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TREE-RING CHRONOLOGIES FROM WESTERN HIMALAYA AND THEIR DENDROCLIMATIC POTENTIAL

by

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SUMMARY

Tree-ring chronologies of Himalayan conifers (viz. *Pinus, Picea, Abies, Cedrus,* etc.) were compiled from more than 300 tree core samples from 11 different sites covering a wide area of the Western Himalaya. Distinct annual growth and little occurrence of double or missing rings are characteristic features of Himalayan conifers. Dating of individual samples was achieved for all sites except for a few from a high elevation glacier which exhibited patches of very narrow rings and a high frequency of resin canals. Moderately high values of common variance and signal-to-noise ratio indicate their usefulness for dendroclimatic studies. Significant improvement of statistical performance is observed for all sites after removing the auto-correlation structure in the series by auto-regressive modeling. A quantitative evaluation of the growth-climate relationships based on response function analysis on a monthly and seasonal scale indicates a similar pattern across several regions of the Western Himalaya. March–April–May (pre-monsoon) climate (temperature and precipitation) is an important limiting parameter for tree growth and can be successfully reconstructed for the past few centuries.

Key words: Tree-ring chronology, conifers, tree growth, dendroclimatic potential, Western Himalaya.

INTRODUCTION

In India, interest in tree-ring research started in the early 1940s with the pioneering work of Dr. K.A. Chowdhury (1939, 1940a, b), who looked at the wood anatomy in association with the tree phenology to identify tree rings. Unfortunately, his work was not continued until the late 1970s.

Successful attempts in dendroclimatology for the Indian region were done by Pant (1979, 1983). He concluded that trees of the Himalayan zone are suitable for dendroclimatic research because their well-defined growth rings display a very prominent response to temperature. In a preliminary survey, Pant (1979) listed several species of subalpine, temperate, subtropical and tropical regions of the Himalayan zones which are useful in dendroclimatology. Bhattacharyya and Yadav (1999) discussed the dendroclimatic potential and dating problems of tropical and subtropical trees from the Indian subcontinent. Pant (1979) suggested two climatic regions in India where extensive sampling and tree-ring analysis should be conducted. These are the forests of the mountains adjacent to the Himalayan snow-line including the sub-Himalayan forest belts and the semi-arid regions of the country.

From an examination of specimens of two Juniper trees (*Juniperus macropoda*) collected from the Karakoram mountains in the Western Himalaya, Bilham et al. (1983) found that the ring-width series have the same climate sensitivity as conifers growing in temperate regions. They also found individuals of over 1200 years old, which is another justification of their use in dendroclimatological studies. Pant (1983) and Pant and Borgaonkar (1984) studied the tree rings in chir pine (*Pinus roxburghii*) of the Kumaon (Uttar Pradesh) region in relation to the salient features of year-to-year variation and long-term changes in rainfall and temperature of the region. Discs from four chir pine trees were used to develop a ring-width chronology. The growth rates were high in the juvenile part and declined exponentially as the trees grew. It is important to identify such age trends which have to be removed prior to modeling the climate response. Temperature was found to be the most growth-responsive climate variable. Bhattacharyya et al. (1988) collected tree-ring samples from six coniferous species in the Western Himalaya to evaluate their potential for dendroclimatic reconstructions. They found that the samples taken from *Cedrus deodara* and *Pinus gerardiana* at lower altitudes in the dry inner valleys of the Pir Panjal Range, south of Kashmir, exhibit a high age (up to 500 years), high mean sensitivity and good intra- and inter-species correlations.

Hughes and Davies (1986) analyzed many individuals of *Abies pindrow* and *Picea smithiana* from the Kashmir valley. They measured density profiles as well as ring width and their samples date back to the early 17th century. Cross-dating and analysis of variance have shown the existence of a strong regionality in the year-to-year variation of the tree-ring variables, especially in *A. pindrow*. This is particularly true for maximum latewood density showing great similarity in the series from sites quite far apart. The environmental factor producing such remarkable common signal in ring density and ring width is most likely the growing season temperature. Calibration and verification tests proved that a reconstruction of August–September mean temperature in Kashmir back to the late 18th century and quite possibly back to the late 17th century is reliable. The April–May mean temperature also showed some promising calibrations useful in a reconstruction. Hughes (1992) presented reconstructions of the mean temperature for spring and late summer and of the growing season precipitation since A.D. 1780 at Srinagar using *A. pindrow* chronologies. Borgaonkar et al. (1994) presented a reconstruction for summer precipitation at Srinagar starting at A.D. 1775 using tree-ring chronologies of *P. smithiana* and *A. pindrow*. Borgaonkar et al. (1996) reported a significant relationship between pre-monsoon summer (March–April–May) climate (temperature and precipitation) and *Cedrus deodara* chronologies from the Western Himalayan region. Further, they discussed the potential of the species for reliable reconstructions of pre-monsoon summer temperature for that region. Thus, the possibility of using tree-ring chronologies from subalpine sites to reconstruct spring and early summer temperatures, or even whole summer temperature and precipitation, demonstrates that dendroclimatology is a tool to study the effect of climate variability on systems such as crops, rivers and glaciers in the Western Himalaya.

