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February–June temperature variability in western Himalaya, India, since AD 1455

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ABSTRACT

February–June (FJ) mean temperature records (AD 1455–2002) were developed using ring-width chronologies of *Cedrus deodara* from three sites in Tons valley, western Himalaya, India. The reconstructed series captured 30-year coolest (AD 1911–1940) and warmest (AD 1941–1970) periods in the 20th century in the last 548 years. The 20th century warming trend is not evident in our reconstructed temperature data, which is also consistent with the instrumental records. The reconstruction showed strong association with corresponding season's rainfall in the northern mountainous region, north-west India and February–May rainfall in north central India. The reconstructed temperature data also revealed inverse relationship with precipitation record developed from adjacent sites in Kumaon region, western Himalaya. Such a strong association with precipitation underscores the utility of data in understanding climate change behavior over this region of the western Himalaya, India.

1. Introduction

Weather records show that the global mean temperature has increased over the last century, and this has been linked to increased anthropogenic activities (IPCC, 2007). However, this warming is not found to be uniform throughout the globe. Understanding this heterogeneity in geographic response to climate change requires a close network of data across the Earth. The weather data from the orographically dissected Himalayan region is very sparse and limited to the past few decades, or to a maximum of a century in some cases. Recently, contrary to the earlier belief, it has been also observed that the global warming is not in phase with atmospheric greenhouse gas concentration, instead showing a flattening in warming trend (Solomon et al., 2010) or slight cooling in the 21st century (Easterling and Wehner, 2009). This hiatus in temperature trend has been assumed to be associated with La-Nina-Like decadal cooling (Kosaka and Xie, 2013). High-resolution proxy climate records from different geographic regions should help in understanding land-ocean-cryosphere linkages. The present study aims to provide long-term temperature data for the data scarce Himalayan region.

In the Himalayan region, several tree species, e.g. *Cedrus deodara* (Singh et al., 2004), *Pinus geradiana* (Singh and Yadav, 2007), and *Juniperus macropoda* (Yadav et al., 2006; Yadav, 2012) are known to grow very old, over 1000 years. However, to date only a few temperature reconstructions have been developed from arid to semi-arid regions of the western Himalaya (Yadav et al., 1997, 1999, 2004, 2011; Yadav and Singh, 2002). Robust regional temperature records developed for the Himalayan region should provide valuable data base for understanding past climate variability and linkages with other continental and oceanic features in longer perspective. Here, we present February–June (FJ) mean temperature record for Tons valley in the western Himalaya, India using ring-width chronologies of Himalayan cedar from three distantly located but ecologically homogeneous sites.

2. Data and methods

2.1. Tree ring data

For the present study, increment cores of *Cedrus deodara* were collected from three distantly located forest sites in Tons valley, Uttarakhand, India (Fig. 1). All the trees selected for sampling were growing on rocky substrate with thin soil cover. Only healthy trees without any visible marks of damage due to injury were selected and efforts were made to extract the maximum number of rings by targetting the pith. Sampled tree cores were air dried at room temperature and fixed using glue onto wooden mounts, keeping the cross section atop. The cross surfaces were cut with a sharp razor blade in the lab for further analyses. Tree core samples were

