chronologies of two sites.

The scarcity of close weather records at tree-ring sampling sites makes it difficult to calibrate tree-ring data against climate data, especially precipitation because of high variability in the mountain ranges. Due to lack of meteorological stations near the sampling sites at high-altitude, the monthly rainfall, mean temperature and vapour pressure data of two grid points (34.75°N, 73.25°E, 2552 m amsl; 34.75°N, 74.25°E, 3038 m amsl) were obtained from the Climate Research Unit (CRU)[23]. A regional series of rainfall and temperature was prepared by merging two gridded datasets so that more reliable data can be used in establishing the relationship between tree growth and climate.

The gridded data are representative of meteorological station near the sampling sites in the absence of observed data. Therefore, the longest period and more reliable data of rainfall and temperature of the surrounding area near the sampling sites were used. PDSI (1870–2002)[24] has

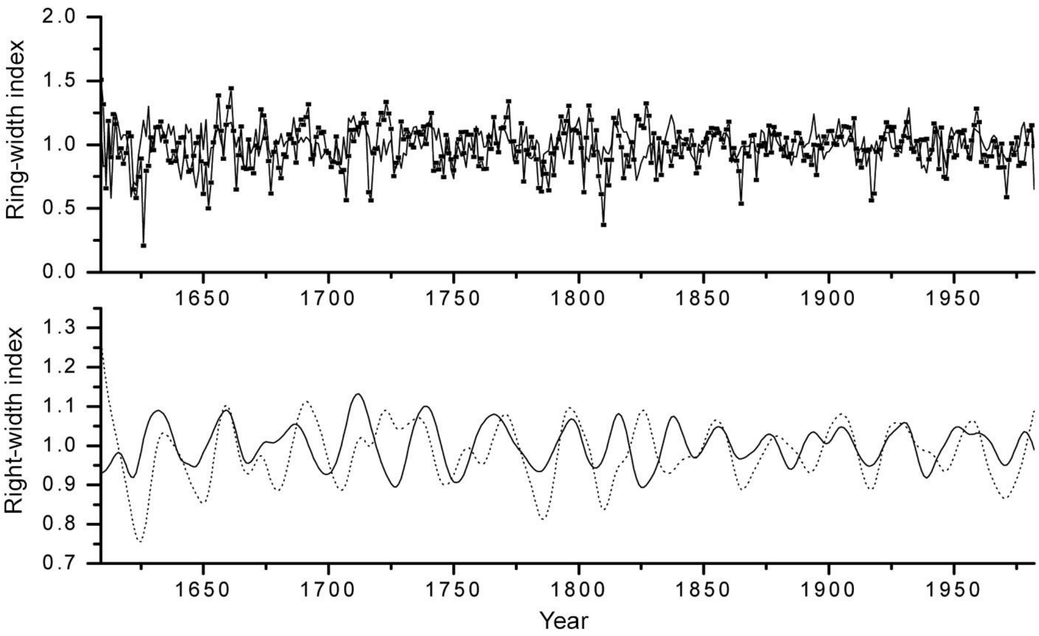

Figure 2. ***a***, The regional tree-ring chronology of Kashmir (- -) and Karakoram (--■--) in Western Himalaya. ***b***, Tree-ring chronology of Kashmir (solid smooth line) and Karakoram (dotted line) after cubic smoothing spline fit of 30 years.

Table 2. Statistics of monthly regional climate

		1	2	3	4	5	6	7	8	9	10	11	12
RF	X	65.2	67.5	86.7	72.6	54.1	60.5	87.3	109.2	60.3	28.9	16.3	27.9
	Sd	45.3	45.6	58.7	44.1	36.8	42.2	60.0	76.1	43.0	32.2	22.7	31.4
	Tr	–0.14	0.20	0.57***	0.31*	0.16	0.07	0.70***	0.23	–0.06	0.03	0.12	0.22*
Tm	X	–2.6	–1.8	2.6	7.9	12.0	16.1	17.5	16.9	14.0	9.7	4.8	0.2
	Sd	1.6	1.7	1.4	1.3	1.4	1.0	1.0	0.8	1.0	1.1	0.9	1.0
	Tr	0.00	0.01***	0.01***	0.01***	0.00	–0.00	–0.00	–0.00	0.00	0.00	0.005*	0.009***
PDSI	X	–0.58	–0.32	–0.22	–0.23	–0.45	–0.45	–0.53	–0.59	–0.65	–0.65	–0.71	–0.64
	Sd	2.2	2.2	2.3	2.4	2.4	2.4	2.2	2.3	2.3	2.3	2.3	2.2
VP	Tr	–0.00	–0.00	–0.00	–0.00	0.00	0.00	–0.00	0.00	–0.00	–0.00	–0.00	–0.00
	X	1.5	1.5	2.5	4.0	4.7	6.1	9.9	10.6	6.3	3.4	1.9	1.4
	Sd	0.4	0.5	0.5	0.7	0.6	0.7	0.9	1.1	0.8	0.7	0.4	0.4
	Tr	0.00	0.00	0.003*	0.01***	0.01***	0.00	0.00	0.00	0.00	0.00	0.002*	0.002**