In this paper, analysis of about 14 tree-ring chronologies based on more than 300 tree cores covering the entire Western Himalayan region are presented. This provides a wide network of tree-ring data over a large area useful for reconstruction of the climate over the region during the last few centuries.

STUDY AREA

The Western Himalayan ranges have a diverse climate ranging from dry cold desert, moist temperate, wet temperate to subtropical. Forests are spread over a vast area and exhibit great diversity with numerous vegetation types ranging from alpine, subalpine to temperate, grading from higher elevation to the subtropical at lower elevation.

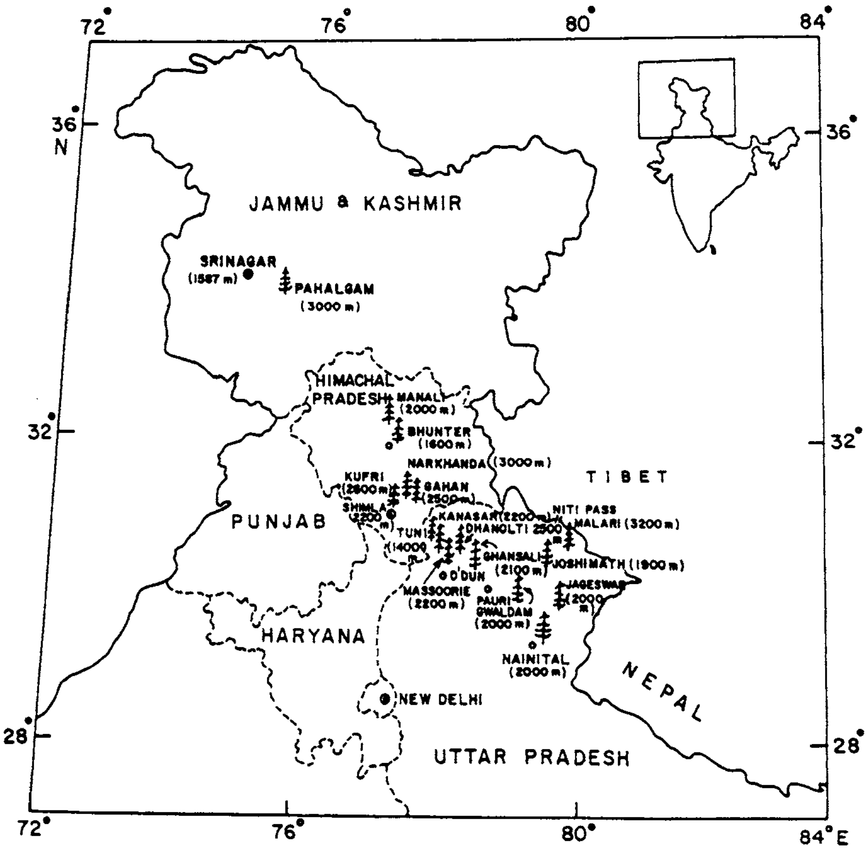

Fig. 1. Location map of the sampling sites.

Conifers occupy a major part of the forest area of the Himalaya. *Cedrus, Abies, Picea,* and *Pinus* are the main genera that form extensive forests over the region.

About 315 tree cores from 11 different sites in the Western Himalaya from Kashmir through Himachal Pradesh and the Hills of Uttar Pradesh were collected using increment borers. Figure 1 represents the locations of the sampling sites. Detailed information for each site is listed in Table 1. We tried to maintain the two-cores-per-tree criteria for most of the sites to account for the variability within an individual tree. *Cedrus deodara, Abies pindrow, Picea smithiana,* and *Pinus roxburghii* are the main species we have sampled.

Table 1. Sampling sites and tree species.