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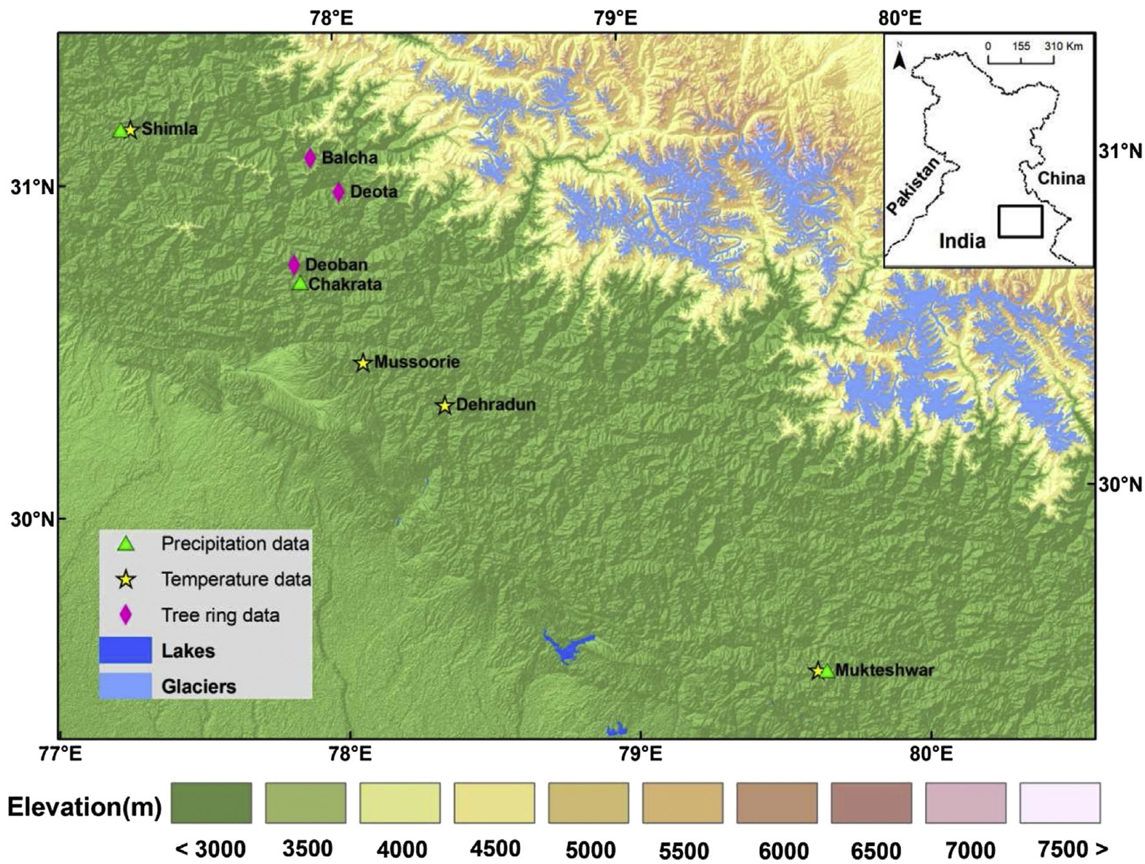

Fig. 1. Digital elevation map showing tree-ring sampling sites and climate (temperature and precipitation) stations.

polished using different grades of abrasives (400–800) until cellular details became clear under the binocular microscope. Skeleton plotting (Stokes and Smiley, 1968) and TSAP software (Rinn, 1991) were used to precisely date the growth ring sequences to the level of calendar year of their formation. Ring-widths of dated samples were measured with an accuracy of 0.01 mm using the linear encoder "LINTAB". The dating accuracy and possible measurement errors were crosschecked with computer program COFECHA (Holmes, 1983). Tree ring series showing dating error were crosschecked and remeasured and errors, if any, corrected. The ring-width measurement series were standardized using standard dendrochronological methods. We used a cubic smoothing spline with a frequency cutoff of 50% at 2/3 of the individual series length for detrending of ring-width measurement series (Cook and Peters, 1981). To minimize the effect of varying sample size in the mean chronology, we stabilized the variance in the chronologies (Osborn et al., 1997). The ring-width indices were derived after dividing the ring-width measurements by the fitted curve values in each year producing dimensionless indices with a mean of 1.0. Finally, mean ring-width indices were calculated by combining all series for each year using a biweight robust mean to discount the influence of outliers (Cook, 1985). The standard ring-width chronologies of *Cedrus deodara,* number of series used in chronology over time, expressed population signal (eps) and mean series inter correlation (rbar) are shown in Fig. 2. The eps and rbar (Wigley et al., 1984) in the mean ring-width chronology were taken into consideration to decide the length of chronology for further analysis. The ring-width chronologies were truncated on the year attaining eps value above 0.80 for further study. The site chronologies showed significant correlations indicating a strong common signal (Table 1).