1, January; 2, February; 3, March; 4, April; 5, May; 6, June; 7, July; 8, August; 9, September; 10, October; 11, November; 12, December; Tr, Trend in mm/year for rainfall and °C/year for temperature; X, Mean; Sd, Standard deviation; RF, Rainfall; Tm, temperature; PDSI, Palmer Drought Severity Index; Vp, Vapour pressure. *Significant at 5% level; **Significant at 1% level and ***Significant at 0.01% level.

also been used for the tree growth–climate relationship. The nearest grid point data (33.75°N, 73.75°E) of PDSI, having the longest and continuous records of the region have been used in tree growth–climate relationship. The statistics of regional data is shown in Table 2 on a monthly scale. Climatic diagram of the regional data is shown in Figure 3. Correlation analysis has been carried out between the first principal component (PC1) and climatic variables using the program DendroClim 2002 (ref. 25; Figure 4).

Figure 2 *a* and *b* reveals the variation in ring-width index chronology prepared from Jammu and Kashmir, and the adjacent area of Karakoram. The correlation coefficient between the two series is 0.24 from 1609 to 1980, showing significance at 0.1% level (Figure 2 *a*). The smoothed line in Figure 2 *b* shows the 30 year cubic smoothing spline fit. Except AD 1816–1846, both series are well matched during the entire period. The correlation coefficients during 1609–1815 and 1847–1980 are 0.36 and 0.60 respectively (significant at 0.1% level; Figure 2 *b*). The poor replication during early part of the chronology might be responsible for low correlation. However, both the series show uniform growth behaviour over the region. There are some differences in magnitude, but both series showed almost similar patterns during the entire period (Figure 2 *b*). The strong relationship between these two series shows that there is common forcing in ring-width variations, i.e. climate influencing tree-growth pattern over the wide area of Western Himalaya. PC1, which explained 61.2% of the common variance in the series, has been used for the present analysis (Figure 4).

The mean, standard deviation and trend/year of the regional climate data for individual months are shown in Table 2 for the common period 1901–2002. For rainfall, the significant increasing trend was observed in March, April, July and December. In case of temperature, February–April, November and December showed significant increasing trend (Table 2). For PDSI, none of the months showed significant increasing/decreasing trends (Table 2). In case of vapour pressure, the increasing trends were observed during March–May, November and December, representing climatic condition of surrounding area of the sampling sites.

Based on the long-term average of regional rainfall and temperature data, July is the hottest month (17.5°C), January is the coldest month (–2.6°C) and August is wettest month (109.2 mm) over the region (Figure 3). However, this region receives less rainfall during monsoon season (JJAS) compared to rest of the country. During non-monsoon months, the region receives good amount of rainfall in the form of snow due to western disturbance (Figure 3).

The relationship for the common period (1901–1982) between PC1 and climatic variables (rainfall, temperature, PDSI and vapour pressure) was analysed from the previous October (end of previous year's growing season) to end of the current year October (end of current year's growing season) using the program DendroClim 2002 (ref. 25; Figure 4). The relationship of PC1 with seasonal climate (May–July) of rainfall, temperature, PDSI and vapour pressure (Vp) are shown in Table 3. The seasons have been made on the basis of the response given by

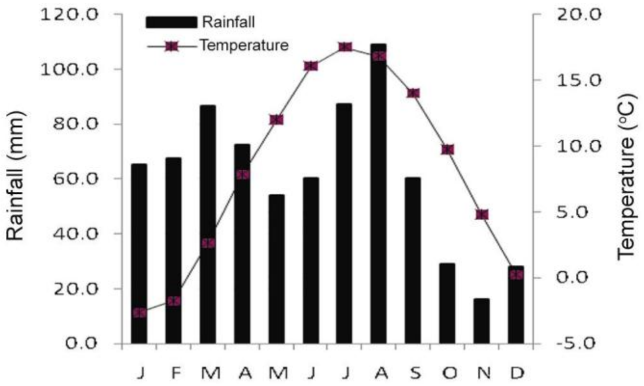

Figure 3. Long-term variation of regional rainfall and temperature over Western Himalaya during 1901–2002.