Site No.	Site name (state)	Location	Elevation (in m)	Date of collection	Species name	Trees sampled[1]
1	Pahalgam (J&K)	34° 02' N 75° 42' E	2600–2900	Sept. 1982	*Abies pindrow* *Picea smithiana*	9 (1)
2	Kanasar (U.P.)	30° 45' N 77° 48' E	2200	June 1989	*Cedrus deodara* *Pinus wallichiana*	22 (2) 4 (2)
3	Tuni (U.P.)	30° 50' N 77° 26' E	1400–1800	June 1989	*Pinus roxburghii* *Cedrus deodara*	16 (2) 8 (2)
4	Kufri (H.P.)	31° 07' N 77° 10' E	2400–2700	June 1989	*Cedrus deodara*	19 (2)
5	Manali (H.P.)	32° 16' N 77° 10' E	2000	June 1989	*Cedrus deodara*	27 (2)
6	Narkhanda (H.P.)	31° 12' N 77° 14' E	3000	April 1990	*Abies pindrow* *Cedrus deodara* *Picea smithiana*	15 (2) 9 (2) 9 (2)
7	Gahan-Nankheri (H.P.)	31° 11' N 77° 16' E	2500	April 1990	*Picea smithiana* *Abies pindrow* *Pinus wallichiana* *Cedrus deodara*	27 (2) 10 (2) 2 (1) 1 (2)
8	Dhanolt (Jwarna, U.P.)	30° 45' N 78° 25' E	2400	April 1991	*Picea smithiana* *Cedrus deodara*	9 (2) 2 (2)
9	Ghansali (U.P.)	30° 37' N 78° 45' E	800–2100	April 1991	*Pinus roxburghii*	23 (2)
10	Malari (U.P.)	30° 50' N 79° 55' E	3200	May 1991	*Cedrus deodara*	16 (2)
11	Jageswar (U.P.)	29° 46' N 79° 10' E	2000	May 1991	*Cedrus deodara*	11 (2)

1) Number of trees sampled; between brackets the number of cores per tree.

TREE-RING DATA

In the process of developing ring-width series of individual samples and the preparation of site chronologies, all samples of each site were cross-dated using the skeleton plot method (Stokes & Smiley 1968). Distinct growth patterns and gradual to abrupt transition from earlywood to latewood made the cross-dating exercise easy. Good cross-dating was possible for the samples of almost all sites except Malari. False or double rings were observed in only a few cases. The frequency of resin canals was very low and in many cases clearly distinguishable from the true ring boundary. The situation is critical for the Malari site, where most of the *Cedrus deodara* samples are older than 400 years. This site is close to the glacier. The rings are very narrow. In most of the cases resin rings were observed very close to the true ring boundary and less often in the middle of the rings. Due to very narrow rings and the association of resin canals with ring boundaries, it was very difficult to distinguish the correct ring boundaries in more than 70 percent of the cores and cross-match among them.

Ring-width measurements were done using a stereo microscope hooked up to an increment measurement table. The ring-width data are passed on to the computer where they are processed to the standard ITRDB [International Tree-Ring Data Bank] format. The system is capable to measure ring widths to the nearest 10^{-3} cm. All ring-width series have been checked for possible measurement or dating errors using the computer program COFECHA (Holmes et al. 1986). Problems indicated by this program due to the ambiguous nature of a core segment or a core group of a particular site might be the result of measurement or dating errors. Such problems have been taken into account to improve dating quality by measuring or re-checking particular core segments or core groups. More problematic segments of the cores were not included in the further analysis. In the case of *Cedrus deodara* from Malari glacier COFECHA showed unresolvable problems at various segments of many samples. This may be due to groups of narrow rings exhibited by many samples. Only five cores out of 25 were less problematic and have been used to prepare a tree-ring chronology of the site. Therefore the Malari site was excluded from further analysis.

CHRONOLOGY DEVELOPMENT

Age trends following a negative exponential curve were observed for most of the ring-width series. Many ring-width series from Manali, Kufri, Tuni and Jageswar show a pronounced juvenile effect. Also suppression and release of tree growth were seen in many series. This may be due to natural survival competition among the trees. Therefore, selection of the detrending method was done at the individual tree level for optimum performance. Table 2 represents the options used in the standardization process to achieve the best signal of the common forcing parameter, which is assumed to be climatic, responsible for tree growth over the wide area. The first three letters of the site identification in Table 2 indicate the site and the remaining two letters correspond with the species name.

Table 2. Standardization of western Himalayan tree-ring chronologies.
CS: cubic spline; wl: wave length; N = series length.