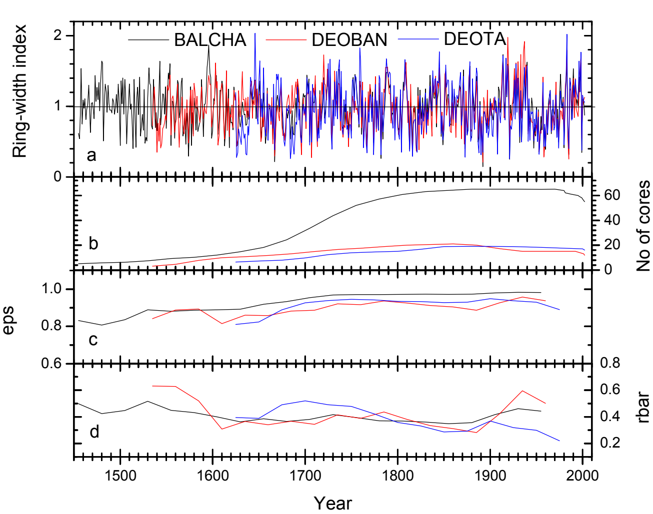

Fig. 2. Ring-width chronologies of Balcha, Deoban and Deota (a), number of cores included in the chronology over time (b), with eps (c) and running rbar (d) in lower panels respectively.

Table 1
Correlation between ring width chronologies (AD 1625–2002). All the correlations were significant at 0.0001 level.

Site	Deoban	Deota
Balcha	0.844	0.897
Deoban		0.745

2.2. Climate data

Weather records for the Himalayan region are limited and restricted to lower elevations relative to the tree ring sites, and also the stations with continuous records are few. In view of this, regional climate series prepared using climate data of available stations with homogenous data sets, though at variable distance from the tree ring sites, have been used in earlier dendroclimatic studies as well (Yadav et al., 2004, 2011; Singh et al., 2006; Yadav, 2011a, b). The temperature records in the orography dominated Himalayan region are more coherent as compared to precipitation. Therefore, we prepared regional temperature series using the long series available in the western Himalaya. The temperature series of Shimla, Mukteswar, Mussurie, and Dehradun were averaged to prepare the regional mean temperature series for use in present study (Fig. 1). The precipitation records in the western Himalaya due to strong orographic influence show spatial variability and are poorly correlated as compared to the temperature records. In the present study, we used precipitation data of Shimla, Mukteswar, and Chakrata to prepare the regional mean series. For the preparation of regional mean temperature data, the monthly values of all the stations were normalized relative to AD 1948–1978 before averaging. The regional mean temperature series showed that June is the warmest month and January the coolest. The maximum precipitation occurs in July and lowest in November (Fig. 3). The regional rainfall data of northwest, north central and northern mountainous India (http://www.tropmet.res.in; Sontakke et al., 2008) were used to understand the association with the reconstructed data.

2.3. Tree growth-climate response

To understand tree growth response to climate (temperature and precipitation), cross correlation analysis were performed using the computer programme DENDROCLIM 2002 (Biondi and Waikul, 2004). For this purpose, residual ring with chronologies containing high frequency variations were used. The growth of *Cedrus deodara* in the Himalayan region usually starts in April or early May and ends in late September or early October. Hence, we used previous year September to current year October data in tree growth climate relationship study.

All three site chronologies revealed significant negative relationships with previous year November–December and current year February–June mean temperature. The relationship with precipitation was positive over these months. However, a significant relationship was noticed only with previous year November and current year February–May except for the chronology from Deoban, where the relationship with February–March is not significant (Fig. 4). As ring width chronologies had significant strong relationship with February–June mean temperature, this season was selected for reconstruction. Recently, it has been demonstrated that the relationship between temperature and tree growth has changed in some geographic regions of the world (D'Arrigo et al., 2008). To understand stability in the tree growth climate relationship, we performed running correlations between the chronologies and February–June seasonalized mean temperature in a 31 year running window with slide of one year using the computer program DENDROCLIM2002 (Biondi and Waikul, 2004). Analysis revealed that all the site chronologies have consistent relationship with seasonalized February–June mean temperature over time (Fig. 5).

