

# Spring temperatures in the far-western Nepal Himalaya since AD 1640 reconstructed from *Picea smithiana* tree-ring widths

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**Abstract** We developed a new, 422-year long tree-ring width chronology (spanning AD 1591–2012) from *Picea smithiana* (Wall.) Boiss in Khaptad National Park, which is located in the far-western Nepalese Himalaya. Seasonal correlation analysis revealed significant indirect relationship with spring temperature and lead to the reconstruction of March–May average temperature for the past 373 years (AD 1640–2012). The reconstruction was found significant based on validation statistics commonly used in tree-ring based climate reconstruction. Furthermore, it was validated through spatial correlation with gridded temperature data. This temperature reconstruction identified several periods of warming and cooling. The reconstruction did not show the significant pattern of cooling during the Little Ice Age but there were few cold episodes recorded. The spring

temperature revealed relationship with different Sea Surface Temperature index over the equatorial Pacific Ocean, which showed linkages with climatic variability in a global scale.

**Keywords** Khaptad National Park · Nepal · *Picea smithiana* · Spring temperature · Tree-rings

## 1 Introduction

According to instrumental temperature records, the Himalaya of Nepal have warmed more rapidly than global mean temperatures, with the greatest rate of warming occurring at high elevations (Shrestha et al. 1999, 2012; IPCC 2007; Shrestha and Aryal 2011). However, meteorological stations in Nepal are few, particularly in mountain regions, and are sparsely distributed through the country (IPCC 2007; Shrestha et al. 1999, 2012; Cook et al. 2010), making it difficult to estimate the rate and geographic extent of recent warming. Among the widely distributed weather stations throughout Nepal, precipitation records are available only after the year 1960 and temperature after 1970 (Shrestha et al. 1999, 2000). Thus to further extend the existing climate records of the region, tree-ring based climate reconstruction is needed. Tree-ring records have been used to extend climate records in the Indian Himalayan region (Bhattacharyya et al. 1988; Borgaonkar et al. 1994, 1996; Yadav et al. 1997, 1999; Singh and Yadav 2005; Singh et al. 2009; Yadav 2010), as well as the Tibetan Plateau (Yu et al. 2006; Huang and Zhang 2007; Gou et al. 2007; Liang et al. 2008; Li et al. 2012), but Nepal remains a ‘frontier’ region for dendroclimatological studies.

Rudolf Zuber collected the first tree-ring specimens from Nepal in 1979 and 1980, and their subsequent analysis by