Site No.	Site name	Site ID	No. of cores (trees)	Detrending method	Chronology span
1	Pahalgam	PHAAP	8 (8)	CS at 60 yrs wl	1612–1982 (371 yrs)
		PHAPS	13 (13)	CS at 40 yrs wl	1775–1982 (208 yrs)
2	Manali	MNLCD	42 (21)	neg. expon. + CS at 70% N wl	1676–1988 (313 yrs)
3	Kufri	KUFCD	33 (18)	neg. expon. + CS at 60 yrs wl	1775–1988 (214 yrs)
4	Narkhanda	NARCD	20 (12)	CS at 70% N wl	1685–1989 (305 yrs)
		NARAP	17 (9)	CS at 60% N wl	1590–1989 (400 yrs)
		NARPS	14 (9)	CS at 60% N wl	1724–1989 (266 yrs)
5	Gahan	GAHAP	12 (10)	CS at 60% N wl	1745–1989 (245 yrs)
		GAHPS	45 (26)	CS at 60% N wl	1673–1989 (317 yrs)
6	Kanasar	KANCD	27 (14)	CS at 60% N wl	1711–1988 (278 yrs)
7	Tuni	TUNPR	29 (16)	neg. expon. + CS at 60 yrs. wl	1801–1988 (188 yrs)
8	Dhanolti	DHAPS	12 (7)	CS at 60% N wl	1720–1990 (271 yrs)
9	Ghansali	GHAPR	25 (16)	CS at 60% N wl	1796–1990 (195 yrs)
10	Jageswar	JAGCD	13 (10)	neg. expon. + CS at 70% N wl	1657–1990 (334 yrs)
11	Malari	MLRCD	5	polynomial	1456–1990 (525 yrs)

Detrending of individual series and preparation of site chronologies were carried out with the computer program ARSTAN (Holmes et al. 1986). Index series of individual samples were obtained by the quotient method and site chronologies were formed by calculating the biweight mean. Two chronologies from Pahalgam, viz. PHAAP and PHAPS, were detrended with a cubic spline (Cook & Peter 1981) with 50% Variance Reduction Frequency (VRF) corresponding to 60 and 40 years wavelength, respectively. The double detrending method (Holmes et al. 1986) was found to be more suitable for the MNLCD, KUFCD, TUNPR, and JAGCD series. The first detrending using a negative exponential curve removes most of the signals associated with a strong juvenile effect in the early portion of the series, whereas the second detrending was performed by applying an appropriate cubic spline (Table 2) to minimize the effect of residual noise. For many sites the performance of cubic spline was observed to be better if the spline stiffness is expressed in percentage of the series length (% N criterion, where N is series length; Cook et al. 1990) rather than the fixed stiffness. Better performance was observed for detrending with a stiffness of 60 to 70% N years. More persistence in the series is observed as a common feature of Himalayan conifers. Lag-1 auto-correlation is significant in many series. Hence the auto-regressive modeling option in the program ARSTAN was used to remove auto-correlation from the series. Figure 2a gives the time series plot of the *Cedrus deodara* tree-ring chronologies and Figure 2b is for the other conifer species of the Western Himalaya.