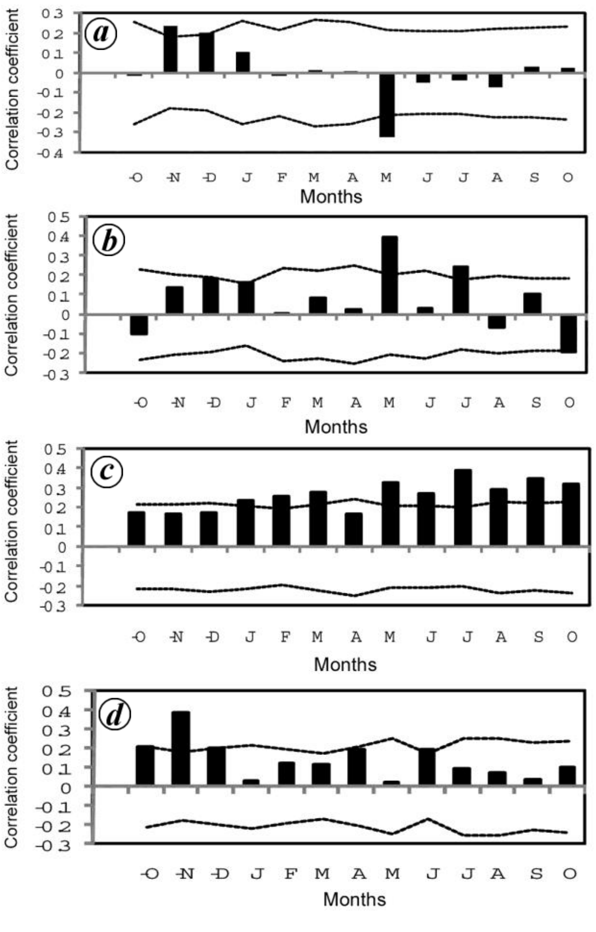

Figure 4. Correlation analysis of the first principal component (PC1) using mean monthly temperature (***a***), precipitation (***b***), PDSI (***c***) and vapour pressure (***d***). Dahsed lines are 95% confidential level.

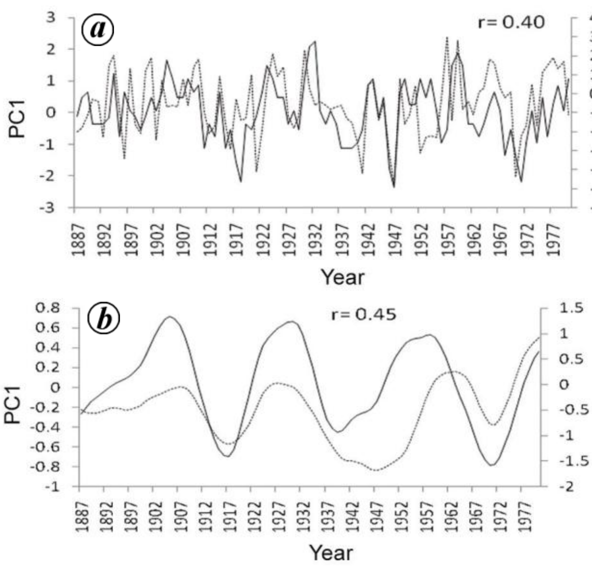

Figure 5. (Upper panel) Variation in PC1 (black solid line) and summer PDSI (black dashed line) during 1877–1980. (Lower panel) Smoothed line is a 30-year cubic smoothing spline fit.