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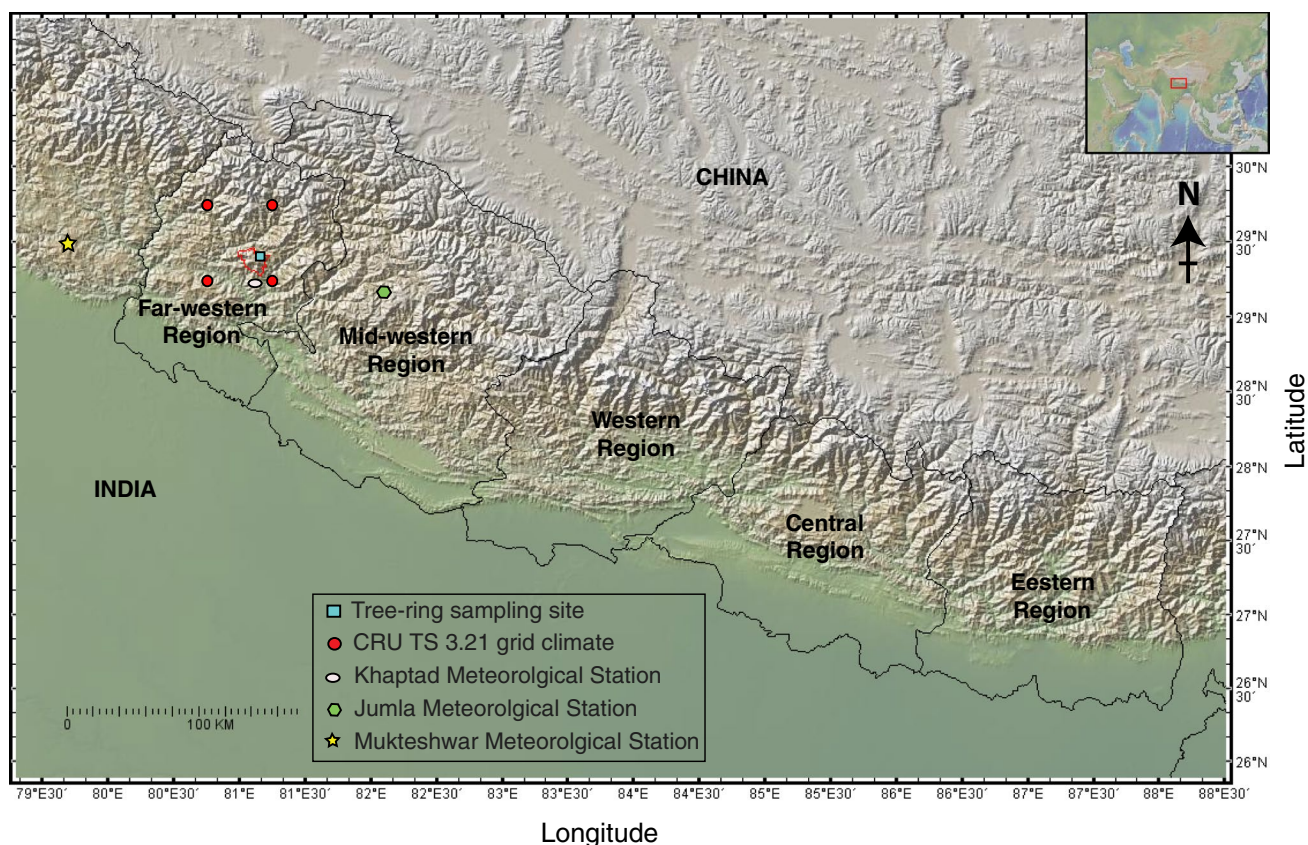
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**Fig. 1** Map showing the location of the Lokhada *P. smithiana* tree-ring sample collection, nearby meteorological stations, and grid points from the Climate Research Unit's TS 3.21 compilation. The red online marks the boundaries of Khaptad National Park

Bhattacharyya et al. (1992) indicated that *Cedrus deodara*, *Pinus roxburghii*, *P. wallichiana*, *Abies spectabilis* and *Abies pindrow* exhibited clear annual bands and, in some cases, common growth patterns. To date, the most extensive survey of climate information preserved within Nepalese trees was conducted by Cook et al. (2003), who established a 46-site network of tree-ring width records spanning most of the country and used those data to reconstruct average early-season (February–June) temperatures back to the mid-sixteenth century. Ring-width, density, and stable isotope records from *Abies spectabilis* have been used to hind-cast temperature and moisture conditions in the far-north western corner of Nepal (Sano et al. 2005, 2011). But most other dendroclimatic studies have focused on identifying the climate signals recorded by tree-ring records (Bhujju et al. 2010; Chhetri and Thapa 2010; Gaire et al. 2011; Dawadi et al. 2013; Liang et al. 2014), rather than producing palaeoclimatic reconstructions.

Dendroclimatic studies of *Picea smithiana* (Wall.) Boiss (West Himalayan Spruce) growing in Pakistan and northern India has established the sensitivity of the species to early-spring temperatures (Borgaonkar et al. 1994; Yadav et al. 1997; Ahmed and Naqvi 2005; Khan et al. 2008; Ahmed

et al. 2009, 2011; Zafar et al. 2010; Borgaonkar et al. 2011; 2012; Ram 2012). However, this species has not previously been the target of palaeoclimatic studies within far western Nepal. In this study, we report the development of a new tree-ring width record from *P. smithiana* in the far-western Nepalese Himalaya. We compare this new record against climate data and produce a new reconstruction of spring temperatures back to the mid-seventeenth century.

