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RING-WIDTH VARIATIONS IN *Cedrus deodara* AND ITS CLIMATIC RESPONSE OVER THE WESTERN HIMALAYA

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ABSTRACT

Tree-ring anlaysis of *Cedrus deodara* from three different sites of western Himalaya has been carried out. The chronologies include 47 cores (26 trees) from Manali, 33 cores (18 trees) from Kufri (Shimla) and 25 cores (13 trees) from Kanasar forest sites. Moderately high values of common variance exhibited by all three chronologies indicate the great potential of the species for dendroclimatic studies.

Response function and correlation analyses using the above tree-ring-width data and Shimla climate show a significant negative relationship with summer temperature and positive relationship with summer precipitation. Based on these results, calibration equations have been developed for different periods, and appropriately verified using independent data, to reconstruct the pre-monsoon (March–April–May) temperature at Shimla. The reconstruction has extended the temperature record of the region back to the eighteenth century.

KEY WORDS: western Himalaya; *Cedrus deodara;* dendroclimatic reconstruction; summer temperature; summer precipitation.

INTRODUCTION

The Himalayan region is of prime importance in the context of global climate change because of its influence on the Asian summer monsoon circulation, which affects the climates of the most populated countries of the world. The climatology of the Himalaya so far has been based largely on instrumental records, which go back to about 100 years. In views of this, palaeoclimatic studies, specifically during the Holocene period, are important for understanding the role of the Himalaya in global climate change on century and longer time-scales. In this context, the rich conifer forests of the Himalaya offer excellent dendroclimatic tools to reliably reconstruct the past climatic variations, even going back to about 1000 years. Several studies (Pant, 1979, 1983; Pant and Borgaonkar, 1984; Ramesh *et al.*, 1985, 1986; Bhattacharyya *et al.* 1988; Bhattacharyya and Yadav, 1989) have conclusively established the dendroclimatic potential of Himalayan conifers such as *Abies*, *Pinus*, *Picea*, and *Cedrus*. These species show distinct annual growth and exhibit great age. Hughes and Davies (1987) used a wide network of *Abies pindrow* and *Picea smithiana* of Kashmir in order to understand the association between variations in tree-growth parameters (ring width and density) and regional climate. Hughes (1992) later reported a reconstruction of the summer climate of Srinagar since the late eighteenth century using ring-density and ring-width chronologies of *Abies pindrow* from Kashmir, Bhattacharyya and Yadav (1990) reported dendroclimatic analysis of *Cedrus deodara* at a few sites in Joshimath, Uttar Pradesh. They also noted the great age of the species and the significant response to summer climate of the region. Borgaonkar *et al.* (1994) presented the dendroclimatic reconstruction of summer precipitation at Srinagar back to the late eighteenth century using multiple species tree-ring network. However, various other species and sites in the extensive Himalayan forests are still open for dendroclimatic studies, and can provide large-scale scenarios for Himalayan climate during the recent past.

In this paper, we present the analysis of *Cedrus deodara* samples from three different sites. This is the first time that *Cedrus deodara* ring-width chronologies from well-diversified sites of western Himalaya have been studied in order to evaluate a tree-growth–climate relationship and its applicability to dendroclimatic reconstruction.

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THE SAMPLING SITES

Tree-ring samples at three sites, namely Kanasar (Uttar Pradesh), Kufri, and Manali (Himachal Pradesh), have been considered for the present study (Figure 1). *Cedrus deodara* is the main species dominating the forest stands over the region. Few stands of *Pinus* (*Pinus wallichiana*) are also found to exist along with the *Cedrus* forest at the Kanasar site. The Kufri site is at a relatively higher elevation (2500 m above mean sea-level) than the other two (Kanasar at 2200 m and Manali at 2000 m). Many trees are found to be old (> 250 years) from the Kanasar and Manali forests, whereas those from the Kufri region are relatively young. The nearest observatory station having continuous long-period climatic data and located at a similar altitude with related environmental conditions is Shimla (altitude: 2200 m a.m.s.l.) in Himachal Pradesh (Figure 1). The Shimla station is located at about 180 km from Kanasar, 20 km from Kufri and 250 km from Manali. However, by virtue of topography, the aerial distances of the sites from the meteorological station are much less (< 50 per cent of the actual distance). Monthly mean temperature and precipitation data for the period 1876–1982 at Shimla have been used in the analysis.

DATA PROCESSING

Ring-width data

The tree-ring samples considered include 25 cores (13 trees) from Kanasar, 33 cores (18 trees) from Kufri and 47 cores (26 trees) from Manali. Samples were subjected to the skeleton plot method (Stokes and Smiley, 1968) in order to examine the nature of cross-matching required for precise dating of the samples. Ring-widths have been measured to an accuracy of 10^{-2} mm using an incremental measurement machine through a stereomicroscope. The measuring machine has a linear encoder, interfaced with a personal computer system to record the measurements. Possible dating or measurement errors have been checked by the computer program COFECHA (Holmes *et al.*, 1986) and necessary corrections have been made by repeating the measurements and by detailed examination of the problem sections of the samples.

Ring-width series indicate the resultant annual growth patterns of the trees, representing the aggregate effect of many environmental factors, including climate, biological ageing, local endogenous disturbances due to competition amongst the trees and exogeneous disturbances caused by fire, pests, disease, pollution, logging, etc. Appropriate detrending methods (Fritts, 1976; Cook *et al.*, 1990), such as negative exponential, cubic spline smoothing, linear regression, polynomial curve fitting, etc., have to be applied to the ring-width series, depending upon the nature of the series, in order to minimize the non-climatic signals. The ring-width series thus filtered are called ring-width 'index' series and are expected to contain a large variance owing to climatic influences.