2.4. February–June (FJ) mean temperature reconstruction

We used standard version of the ring width chronologies in calibrations to capture low-frequency variations in the reconstruction. To reconstruct FJ mean temperature, linear regression analyses were performed using a nesting approach (Cook et al., 2003). The temperature data were split equally into two sub

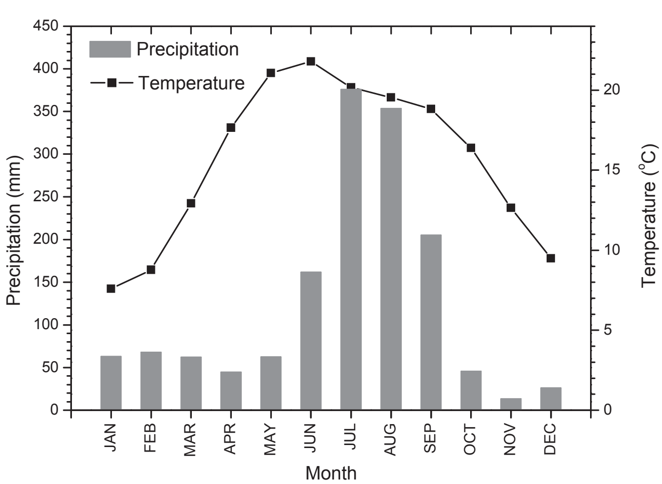

Fig. 3. Monthly precipitation and temperature over Garhwal Himalaya.

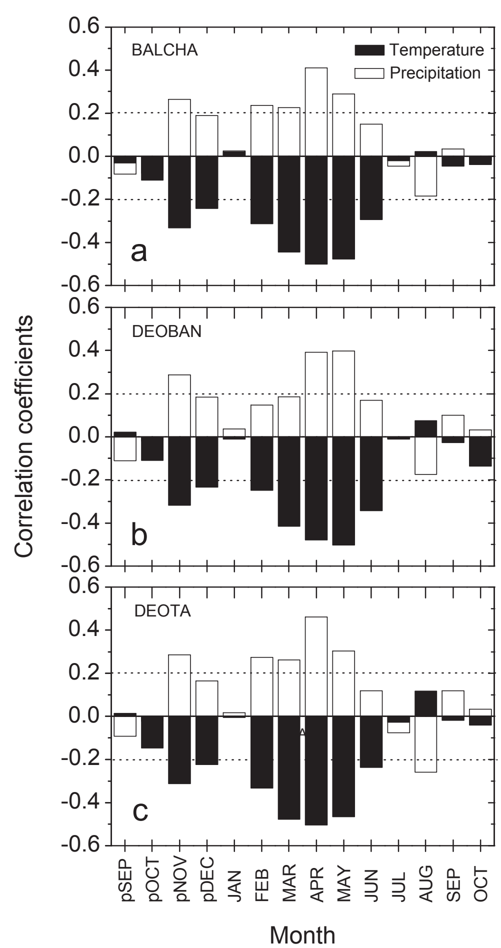

Fig. 4. Correlation functions of residual ring width chronology of Balcha (a), Deoban (b) and Deota (c) with mean monthly regional temperature and precipitation (bars above dotted lines are significant at 95% confidence level).

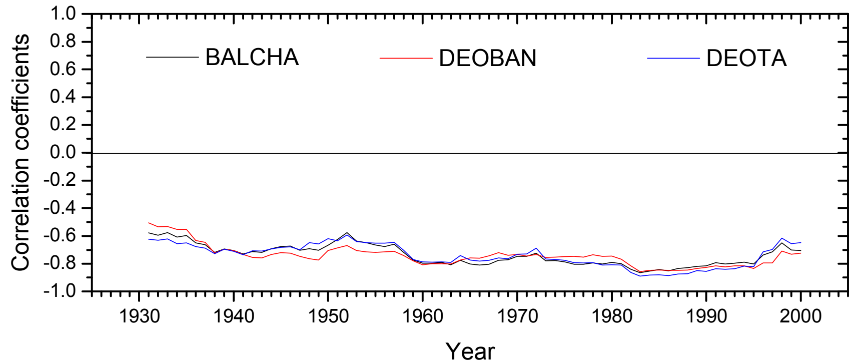

Fig. 5. Correlations between standard ring width chronologies and FJ mean temperature ($p < 0.0001$). The correlations were calculated in 31 year running widow with slide of one year.