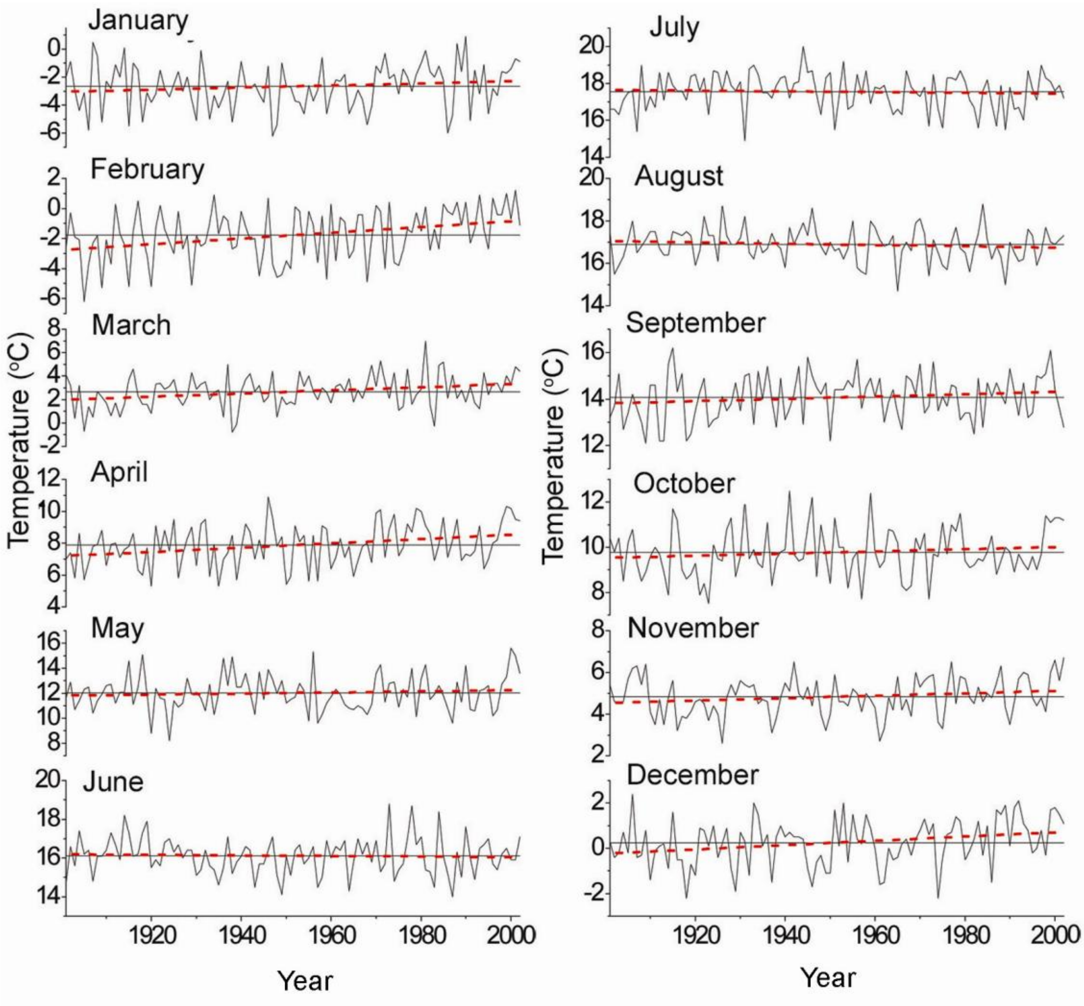

Figure 6. Monthly temperature variations over the region during 1901–2002. Red line represents trends in both panels.

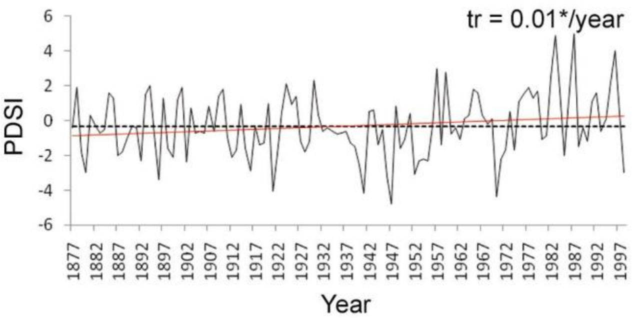

Figure 7. Summer season (May–July) PDSI variations over the region. Horizontal (dashed black) line shows mean. Solid red line reveals the trend line.

monthly climatic variables (Figure 4 *a*–*c*). Figure 5 (upper panel) reveals the variation in PC1 (black solid line) and summer PDSI (black dashed line) during 1877–1980. Smoothed lines are a 30-year cubic smoothing spline fit (Figure 5, lower panel). Figure 6 shows the monthly variations of temperature over the region during 1901–2002. Red line represents trends in both panels.

Tree growth–climate relationship from previous year October to current year October is shown in Figure 4; the dashed lines in Figure 4 reveal 95% confidence intervals. Except April, all the months of current year show significant positive relationship with PDSI (Figure 4 *c*). Tree growth is strongly influenced by the availability of soil moisture during the growing season. It means that moisture availability plays a vital role in tree-growth processes over the region. Loss or accumulation of soil moisture may be precondition for the coming growing season of the trees[13,24,26,27]. Soil moisture availability during dry season is carried forward in physiological processes of the trees[28,29]. But in case of precipitation, only May and July revealed significant positive correlation with tree growth (Figure 4 *b*). In case of temperature, tree-ring index chronology is negatively correlated with May temperature. The increased temperature during May might reduce the availability of soil moisture by increasing potential evapotranspiration resulting in moisture stress condition, which is not found to be conducive for the growth of trees.