Most of the samples from the Kufri site show a prominent juvenile effect, therefore, two-step detrending (Holmes *et al.*, 1986; Cook *et al.*, 1990) has been used, namely, negative exponential followed by cubic spline smoothing. The series from the other two sites, Kanasar and Manali, have been detrended using cubic spline smoothing. The response function of the smoothing spline has 50 per cent variance reduction at wavelengths equal to 70 per cent of the data period, the reduction gradually decreasing to zero at shorter wavelengths and gradually increasing to 100 per cent at longer wavelengths. The detrending options adopted in the analysis give the optimum value of signal-to-noise ratio and allows the retention of even low-frequency signals, if any, that are common to the samples. Ring-width index series have been obtained by dividing the raw ring-width series by the smoothed series and the site chronologies have been prepared by averaging all the index series from a particular site. Thus, ring-width chronologies have been prepared for three different sites, namely Kanasar (KANCD), Kufri (KUFCD), and Manali (MNLCD). The labels in parentheses provide chronology identification for the site and species. Graphical representation of these chronologies and their various statistics are presented in Figure 2 and Table I respectively. The Manali and Kanasar chronologies are longer than the Kufri chronology. Average interannual variation, defined by the mean sensitivity, is generally high in all the chronologies, which may be presumed to be associated with the influence of common environmental parameters, predominantly the climate. However, the series at Kanasar and Manali also show significant persistence. In the analysis of variance the common signals (percentage *Y*) of the chronologies are comparatively large, which indicate a good potential of the species for dendroclimatic studies.

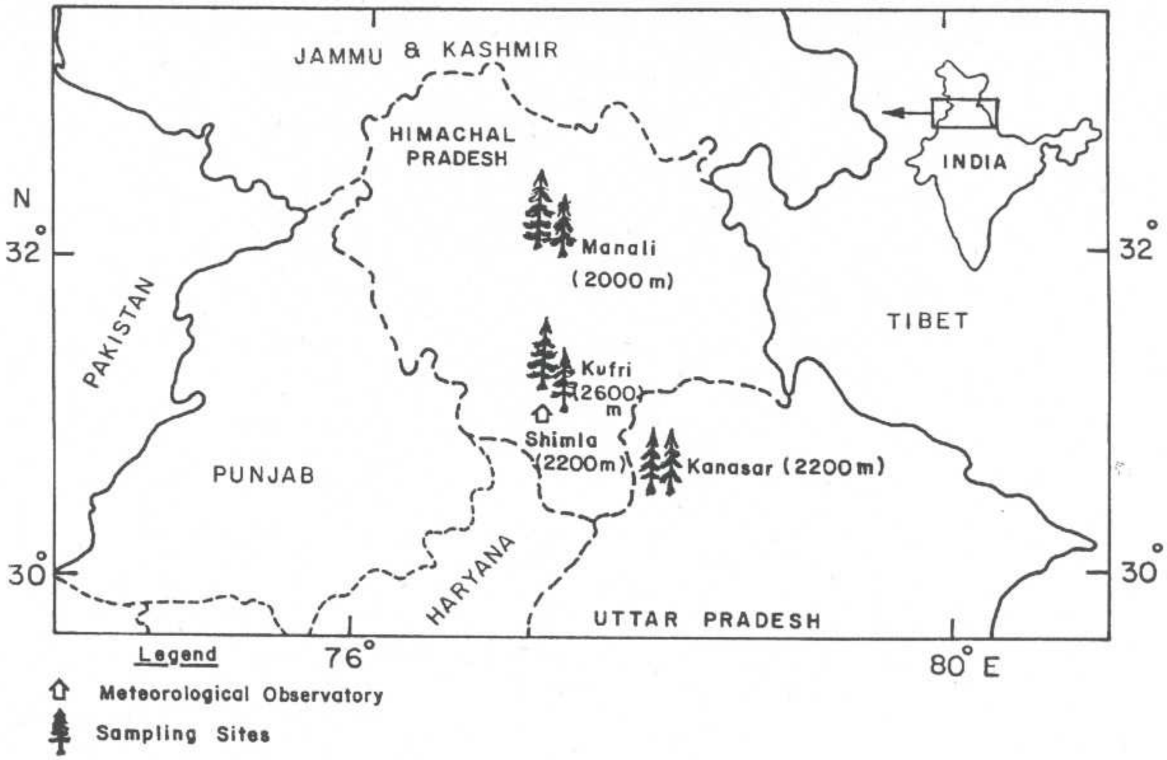

Figure 1. Location map of sampling sites (values in parentheses are average altitude)

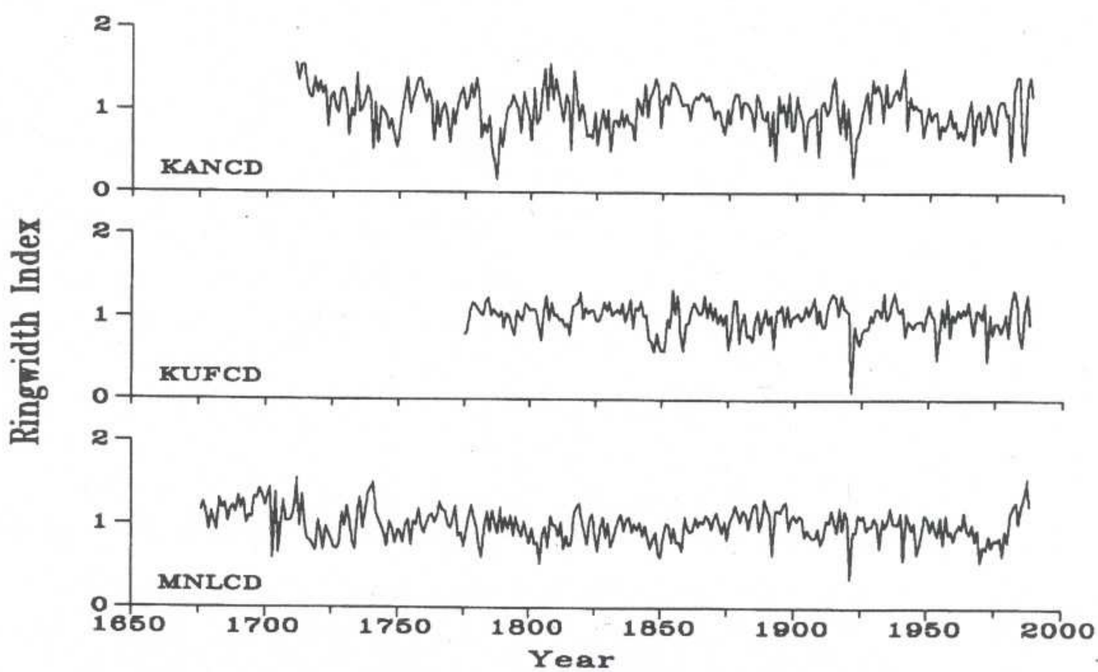

Figure 2. Mean ring-width index chronologies of *Cedrus deodara* at Kanasar, Kufri, and Manali