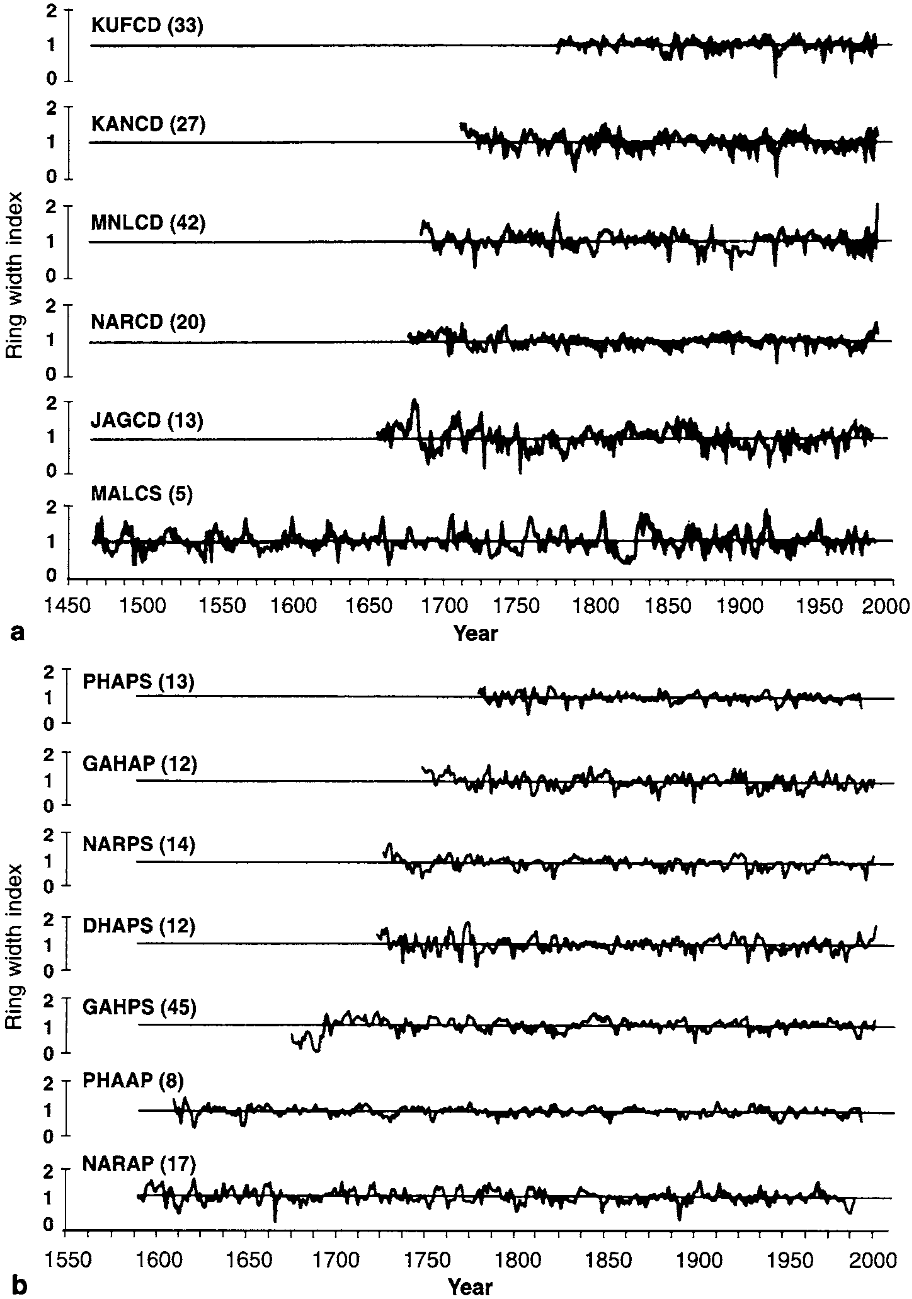

Fig. 2. Western Himalayan *Cedrus deodara* tree-ring chronologies (**a**) and other Western Himalayan tree-ring chronologies (**b**).

Table 3a. Descriptive statistics of western Himalayan tree-ring chronologies.

Site ID	Time span	Number of years	Mean sensitivity	Stand. dev.	lag-1 auto-corr.	Common variance (period)	Signal-to-noise ratio
PHAAP	1612–1982	371	.094	.15	.65	0.29 (1676–1981)	3.3
PHPPS	1775–1982	208	.143	.167	.43	0.35 (1865–1981)	7.0
MNLCD	1676–1988	313	.173	.189	.37	0.18 (1882–1981)	3.6
KUFCD	1775–1988	214	.177	.179	.25	0.27 (1901–1987)	6.7
NARCD	1685–1989	305	.197	.240	.47	0.22 (1835–1982)	3.4
NARAP	1590–1989	400	.165	.213	.53	0.30 (1749–1986)	3.8
NARPS	1724–1989	266	.160	.209	.57	0.26 (1805–1988)	2.5
GAHAP	1745–1989	245	.218	.263	.50	0.34 (1844–1989)	4.69
GAHPS	1673–1989	317	.170	.247	.71	0.19 (1857–1984)	4.77
KANCD	1711–1988	278	.252	.251	.34	0.23 (1876–1985)	3.85
TUNPR	1801–1988	188	.212	.218	.22	0.27 (1903–1986)	5.04
DHAPS	1720–1990	271	.243	.270	.42	0.26 (1852–1988)	1.79
GHAPR	1796–1990	195	.213	.206	.31	0.35 (1861–1982)	5.32
JAGCD	1657–1990	334	.282	.322	.50	0.23 (1798–1990)	2.94

EVALUATION OF DENDROCLIMATIC POTENTIAL

Various climatic and non-climatic environmental factors are responsible for tree growth. Proper standardization removes most of the unwanted low frequency signal caused by the aging factor, and endogenous or exogenous disturbances (Fritts 1976). The residual signal in the series after standardization expresses mainly the high frequency signals acting over a wide area of the sites. This signal is of prime importance in dendroclimatic analysis as it is supposed to be mainly the effect of climate on tree growth. To evaluate the strength of those signals in tree-ring series and their applicability in dendroclimatic reconstruction, statistical testing is essential.