Higher temperature and vapour pressure during November and December of the previous year might increase the capability of the roots to absorb water and nutrients from the soil. The winter month temperature significantly increases compared to summer (Table 2), as shown by Ram[15]. The relationship between tree growth and winter temperature reveals that Himalayan trees might carry significant amount of photosynthesis during warm period, which is used for the subsequent growing season of the trees. The results are consistent with the finding of Yadav *et al.*[30]. Also, the increasing temperature during winter months (Figure 6) might be responsible for early snow melt over the region, which maintains enough soil moisture during subsequent growing seasons. PDSI also reveals increasing trend over the region, which is significant at 5% level (Figure 7).

Based on the response given by climatic variables to tree growth, seasonally averaged climatic variables might be more useful than single-month climatic variables. The correlation coefficients (CCs) for the common period 1901–1980 were computed between PC1 and rainfall, temperature, PDSI and vapour pressure of the region during summer season (May–July; Table 3). Except vapour pressure, all parameters are significantly correlated with PC1. CC between PC1 and rainfall, temperature and PDSI is 0.33, –0.30 and 0.42 respectively, showing statistical significance at 1%, 1% and 0.1% level respectively

Table 3. Correlation coefficients between the first principal component (PC1) and RF, Tm, PDSI and Vp during summer season for the common period 1901–1980

	RF	Tm	PDSI	Vp
PC1	0.33**	–0.30**	0.42***	0.16

**Significant at 1% level; ***Significant at 0.1% level.

Figure 8. The 31-year sliding correlation between PC1 and summer PDSI for the common period 1877–1980. Correlation coefficients are plotted against the central year of the 31-year period. Dashed lines are significant at 5% level.

(Table 3). There is a strong significant positive correlation between PC1 and PDSI (Table 3). This means that tree growth over the region is modulated by the availability of soil moisture of the region.

Moreover, to compute the temporal stability between PC1 and PDSI, a 31-year sliding window has been performed during the entire period 1877–1980, and CCs are plotted against the central year of the 31 year period (Figure 8). It can be seen from Figure 8 that PC1 is more stable with PDSI from 1901 to 1962, which is significant at 5% level. This means that soil moisture availability of the region has a significant role in the development of annual ring-width patterns. However, the increased temperature is not found conducive for the growth of trees during summer season. It accelerated the deficit of soil moisture by enhancing evapotranspiration, whereas moisture availability during summer season (May–July) plays a vital role in tree growth over the region (Table 3, Figures 5 and 7). This means that the increasing/decreasing soil moisture might have influence on tree growth pattern. Tree growth is highly sensitive to PDSI compared to rainfall during summer seasons. It is well correlated with PDSI on monthly and seasonal basis (Figures 4 *c* and 5). This result indicates the potential of PDSI reconstruction as an indicator of soil moisture variation over the region, as described by Mika *et al.*[31].

In Figure 5 (lower panel), the smoothed line reveals 30 year cubic smoothing spline fit. It is well matched during the entire period, showing almost similar pattern. The CC between PC1 and summer PDSI is 0.45 (significant at 0.01% level; lower panel, Figure 5). These results reveal that trees growing in the same region but at different locations might have been controlled by summer season moisture availability. The influence of PDSI on conifer ring-width is more pronounced over the region. Overall, PDSI revealed significant positive correlation with conifer trees over Western Himalaya during summer season, as supported by Cook *et al.*[32].

This analysis shows that PDSI has a significant role in the development of annual tree growth pattern over Western Himalaya. Tree growth in this area is largely modulated by the regional moisture availability in and around the sampling sites. Besides, there is opposite phase in relationship between PC1 and PDSI during some years, indicating additional disturbance of biotic and abiotic factors influencing tree growth over the region, which makes it difficult to understand the interaction between tree growth and climate. Therefore, it is necessary to explore tree growth relationship with a variety of climate parameters to understand the complex relationship between tree growth and climate variability. A good network of tree-ring data from Western Himalayan region is required for better understanding of tree growth–climate relationship. This proxy record climate may give a better idea to study the long-term soil moisture variability on different timescales; and to describe the wet and dry periods over the region. Such information may be useful from the hydrological point of view, for agriculture operation, forest management and the possible impact of human activity in the region.

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ACKNOWLEDGEMENTS. We thank Prof. B. N. Goswami, Director, Indian Institute of Tropical Meteorology, Pune for encouragement and providing necessary facilities. We also thank the NOAA website for providing tree-ring data and CRU for providing climatic data.

Received 9 January 2013; revised accepted 14 May 2013