Table I. Statistics of western Himalayan *Cedrus deodara* chronologies

	KANCD	KUFCD	MNLCD
Period	1711–1988	1775–1988	1676–1988
Number of years	278	214	313
Mean ring-width (mm)	2·270	3·110	2·401
Mean index	0·989	1·000	0·999
SD	0·204	0·182	0·218
Mean sensitivity	0·275	0·345	0·285
Lag-1 autocorrelation	0·460	0·255	0·344
Analysis of variance			
Period	1876–1985	1900–1987	1872–1985
Number of years	110	88	143
Mean ring-width (mm)	1·870	2·510	2·110
Mean index	0·998	0·999	0·999
Common variance (per cent *Y*)	32	37	32

Climatic data

Monthly variations of temperature and rainfall at Shimla based on long-period averages are illustrated in Figure 3. Seventy-five per cent of the annual rainfall is contributed by the monsoon (June through to September) months. The post-monsoon (October–November) rainfall is negligible, contributing only 3 per cent of the total precipitation, and the remaining part of the annual rainfall is realized during winter (December–January–February) and pre-monsoon (March–April–May), including occasional heavy snowfall in the winter. May and June are the hottest months and temperature decreases gradually in the following summer months (July–August–September) owing to the monsoonal rains. Table II gives the detailed analysis of Shimla climate, including long-term trends. July temperature shows a significant decreasing tendency whereas post-monsoon (ON) temperature shows increasing trend. During pre-monsoon and monsoon months the temperature tendency is decreasing but not significantly. In the case of precipitation, decreasing trend is observed in all the seasons except for post-monsoon season (ON), which shows negligible increasing trend (0·7 cm/100 years). Figures 4 and 5 represent the interannual variations in temperature and rainfall, respectively, at Shimla for different seasons over the period of 100 years.

TREE-GROWTH–CLIMATE RELATIONSHIP

The active growth period of Himalayan deodar is March through to October. The new shoots appear in March and early April. The growth of xylem cells is rapid if the necessary minimum moisture is received during the spring and summer (FRI 1976). Therefore, the climatic conditions during these months play a very crucial role in annual tree growth. The growth remains dormant throughout the winter, but the precipitation in the form of rain or snow during these months is an important source for the moisture available at the root zone during the early period of growth.

Response function analysis

A precise quantitative analysis of the climate–tree growth relationship can be obtained by response function analysis (Fritts, 1976). In this procedure, a set of 27 variables, containing 26 monthly mean climatic variables (temperature and rainfall) from the previous October (ending month of prior growth period) to the current October (ending month of current growth period) at Shimla for the period 1876–1982 and one variable representing prior growth of the respective chronology to account for the persistence in the tree-ring series, have been used as a predictor set in the stepwise multiple regression analysis, with the current ring-width as the predictand. The climatic variables themselves are characteristically highly correlated among themselves; this leads to an unnecessary loss in the degrees of freedom. To conserve the degrees of freedom and obtain a statistically significant relationship, the set of preditor variables has been transformed into an equal number of uncorrelated

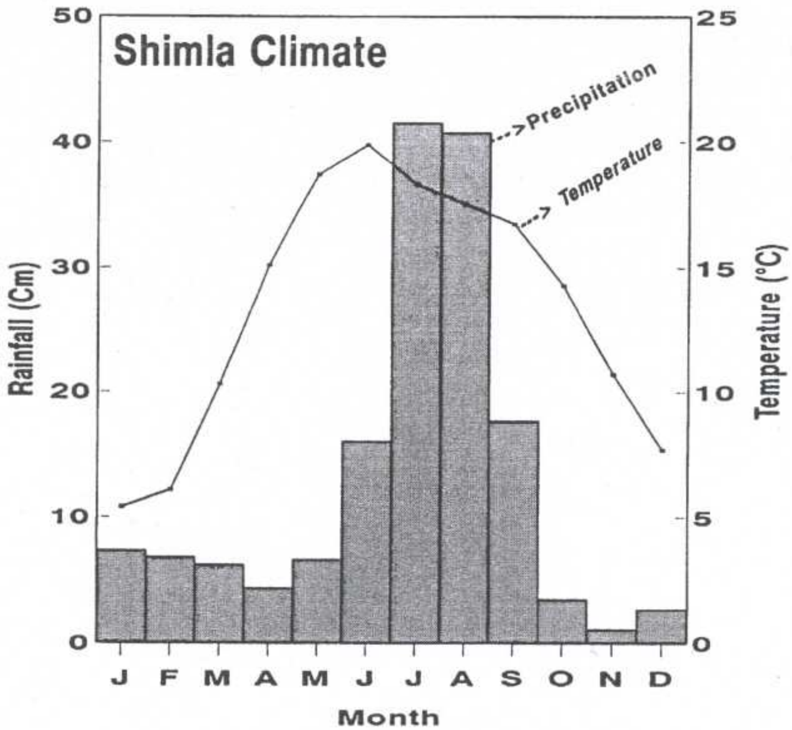

Figure 3. Mean monthly variations in temperature and rainfall at Shimla during 1876–1982

Table II. Statistics of Shimla climate (period: 1876–1982)

Month	Temperature (°C)			Precipitation (cm)		
	Mean	SD	Trend 100 years^{-1}	Mean	SD	Trend 100 years^{-1}
January	5·4	1·6	−0·7	7·3	7·4	−1·8
February	6·1	1·8	0·8	6·8	5·1	−4·3
March	10·3	1·9	−0·1	6·2	4·5	0·1
April	15·1	1·8	−0·3	4·4	3·7	−1·1
May	18·7	1·7	−0·5	6·6	5·2	−3·0
June	19·9	1·1	−0·4	16·1	9·5	−2·7
July	18·3	0·7	−0·8*	41·6	13·9	−3·5
August	17·5	0·6	−0·3	40·8	16·2	−13·1*
September	16·7	0·7	−0·2	17·7	10·3	5·0
October	14·3	1·0	0·6	3·5	4·6	1·5*
November	10·7	1·0	0·3	1·1	2·0	−0·9
December	7·7	1·4	−0·1	2·7	3·2	−1·9
DJF	6·4	1·1	0·2	16·8	9·9	−7·7*
MAM	14·7	1·3	−0·2	17·3	8·5	−3·9
JJAS	18·1	0·6	−0·4	116·2	26·7	−14·3*
ON	12·5	0·9	0·4*	4·6	5·0	0·7
Annual	13·4	0·7	−0·1	154·9	30·0	−25·5*