Table 3b. Descriptive statistics of western Himalayan tree-ring chronologies (after auto-regressive modeling).

Site ID	Time span	Number of years	Mean sensitivity	Stand. dev.	lag-1 auto-corr.	Common variance (period)	Signal-to-noise ratio
PHAAP	1613–1982	370	.121	.131	.01	0.30 (1676–1981)	3.4
PHPPS	1776–1982	207	.167	.151	.07	0.36 (1865–1981)	7.3
MNLCD	1680–1988	309	.191	.163	.02	0.32 (1882–1981)	6.88
KUFCD	1778–1988	211	.220	.191	.01	0.37 (1901–1987)	10.37
NARCD	1687–1989	303	.221	.204	.07	0.27 (1835–1982)	4.48
NARAP	1592–1989	398	.203	.179	.00	0.38 (1749–1986)	5.58
NARPS	1725–1989	265	.191	.167	.01	0.30 (1805–1988)	3.02
GAHAP	1747–1989	243	.256	.219	.02	0.44 (1844–1989)	6.99
GAHPS	1676–1989	314	.168	.153	.01	0.27 (1857–1984)	7.81
KANCD	1713–1988	276	.263	.223	.02	0.34 (1876–1985)	6.68
TUNPR	1803–1988	186	.221	.203	.01	0.32 (1903–1986)	6.53
DHAPS	1721–1990	270	.289	.243	.09	0.36 (1852–1988)	2.76
GHAPR	1797–1990	194	.246	.196	.01	0.38 (1861–1982)	6.18
JAGCD	1662–1990	329	.279	.255	.01	0.35 (1798–1990)	5.27

Statistical analysis

Table 3a shows descriptive statistics for 14 chronologies and Table 3b presents the performance of the chronologies after the auto-regressive modeling. The common variance and signal-to-noise ratio were calculated over the common period of the chronologies.

All chronologies except *Pinus roxburghii* are longer than 200 years. *Abies* chronologies from Narkhanda and Pahalgam are the longest. Mean sensitivity and standard deviation values are moderately high for all chronologies except for those of

Table 4. Years showing the minimum ring-width index value for 14 western Himalayan chronologies (the value in brackets indicates the index value of year 1921 of the respective chronology).

	Site ID	Minimum Index Value	Year
1	MNLCD	.354	1921
2	KUFCD	.096	1921
3	NARCD	.200	1921
4	KANCD	.005	1921
5	JAGCD	.009 (0.173)	1753
6	NARAP	.161 (0.888)	1667
7	GAHAP	.166 (0.517)	1892
8	NARPS	.378 (0.434)	1816
9	GAHPS	.027 (0.612)	1687
10	DHAPS	.146 (0.318)	1774
11	TUNPR	.269 (0.986)	1816
12	GHAPR	.346	1921
13	PHAAP	.392 (0.998)	1620
14	PHAPS	.347 (0.699)	1802

Pahalgam. Lowest values are found for the PHAAP chronology and the highest for the JAGCD chronology. The persistence in the series defined by auto-correlation values is highest for GAHPS and lowest for TUNPR. The high first order auto-correlation and low mean sensitivity indicates the presence of more low-frequency variance in the series. In the reverse case, the high-frequency variations are more prominent. The high-frequency variance is of more interest in dendroclimatic studies. The persistence in the series can be removed by auto-regression modeling which helps to improve the high-frequency variation.

The common variance is a mean of the correlation coefficients of all possible pairwise combinations of ring-width index series over the common interval period. This signal indicates the variance due to the common forcing factor for a site. This might be a common climatic effect experienced by all trees over a wide area of the site. The values of the common signal are sufficiently large for all the sites. Signal-to-noise ratios (SNR) also indicate the applicability of the tree-ring series in dendroclimatic analysis. There is significant increase in common signal and SNR when the autocorrelation structure in the series is removed by auto-regressive modeling (Table 3b).

An interesting feature observed in all the *Cedrus deodara* chronologies is the low value of ring-width index (lowest growth) that occurred in the year 1921 (Table 4). In some chronologies (e.g. NARPS, DHAPS) the ring-width index of the year 1921 is very low and close to the minimum index value of the chronology.