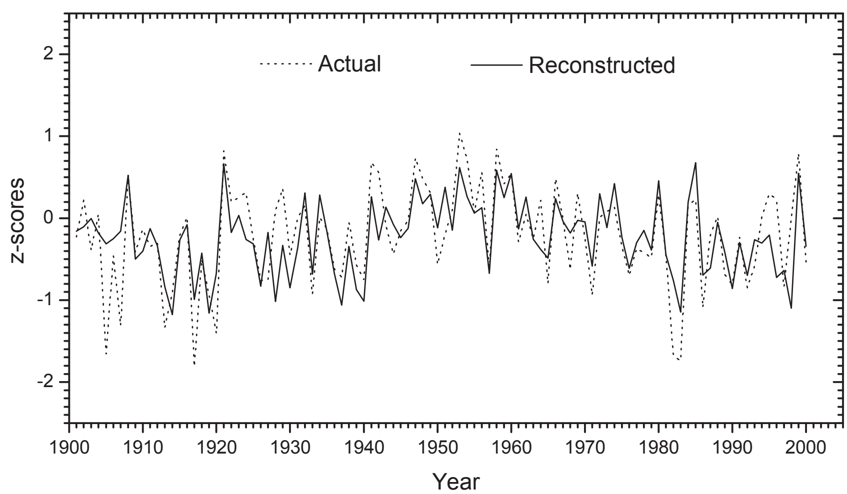

Fig. 6. Comparison between actual (dotted line) and reconstructed (solid line) FJ mean temperature (AD 1951–2000 calibration period was used for reconstruction).

periods, AD 1901–1950 and AD 1951–2000, for calibration and verification purposes. The calibration models captured high variance in the calibration (Table 2). The reliability of the calibration most replicated nest (i.e. AD 1625–2002) temperature reconstruction. The FJ mean temperature reconstruction showed a close resemblance with instrumental data (Fig. 6).

Table 2
FJ mean temperature reconstruction calibration-verification statistics obtained in linear regression analysis.

S. No.	Proxy nests	No. of series	Calibration		Verification					
			Period	ar^2 %	Period	r	T Value	Sign test	RE	CE
1	1625–2002	3	1901–1950	45	1951–2000	0.768***	3.71*	$40^+/10^{-*}$	0.600	0.586
			1951–2000	58	1901–1950	0.676***	4.25*	$37^+/13^{-*}$	0.471	0.471
2	1535–2002	2	1901–1950	43	1951–2000	0.778***	4.43*	$39^+/11^{-*}$	0.602	0.588
			1951–2000	60	1901–1950	0.665***	4.79*	$33^+/17^{-*}$	0.437	0.437
3	1455–2002	1	1901–1950	42	1951–2000	0.753***	4.08*	$39^+/11^{-*}$	0.578	0.563
			1951–2000	56	1901–1950	0.660***	4.54*	$34^+/16^{-*}$	0.451	0.451

Note: ar^2 (captured variance adjusted for degrees of freedom); r is spearman correlation coefficient; RE is the reduction of error; CE is coefficient of efficiency (details given in Fritts (1976), Cook et al. (1999). $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.0001$.

models was further verified using different statistical tests, including T value, sign test, reduction of error (RE) and coefficient of efficiency (CE). The calibration models yielded significant verification statistics in their corresponding verification periods, authenticating the reliability of the reconstruction models (Table 2). As the 1951–2000 calibration model captured higher variance in the instrumental data, this period was used for developing the FJ mean temperature reconstruction. The reconstructed series of each nest were averaged to prepare the mean regional reconstruction. However, before averaging, each series was scaled relative to the