* Significant at the 5 per cent level

variables using principal component analysis (Fritts, 1976; Pant *et al.*, 1988). This new set of principal components (PCs) has been used in the stepwise regression analysis as a predictor set. The resultant regression equation based on principal components is then reconverted back into the terms of the original climatic variables using the corresponding weights of PCs. Thus, the response function coefficients giving standardized response in terms of

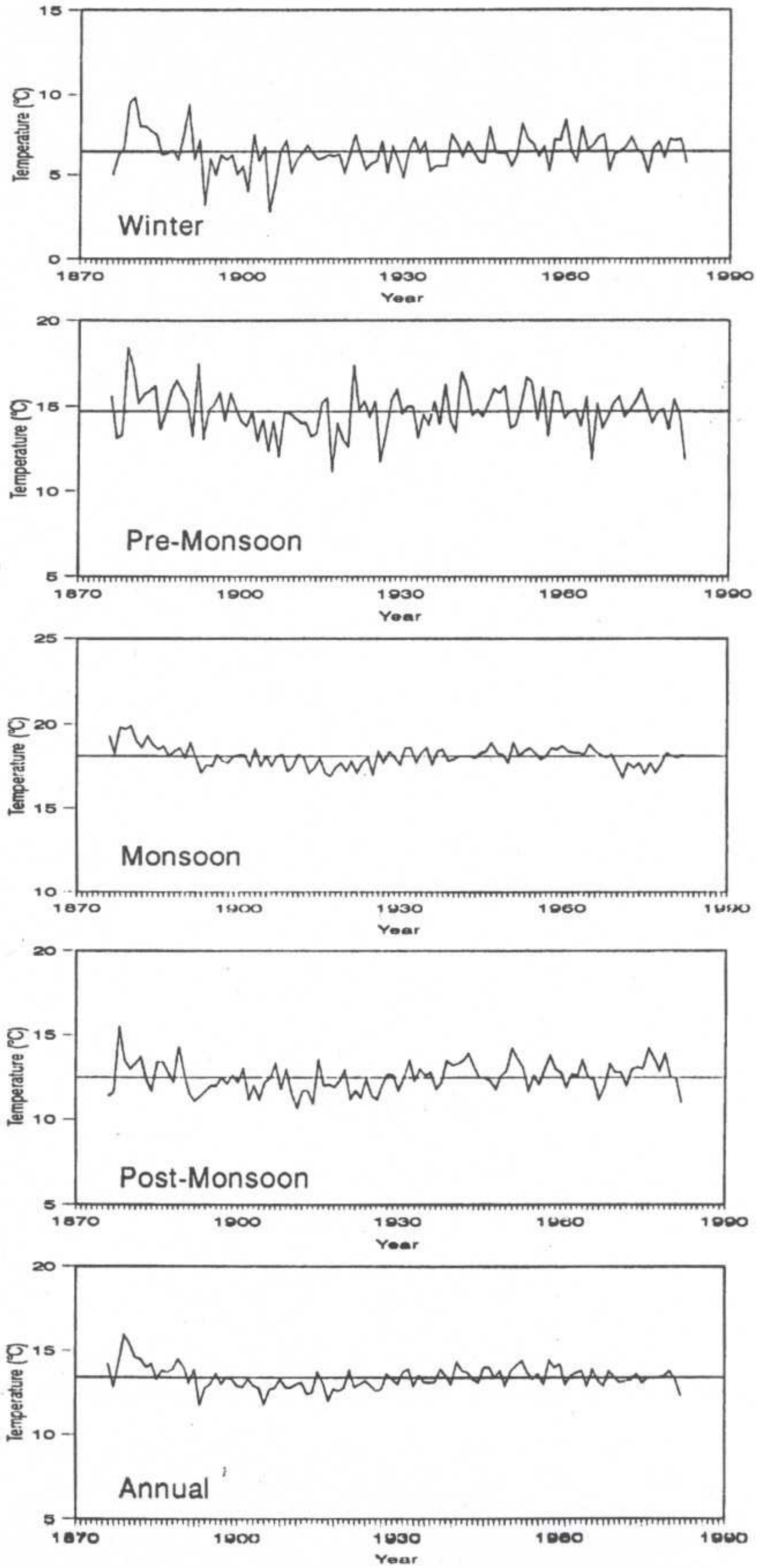

Figure 4. Instrumental record of seasonal and annual mean surface air temperature at Shimla