## 2 Materials and methods

### 2.1 Sample collection, laboratory methods, and analytical methods

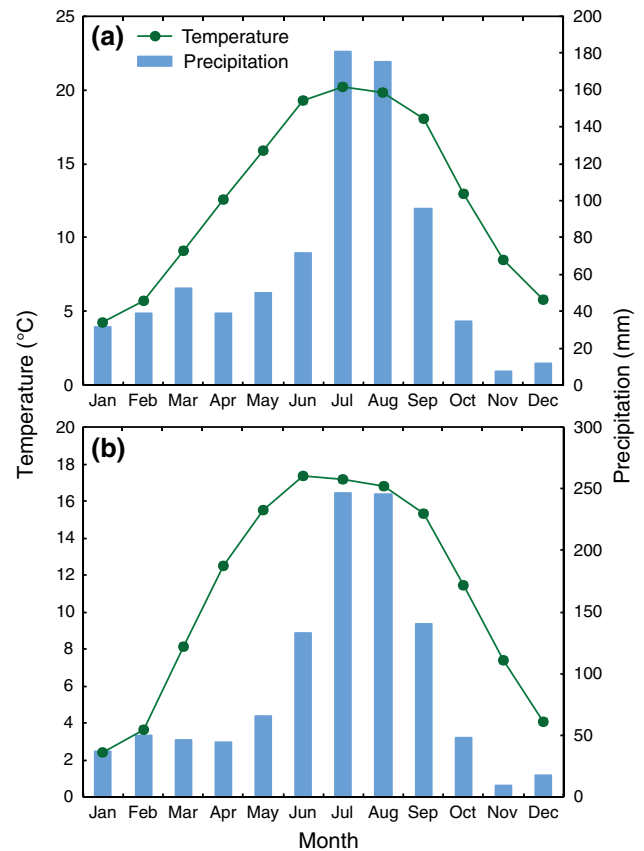
During September 2012, we collected 161 tree-ring samples from 80 *P. smithiana* trees growing within the Lokhada region on the northern half of Khaptad National Park (Fig. 1). Established in 1984, Khaptad National Park has an elevation range of 1,400–3,300 m asl (Bhujju et al. 2007). The sampling site at Lokhada (29°42'N latitude and 81°15'E longitude, 2,700 m asl) had a slope of approximately 30° and was located in the temperate forest zone.

Besides *P. smithiana*, the dominant tree species at the site included *Abies pindrow*, *Juglans regia* and *Rhododendron* spp.

After samples were transferred to the Tree-ring Laboratory of Nepal Academy of Science and Technology, Nepal, they were air dried, mounted, and sanded until ring boundaries were clearly visible under a stereo-zoom microscope. Samples were cross-dated using the skeleton plot technique (Stokes and Smiley 1968) and tree-ring widths were measured using a linear encoder. The program COFECHA (Holmes 1983) was used to confirm dating and identify potential measurement errors. Ring-width measurements for individual trees were standardized using negative exponential curves, and pre-whitened by fitting an autoregressive (AR) model to each series (Cook 1985; Cook and Kairiukstis 1990). The detrended, pre-whitened series were combined to create a mean-value function ('chronology') describing overall tree growth at the site using the program ARSTAN (Cook and Holmes 1986). To assess the quality of the common signal expressed across the entire stand of *P. smithiana*, we computed the between-tree correlation, the expressed population signal, and running-window versions of both statistics (Wigley et al. 1984).