3. Results and Discussion

3.1. Analysis of FJ mean temperature reconstruction

The reconstructed FJ mean temperature series revealed annual to decadal scale variations (Fig. 7). A 30-year running mean calculated over the reconstructed series (AD 1455–2002) showed that both the coolest (AD 1911–1940) and the warmest (AD 1941–1970) periods occurred in the 20th century in the last 548 years (Table 3). The other cool periods were AD 1473–1502, and

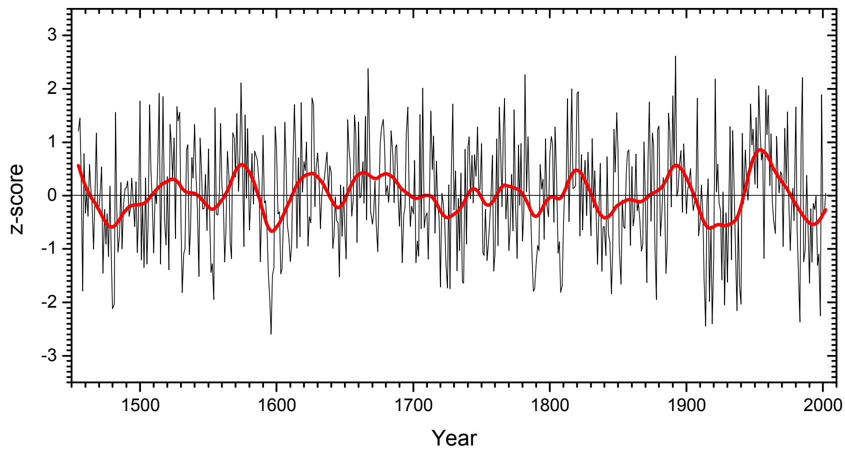

Fig. 7. FJ mean temperature reconstruction (AD 1455–2002), bold line is 30 year low pass filter. Data were normalized relative to the whole length of reconstructed series (AD 1455–2002).

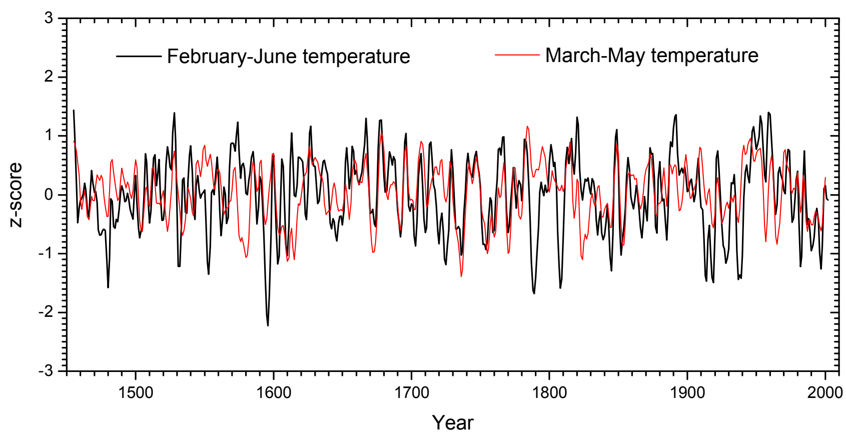

Fig. 8. Comparison between present FJ mean temperature reconstruction and March–May temperature reconstruction (Yadav et al., 2004) (reconstructions were filtered with spline length of 5 years).

1588–1617, with warm periods 1652–1681, 1879–1908, and 1558–1587. The twentieth century warming is not reflected in the present reconstruction, similar to the earlier March–May temperature reconstruction from the western Himalayan region (Yadav et al., 2004), further suggesting that the mean temperature has not warmed in the western Himalayan region during the late twentieth century. However, after the 1990s, temperature is recorded to be increasing (Fig. 7). Earlier spring season temperature reconstruction (Yadav et al., 2004) from the northwestern part of the Himalaya closely matches the present reconstruction ($r = 0.48$, AD 1455–2000). The normalized reconstructions after filtering with 5 year spline showed close resemblances (Fig. 8). However, our present reconstruction does not match the February–June temperature reconstruction developed from Nepal Himalaya (Cook et al., 2003). To understand the causes of dissimilarity between temperature data of corresponding seasons, we correlated the Nepal reconstruction with observed FJ regional mean temperature series used in the present study ($r = 0.35$, 1901–1991) and reconstructed temperature data reported here ($r = 0.22$, 1901–1991). In contrast, we noted a stronger relationship between the recorded FJ mean temperature of Kathmandu, Nepal, and the regional FJ mean temperature of the western Himalaya used in this study ($r = 0.71$, 1951–2000) and the reconstructed FJ mean temperature data of Tons valley, western Himalaya ($r = 0.47$, 1951–2000). Such dissimilarity between two data sets suggests that robust climate records from Nepal Himalaya are required to understand regional variability in temperature.