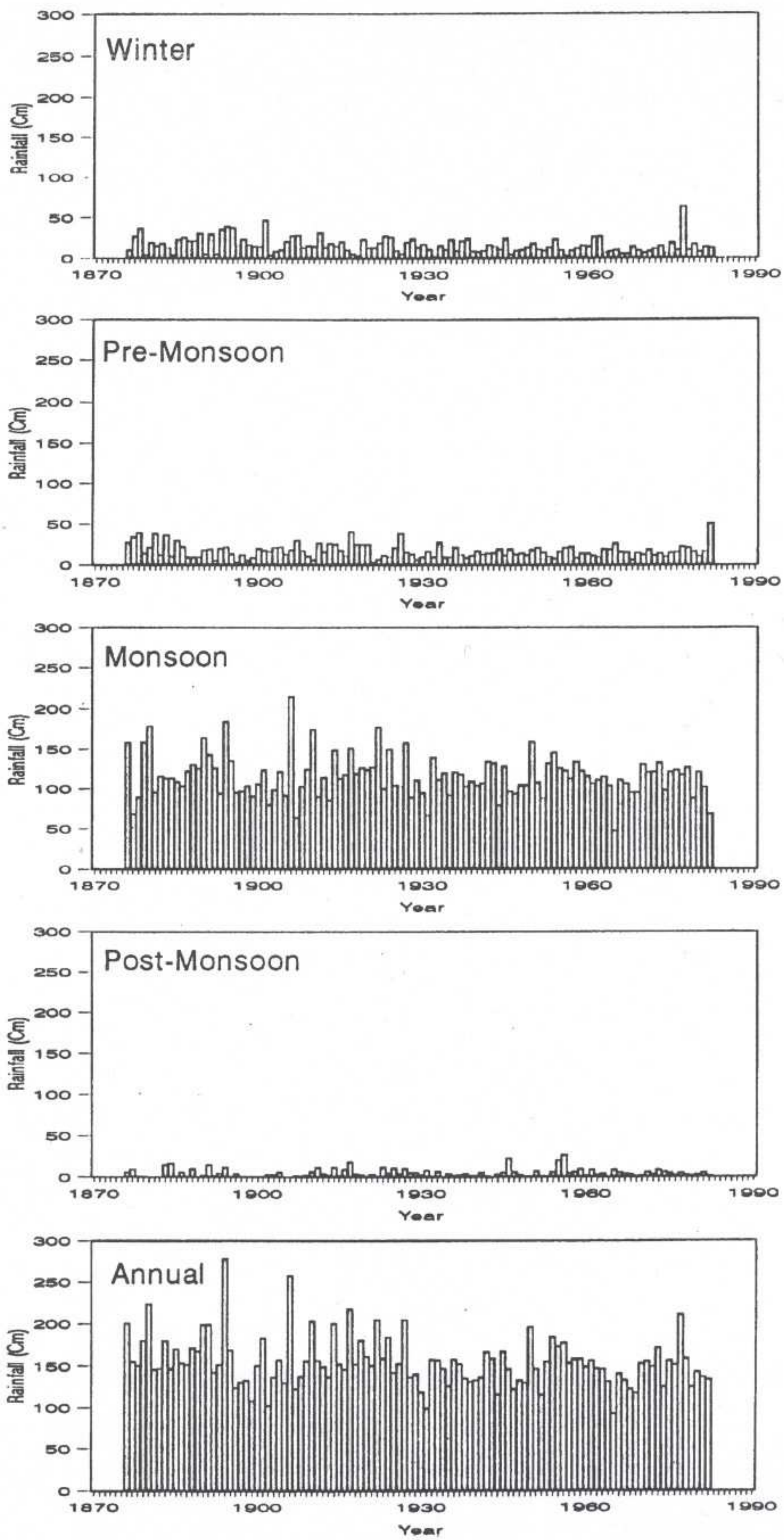

Figure 5. Instrumental record of seasonal and annual precipitation at Shimla

current growth to each of the climatic variables and the prior growth are obtained (see Fritts (1976) for details). Figure 6 shows the three response functions of the three site chronologies to Shimla climate. The effect of prior growth is highly significant for all the three chronologies. The vertical bars in the figure indicate 95 per cent confidence intervals. A conspicuous feature of the response curves is the significant negative response of the tree growth to summer temperatures (March to June), commonly seen in all the three chronologies. During the same months, the tree growth shows positive response to summer precipitation in all the three cases.

Correlation analysis

Correlation analysis has been carried out between the seasonal mean climatic parameters of Shimla and the tree-ring chronologies (Figure 7). The seasons considered are winter (DJF), pre-monsoon (MAM), monsoon (JJAS), and post-monsoon (ON). The previous monsoon and post-monsoon seasons have also been taken into consideration in order to examine the effects of seasonal climate prior to the growing period. The correlations indicate a significant negative influence of pre-monsoon (MAM) temperature on the tree growth at all the three sites (Figure 7). Precipitation during the same season is positively and significantly correlated with the tree growth. In the other seasons, no consistently significant relationships have been noted for all the sites.

As mentioned earlier, about 75 per cent of total precipitation occurs during the monsoon season. Therefore, during this period moisture stress conditions do not persist for prolonged periods, although the temperatures during the season are maintained relatively high. In the pre-monsoon season, however, the situation is different. The temperature increases gradually above the annual average value and May is the hottest month of the season, whereas the amount of precipitation during the pre-monsoon months is very small. As this season coincides with the early part of the active growth period of the trees, a loss of moisture due to extensive heating affects tree growth, while more precipitation is conductive to better growth.

Table III lists some extreme years of temperature and rainfall anomalies in the pre-monsoon season and the corresponding ring-width index anomalies. It should be noted that all the years except 1880 and 1929 listed in the table show below average growth (negative values of ring-width index anomalies) corresponding to seasons of higher temperature (positive anomalies) and low precipitation (negative anomalies). The years 1892 and 1921 show significant positive anomalies for temperature and negative anomalies for precipitation. The corresponding ring-width index values are also least for all the three chronologies (high negative anomalies). In the case of year 1880, although the season's temperature is significantly higher, the precipitation during the season is more than average, hence moderate values of tree-ring index anomalies are observed.

RECONSTRUCTION OF PRE-MONSOON TEMPERATURES AT SHIMLA SINCE AD 1775

The above response function as well as correlation analyses clearly show that the heating during the pre-monsoon season coupled with the availability of water from precipitation during the same period are critically important for tree growth. Using this relationship it is possible to derive calibrations to estimate the pre-monsoon temperature as well as precipitation from ring-width indices. However, reconstruction of summer precipitation is not attempted here because the calibration and verification tests have not given encouraging results. In the present study, for the development of the calibration equation, three chronologies, namely KANCD, KUFCD, and MNLCD, along with the series of preceding and following growth indices have been used as predictor variables in the multiple regression equation. The lagged chronologies (preceding and succeeding) have been considered to account for lag effects as well as for autocorrelation. The calibration equations have been obtained using orthogonalized stepwise multiple regression analysis with nine series of predictor variables (-1, 0, $+1$ series of each chronology) and mean temperature of March–April–May as a predictand for three different periods, namely 1876–1952, 1890–1952, and 1910–1982. The data for the period 1953–1982 have been set aside for independent verification of the multiple regression equations based on first two calibration periods, whereas the data of 1876–1909 are used for verification of the third calibration. Temperature data in Figure 4 indicated a noticeable change in variability in the early period of the series, particularly prior to 1890. Therefore we have chosen two calibration periods—one 1876–1952 and the other excluding the data prior to 1890, i.e. 1890–1952—to investigate any significant impact on calibration equation due to striking behaviour of temperature prior to 1890. These two