The minimum index value does not necessarily indicate an environmental effect. Nevertheless, if the year of the minimum index value is the same at several sites, the cause may be some larger-scale phenomenon of the atmospheric or even the lithospheric environment. The year 1921 shows a minimum index value for all *Cedrus deodara* chronologies. It implies that the growth of *Cedrus deodara* is small in the year 1921 over a large area of the Western Himalaya. This may be due to climate during or prior to that year.

Table 5. Grouping of meteorological stations and tree-ring chronologies (in brackets: mean elevation of the sites in metres).

Sr. No.	Meteorological station	Tree-ring chronology
1	Srinagar (1549)	PHAAP (2700), PHAPS (2700)
2	Shimla (2202)	MNLCD (2000), KUFCD (2600), NARCD (3000), NARAP (3000), NARPS (3000), GAHAP (2500), GAHPS (2500), DHAPS (2400), KANCD (2200)
3	Mussoorie (2042)	KANCD (2200), TUNPR (1600), KHAPR (1600)
4	Dehra Dun (682)	KANCD (2200), TUNPR (1600)
5	Mukteswar (2311)	JAGCD (2000), GHAPR (1600)

Response function analysis

A quantitative evaluation of the relationship between climatic parameters and tree growth can be studied on a better resolved scale using response function analysis (Fritts 1976). It involves principal component and multiple regression analysis, with climatic parameters on monthly and seasonal basis as predictors and the tree-ring index as the predictant. Table 5 represents the grouping of the tree-ring chronologies and the corresponding meteorological stations used in the analysis. This grouping is based on the close locations of tree-ring sites and meteorological stations, their comparable elevations and availability of long and continuous meteorological data (temperature and rainfall). In the analysis, a set of 26 variables were used as predictors which means 13 for temperature and 13 for precipitation from previous October (end of previous growing season) to the current October (end of current growing season). Because the residual (persistence free) chronologies (RES) were used in the analysis, prior growth (lag-1, 2, 3) was not considered. Table 6a & b represents the results of the response function analysis on monthly and on seasonal basis, respectively. These tables only show significant coefficients. Temperature during pre-monsoon (March–April–May) and summer months shows significant negative responses whereas precipitation during the same months shows a positive response. On the seasonal scale (Table 6b) a significant negative response with March–April–May temperature was observed across all sites whereas a significant positive relationship can be seen with

Table 6a. Response function analysis calculated with monthly temperature and precipitation from October of the previous year (-O) to October of the current year (O); significance $p < 0.05$, ● = negative relationship, + = positive relationship.

Srinagar Climate (1893-1982)

	Temperature													Precipitation												
ID	-O	-N	-D	J	F	M	A	M	J	J	A	S	O	-O	-N	-D	J	F	M	A	M	J	J	A	S	O
PHAAP		+	+			+		●	●	●	+					+	+		+	+	+	●	+	+	+	
PHAPS	+	+						●	●	●	●	●					+		+		+	●	+	+	+	●

Shimla Climate (1876-1982)

	Temperature													Precipitation												
ID	-O	-N	-D	J	F	M	A	M	J	J	A	S	O	-O	-N	-D	J	F	M	A	M	J	J	A	S	O
MNLCD		●				●	●	●					+		+	+				+	+			●		●
KUFCD		●	●			●	●	●			+		+					+	+	+	+	+		●		
KANCD						●	●	●	●	●	+		+		+			+		+	+			●		
NARCD				●	+		●	●							●				+	+				●	●	+
NARAP						●	●	●						●					+							+
NARPS						●	●	●	●	●			+		+	+			+	+				●	+	
GAHAP	+	●					●	●		●	+		+						+	+	+	+		●		+
GAHPS	+		●			●	●	●		●	+		+						+	+		+	+	●		+
DHAPS			+								+	+								+	+		+			

Mussoorie Climate (1930-1980)

	Temperature													Precipitation												
ID	-O	-N	-D	J	F	M	A	M	J	J	A	S	O	-O	-N	-D	J	F	M	A	M	J	J	A	S	O
TUNPR						●		●			●		●							+	+	+		+		
GAHPR					●	●	●				+		●					+		+			+		+	
KANCD		●			●	●	●					+				+		+	+	+				●		

Dehradun Climate (1901-1980)