Table 3
A 30-year warm and cool periods of FJ mean temperature reconstruction.

Warm		Cool	
Period	z-scores	Period	z-scores
30-year mean			
1941–1970	0.635	1911–1940	−0.655
1652–1681	0.435	1473–1502	−0.393
1879–1908	0.394	1588–1617	−0.373
1558–1587	0.358		

Cooling over a region is governed by several weather parameters, and the precipitation regime is one of the most important factors. To check the relationship between two variables, we correlated reconstructed FJ mean temperature with rainfall data of the northern mountainous region, northwest India, and north central India. The results showed strong negative correlations with rainfall of February–June in the northern mountainous region ($r = -0.54$, AD 1845–2002), north west India ($r = -0.35$, AD 1844–2002) and February–May rainfall in north central India ($r = -0.47$, AD 1842–2002). Such a strong linkage in temperature and rainfall suggests that temperature variations in the Himalayan

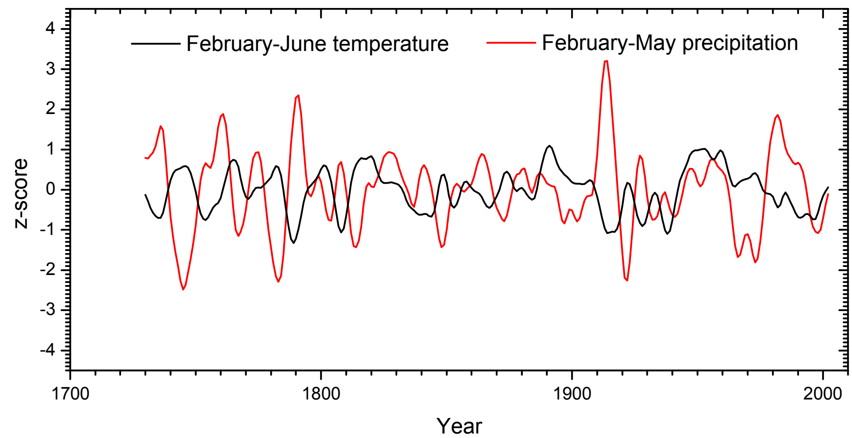

Fig. 9. Comparison between present FJ reconstructed mean temperature and February–May precipitation (Yadav et al., 2014) after smoothing with spline length of 10 years.

region are strongly influenced by the rainfall variability over the region and other parts of northern India. Further, to understand the linkage between temperature over the Himalayan region and precipitation in longer scale beyond instrumental records, we correlated present FJ reconstructed mean temperature data with the February–May precipitation reconstruction from Kumaon, the western Himalaya (Yadav et al., 2014). This showed a strong negative relationship ($r = -0.57$, AD 1730–2002). The 10 year filtered data also showed an inverse relationship (Fig. 9). The correlation of FJ reconstructed mean temperature record with the March–May precipitation reconstruction developed from Garhwal Himalaya (Singh et al., 2006) also showed significant correlations ($r = -0.41$, AD 1560–1997). Such a strong relationship in longer perspective revealed a close association between temperature and precipitation variations in the Himalayan region. The relationship also indicates that warm periods are associated with drought phases and cool periods with wet phases in the Himalayan region. This also suggests that increase in boreal spring precipitation could be the possible reason for the 20th century temperature decrease in the Himalayan region.