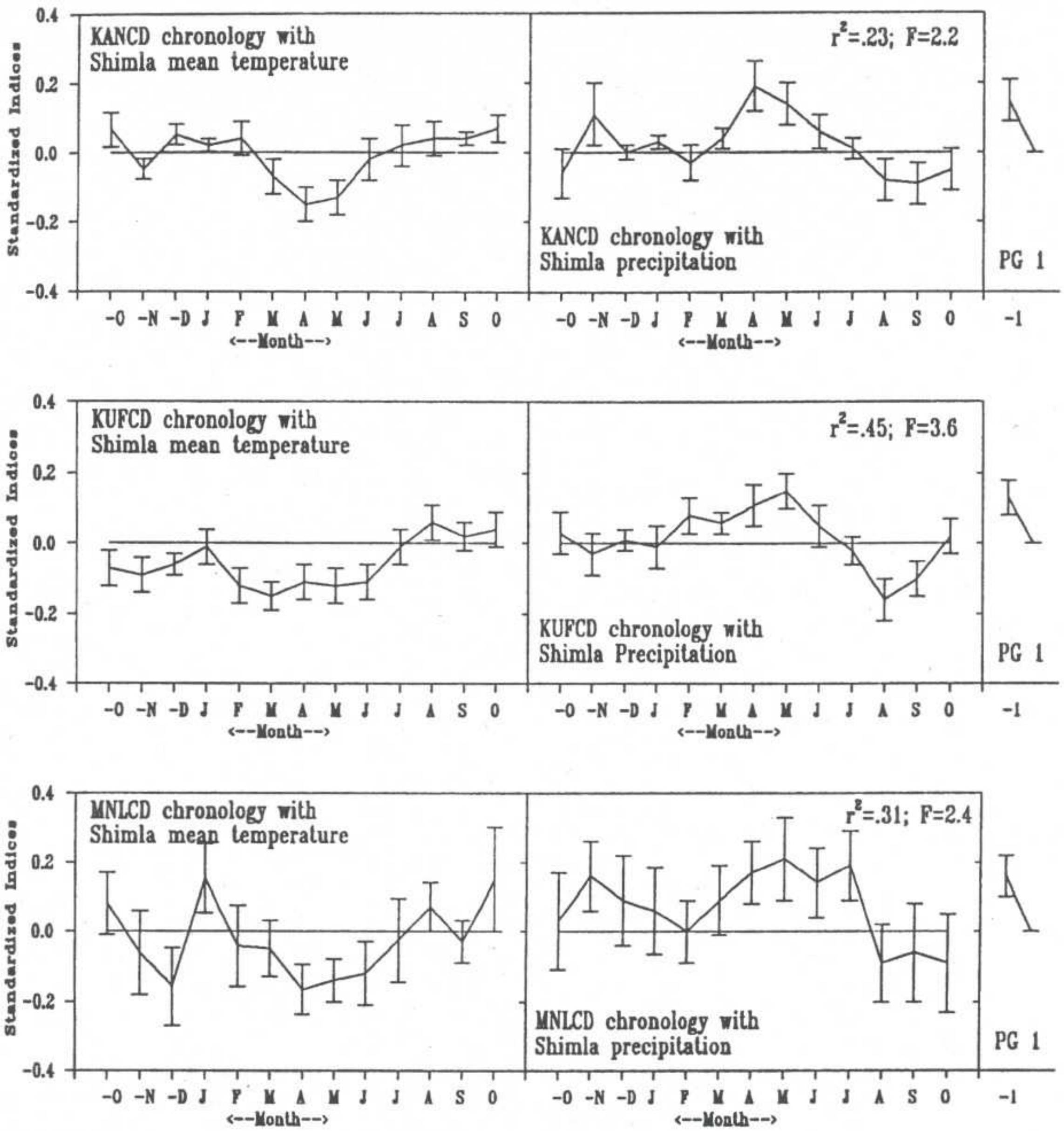

Figure 6. Response functions of tree-ring chronologies using mean monthly temperature and precipitation at Shimla. PG1 is the prior growth of lag 1. Vertical bars are 95 per cent confidence interval

calibration equations have been verified with the data of 1953–1982. The third calibration equation has been developed by reversing the calibration and verification period to check for any improvement in the calibration. The latest data from 1910 to 1982 have been used for calibration, and subsequent verification has been carried out for the period 1876–1909.

The nine predictor variables have been subjected to principal component analysis to deal with multicollinearity. Then only the components with an eigenvalue exceeding unity have been considered to be included in the multiple regression scheme. Other components are assumed to contain noise in the data. The results of calibration and verification analysis for three different periods are reported in Table IV. The performance of the calibration equations for 1876–1952 and 1890–1952 is more or less similar during calibration and subsequent verification periods. However, the performance of the third calibration (1910–1982) equation is poor compared with the performance of the first two calibration equations. The total variance explained by the reconstructed series during