	Temperature													Precipitation												
ID	-O	-N	-D	J	F	M	A	M	J	J	A	S	O	-O	-N	-D	J	F	M	A	M	J	J	A	S	O
TUNPR		●			+	●		●						●	+			+	+		+			+		●
KANCD			●			●			●	●					+	+	+	+		+			+			+

Mukteswar Climate (1901-1982)

	Temperature													Precipitation												
ID	-O	-N	-D	J	F	M	A	M	J	J	A	S	O	-O	-N	-D	J	F	M	A	M	J	J	A	S	O
GAHPR					●	●		●	●		+	+			+		+	+	+							●
JAGCD	●			●		●	●	●	●	●	+	+	+	+		+		+		+	+					

precipitation for the same season. The response function for the Pahalgam site using the climatic data from Srinagar differ from the others due to their higher northern latitudes. May–June–July temperature shows a negative relationship and May–September precipitation a positive relationship to tree growth.

Table 6b. Response function analysis calculated with seasonal temperature and precipitation; significance $p < 0.05$, ● = negative relationship, + = positive relationship.

Srinagar Climate (1893-1982)

	Temperature						Precipitation					
ID	-ON	DJF	MA	MJJ	AS	ON	ON	DJF	MA	MJJ	AS	ON
PHAAP		●		●		+		+		+	+	
PHAPS	+	●		●		+		+		+	+	

Shimla Climate (1876-1982)

	Temperature						Precipitation					
ID	-JJAS	-ON	DJF	MAM	JJAS	ON	-JJAS	-ON	DJF	MAM	JJAS	ON
MNLCD	+			●					+	+		
KUFCD	+		●	●	●				+	+		
KANCD			●	●		+	+		+	+		
NARCD				●			+			+	●	
NARAP				●			●			+		
NARPS	●			●						+		
GAHAP				●		+				+		
GAHPS				●		+				+		
DHAPS				●					+	+		

Mussoorie Climate (1930-1980)

	Temperature						Precipitation					
ID	-JJAS	-ON	DJF	MAM	JJAS	ON	-JJAS	-ON	DJF	MAM	JJAS	ON
TUNPR				●		●				+		
GAHPR		●	●	●		●	+		+			
KANCD	●			●			●		+			

Dehradun Climate (1901-1980)

	Temperature						Precipitation					
ID	-JJAS	-ON	DJF	MAM	JJAS	ON	-JJAS	-ON	DJF	MAM	JJAS	ON
TUNPR	●	●		●			●			+	+	
KANCD	●			●					+	+		

Mukteswar Climate (1901-1982)

	Temperature						Precipitation					
ID	-JJAS	-ON	DJF	MAM	JJAS	ON	-JJAS	-ON	DJF	MAM	JJAS	ON
GHPAR			●	●	+				+	+		
JAGCD				●					+	+	+	

DISCUSSION AND CONCLUSIONS

In this study a tree-ring network was established for Western Himalaya and the results confirm its dendroclimatic potential. The chronologies exhibit significant persistence (lag-1 auto-correlation) in the series. Sufficiently high values of mean sensitivity, common variance and signal-to-noise ratios show usefulness of the chronologies for dendroclimatic studies.

The response function analyses show a similar pattern across different regions. The relationships between tree growth and climate suggest that the pre-monsoon summer (March–April–May) climate plays a critical role in the tree-growth process. The significant relationship of pre-monsoon climate with tree growth over the wide area of sampling sites could be primarily associated with the availability of moisture which is a function of both temperature and precipitation. The temperature of the region starts increasing in March, and May is the hottest month of the pre-monsoon season. During this season precipitation is very low. The season coincides with the early part of the growing season of the Himalayan conifers (Borgaonkar 1996). Higher temperature of these months accelerates evaporation and evapotranspiration resulting in anomalous moisture stress condition for the growth of the trees, hence the negative response of the temperature as observed in the analysis. However, slightly more precipitation than the season's normal is very useful in maintaining the minimum requirement of moisture and is found to be conducive for tree growth. After May, the temperature is usually stable due to monsoonal rain in the region.

Srinagar, which is located at higher northern latitudes and out of reach of the monsoon influence, has a different annual cycle of temperature and precipitation. The hottest months are May–June–July–August. Precipitation during these months is less. Temperature during May–June–July causes moisture stress, which results in a negative relationship with tree growth. A slight amount of additional precipitation during these months has been observed to enhance tree growth.

This study gives important information about tree-ring analysis of conifers in the Western Himalaya and the relationship governing the growth and their dendroclimatic response. With longer chronologies over a wider area, the reconstruction of the summer climate of the region can be obtained for several centuries.

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