3.2. Spectral analysis of reconstructed FJ mean temperature data

Spectral analysis of reconstructed FJ mean temperature data (AD 1455–2002) using the Multi-Taper Method (Mann and Lees, 1996) indicated spectral peaks at 2, 3, 5, 6, 8, 17, 53, 56, 60, 64, 68, 72 and 78 years (significant at 95% confidence limit, Fig. 10). The periodicities of 2–8 years were earlier observed in reconstructed precipitation records from other parts of the Himalayan region (Singh et al., 2006, 2009; Yadav et al., 2014) and the river discharge reconstruction from Kinnaur Himalaya (Singh and Yadav, 2013). Such high frequency periodicities are similar to ENSO of the Pacific Ocean. To ascertain this pervasive relationship, we correlated FJ mean temperature reconstruction with Sea Surface Temperature (SST) indices [Nino4 SSTs (5°N–5°S, 160°E–150°W, Kaplan et al., 1998)]. A positive relationship was noticed in corresponding months ($r = 0.24$, $p < 0.004$; 1856–2002). The 17 year periodicity is similar to the frequency domain of the Pacific Decadal Oscillation. However, low frequency periodicities of 53, 56, 60, 64 and 68 years fall in the range of the 50–70 year climate variability mode of North Pacific (Minobe,

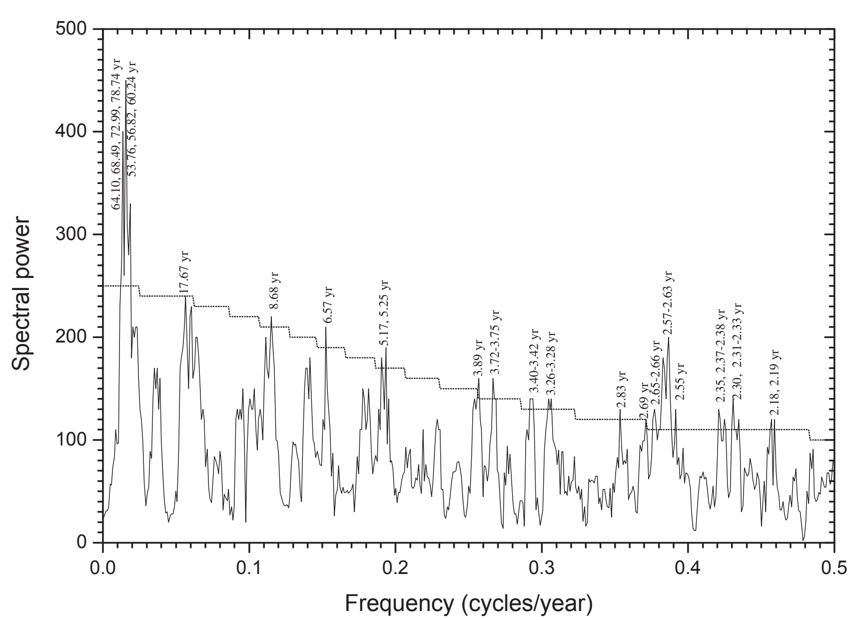

Fig. 10. Power spectrum of FJ mean temperature (AD 1455–2002), dotted line is 95% significance level.

1997). The other low frequency 72 and 78 year cycles could be associated with solar variability.

4. Conclusions

Tree core samples of *Cedrus deodara* collected from three distantly located sites in Tons valley, western Himalaya, were used to develop ring-width chronologies. Cross correlation analyses among site chronologies showed robust relationships, indicating the presence of a common climate signal. Tree growth-climate analyses revealed a significant inverse relationship with temperature of previous year November–December and current year February–June. However, the precipitation showed positive correlations over these months. Strong inverse relationships between FJ mean temperature and all the site chronologies were used to develop a temperature record for the past 548 years. The FJ mean temperature reconstruction showed the warmest and coolest periods in the 20th century in the context of the past 548 years. Strong linkage with precipitation records of northwest, north central and northern mountainous regions of India underscores the utility of present temperature reconstruction in understanding the regional climate behavior over the Himalayan region.

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