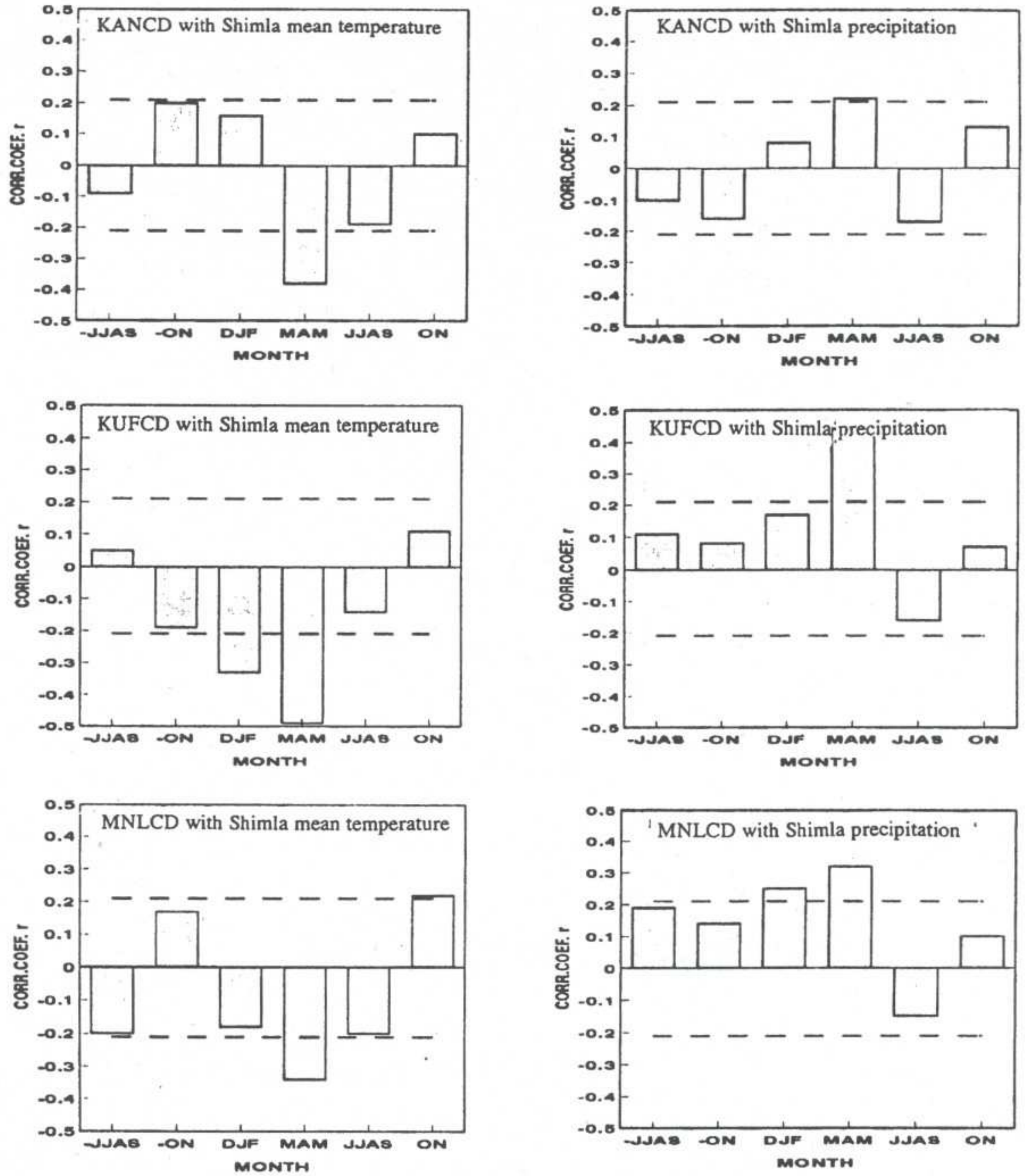

Figure 7. Correlation between tree-ring chronologies and seasonal climate (temperature and precipitation) at Shimla. Dashed lines indicate 5 per cent level of confidence

the second calibration period is maximum (32 per cent) compared with the variance explained by the other two calibrations. The verification tests based on this calibration equation show slightly higher values of various statistics than the values of verification tests of the first calibration (1876–1952). The sign tests for the first two calibrations reveal that more than 50 per cent of estimated and observed values lie on the same side of the mean; the '*t*' values of the product mean series are significant at the 10 and 5 per cent levels, respectively. Reduction of error (RE) statistics are significant at the 5 per cent level in both the cases. The RE statistic is a sensitive measure of the reliability of reconstruction. Positive (> 0) values of RE indicate some skill in the reconstruction (Fritts, 1976; Fritts *et al.*, 1990). Figure 8 (a–c) shows reconstruction of the pre-monsoon temperature during the three different calibration and verification periods, along with the actual values for comparison.

Table III. Extreme years of pre-monsoon temperature and precipitation and corresponding ring-width anomalies at the three sites

	Mean temperature anomaly (°C)	Rainfall anomaly (per cent)	Ring-width index anomaly (per cent)		
	(March–April–May)	(March + April + May)	KANCD	KUFCD	MNLCD
1879	3·7	−15	−15	−31	−2
1880	3·6	25	0	−5	−3
1888	1·8	−45	−3	−2	−10
1892	2·8	−67	−46	−38	−22
1921	2·7	−83	−65	−90	−30
1929	1·3	−60	6	−4	0
1941	2·3	−24	−27	−22	−28
1947	1·3	−25	−35	−3	−19
1953	2·0	−40	−18	−51	−1
1954	1·7	−53	−15	−26	−7
1974	1·3	−40	−25	−18	−16

Table IV. Calibration and verification anlaysis of reconstructed pre-monsoon (March–April–May) mean temperature at Shimla

Calibration	Period	1876–1952 (77 years)	1890–1952 (63 years)	1910–1982 (73 years)
	Total number of predictors	9	9	9
	Number of predictors entered into the regression	4	4	3
	F	4	3·5	2·3
	Multiple *r*	0·53**	0·57**	0·44**
	Variance explained (per cent)	28	32	17
Verification	Period	1953–1982 (30 years)	1953–1982 (30 years)	1876–1909 (34 years)
	r	0·51**	0·54**	0·32
	Sign test	18	21	13
	Product mean '*t*'	1·78	2·42*	0·986
	Reduction of error (RE)	0·15*	0·20*	0·073

* Significant at the 5 per cent level; **significant at 1 per cent level.

Considering the overall performance of the three calibration equations for the three different periods shown in Table IV, we have chosen the second calibration equation based on the period 1890–1952 to reconstruct the pre-monsoon mean temperature of Shimla back to AD 1775, limited by the chronologies based on an acceptable replication of samples (Wigley *et al.*, 1984). The reconstructed series of temperature is shown in Figure 9. The series from 1775 to 1988 shows a slightly increasing non-significant trend (dashed line). It does not show any noticeable difference in pre-monsoon temperature conditions between the pre-instrumental and the instrumental period. In Figure 9 the thick solid line is the cubic spline smooth curve with 50 per cent variance reduction frequency at 30 years. It depicts slightly cooling conditions during 1780–1840 and warm conditions during 1841–1890.

DISCUSSION AND CONCLUSIONS

Cedrus deodara is the main species of the Himalayan conifers and is found throughout the western Himalaya at altitudes between 1000 and 3000 m. Although the three sites considered are not very close to each other, they share the same macro-environment conditions and are nearly at the same altitude. Shimla, which is centrally located

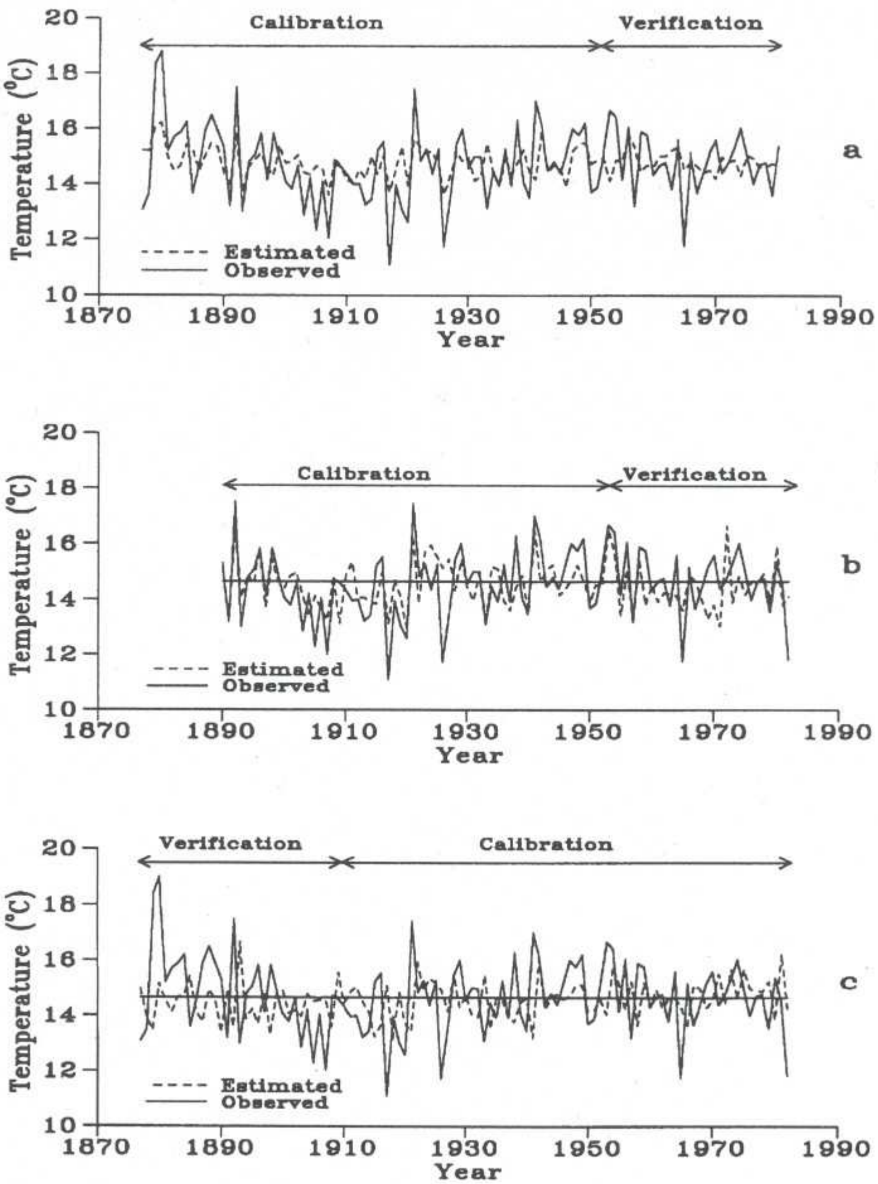

Figure 8. Actual and estimated pre-monsoon (March–April–May) mean temperature at Shimla during three different calibration and verification periods

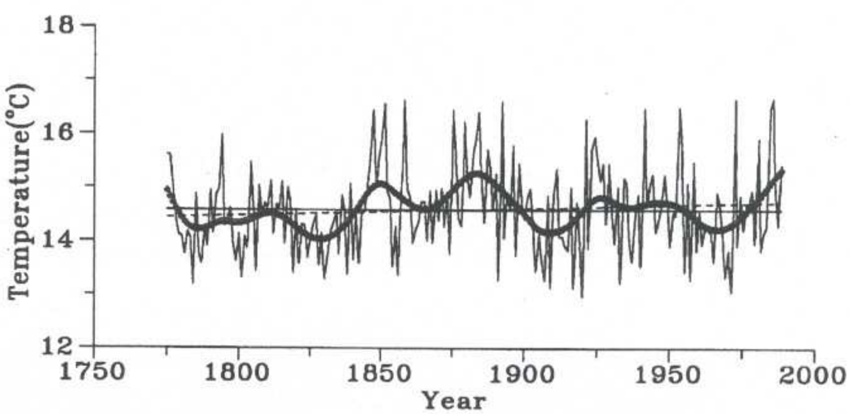

Figure 9. Reconstructed pre-monsoon (March–April–May) mean temperature at Shimla based on KANCD, KUFCD and MNLCD chronologies. Thick solid line indicates low-frequency variations

among the sites and having the same altitude as the sampling sites and longest continuous record of temperature and rainfall, is considered to be a representative meteorological station.

Chronologies developed from three sites show similar characteristics. Year-to-year variation measured by mean sensitivity is considerably high, indicating sensitiveness of the species to the environmental changes. The moderately high values of common variance suggest a comparatively strong common signal, mainly due to the regional climatic variations (Fritts, 1976), useful for dendroclimatic reconstruction.

Summer climate, particularly the pre-monsoon temperature and precipitation, significantly affects the tree-growth, as revealed by the response function and correlation analyses. Although good *deodar* forests are generally found in cool conditions with snowfall in winter and precipitation of 10–20 cm during the monsoon season (Champion and Seth, 1968; FRI, 1976), the temperature during the pre-monsoon season determines the availability of moisture in the early period of growth. Temperature over the region gradually increases above the annual average from March, resulting in the increased rate of evaporation of the available moisture obtained from the small amount of precipitation during the season. Therefore, although the higher temperature accelerates the photosynthesis, significant moisture deficiency occurs due to the high rate of evaporation and evapotranspiration. This may largely explain the negative relationship with temperature as observed in the analysis. More than average precipitation during the season is very useful in maintaining the minimum requirement of moisture and is found to be conducive for tree growth. Similar behaviour of the conifers from Kashmir valley has also been noted by Borgaonkar *et al.* (1994). They studied the relationship of ring-width chronologies of *Picea smithiana* and *Abies pindrow* with Srinagar climate. However, the summer months are slightly different at higher northern latitudes of the region. The valley starts becoming hot in May and is hottest in July, with relatively less precipitation. Hence, marginally excess precipitation during these months has been observed to be better for growth.

The reconstructed pre-monsoon temperature at Shimla shows slightly increasing non-significant trend whereas, during the period of instrumental record, the temperature shows a non-significant decreasing tendency. Low-frequency variations of the reconstructed series depict cooling conditions during 1780–1840 and warm conditions during 1841–1890. The reconstruction of pre-monsoon temperature attempted in the present study, although providing a preliminary glimpse of the Himalayan climate during the late eighteenth century, needs to be further substantiated before making any conclusions regarding the climate variations of the corresponding period. More chronologies of the species from more sites in western Himalaya need to be added to make the chronology network better in time and space. Establishment of such a wide network of long chronologies and the climatic data of additional meteorological stations in the analysis of dendroclimatic modelling will help in the improvement of statistical significance of the reconstructed climatic parameters.

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