## 2.2 Climate data

Climate data are comparatively sparse in far-western Nepal, and there are no meteorological stations located within the boundaries of Khaptad National Park. The station nearest to the tree-ring sampling site is 25 km south is Khaptad having limited meteorological records. In general, the climate of this region is temperate, with cool, wet summers and cold, dry winters (Hindu Kush Himalayan (HKH) Conservation Portal, <http://hkhconservationportal.icimod.org>). Another meteorological record is located in Jumla, roughly 92 km east of the study site and also has short records. But the nearest long meteorological record is available at Mukteshwar, roughly 140 km west of the study site (Fig. 1). This record spans more than 117 years (AD 1897–2013), and, because of its length, has been used regularly as a reference for other dendroclimatic studies in the Nepal Himalayas (Sano et al. 2005, 2010, 2011; Thapa et al. 2013). Missing data within this record (4.5 % in temperature and 5.2 % in precipitation) was estimated using the 'mtsdi' package (Junger and Ponce de 2012) in the R programming environment (R Development Core Team 2014). The general climatic scenario depicted by climate records from meteorological stations, Jumla and Mukteshwar appeared had very similar pattern of monthly and seasonal distribution of temperature and precipitation (Fig. 2). The general overview of the regional climate of the area is derived using an average of four grid points of global CRU TS 3.21 gridded climate datasets (Harris et al. 2014) for the period of



**Fig. 2** Climographs for **a** Jumla, Nepal, and **b** Mukteshwar, India. Data were obtained from Global Historical Climate Network (GHCN) and Department of Hydrology and Meteorology of Nepal. The time span and other details of the climate data are given in Table 1

AD 1901–2012. The details of the entire climate data studied here are given in Table 1. Another significant climate data set is the Gridded Berkeley Earth Surface Temperature Anomaly (<http://berkeleyearth.org/data/>) records based on  $1^{\circ} \times 1^{\circ}$  latitude and longitude grid point is available for AD 1750–2013. Comparison of the temperature records of the Mukteshwar, CRU TS 3.21 and Berkeley Earth Surface Temperature Anomaly for the common time period of AD 1901–2012 showed similar trends (supplementary material, Figure 1). But the variability of Berkeley Earth Surface Temperature Anomaly was lower in comparison to both Mukteshwar and CRU TS 3.21 temperature records.

## 2.3 Assessing tree–climate relations

We assessed the relations between the growth of *P. smithiana* and local climate by comparing the residual ring-width chronology from Lokhada against the Mukteshwar climate record using the seasonal correlation procedure (SEASCORR) developed by Meko et al. (2011). This

**Table 1** Details of the climate (temperature and precipitation) records

	Meteorological and grid station			
	Khaptad	Jumla	Mukteshwar	CRU-TS 3.21
Data source	DHM	DHM	GHCN	CRU
Latitude (°N)	29°23'	29°17'	29°47'	29°25'; 29°75'; 29°25' and 29°75'
Longitude (°E)	81°12'	82°10'	79°65'	80°75'; 80°75'; 81°25' and 81°25'
Elevation (m asl)	3430	2300	2311	–
Time span—AT	–	AD 1969–2012	AD 1897–2013	AD 1901–2012
Time span—P	AD 1976–2009	AD 1957–2012	AD 1897–2013	AD 1901–2012
MTCO (°C)	–	4.3	6.2	2.4
MTWA (°C)	–	20.2	18.7	17.4
MAT (°C)	–	12.7	13.4	11.0
MAP (mm)	Not analysed	791	1268	1082
MP (mm)	Not analysed	524	928.4	765.4

*DHM* Department of Hydrology and Meteorology, Nepal (<http://www.dhm.gov.np/>), *GHCN* Global Historical Climate Network (<http://www.ncdc.noaa.gov/ghcnm/v3.php>), *CRU* Climate Research Unit (<http://www.cru.uea.ac.uk/cru/data/hrg/>), *AT* average temperature, *P* precipitation, *MTCO* minimum temperature of coldest month, *MTWA* maximum temperature of warmest month, *MAT* mean annual temperature, *MAP* mean annual precipitation and *MP* monsoon precipitation

approach calculates Pearson correlations between tree-ring width and monthly mean temperature and total precipitation over a 14-month window (beginning in the September prior to growth and ending in October of the growth year). Because previous research has shown that the radial growth of *P. smithiana* is sensitive to early-spring temperatures, we chose temperature as the primary variable and precipitation as the secondary variable. To identify potential relations between tree growth and climate over long intervals, the monthly analysis was repeated using climate variables aggregated over 3-, 6-, and 12-months. Significance levels calculated by SEASCORR are produced by a Monte Carlo procedure that creates synthetic copies of the original tree-ring record using exact simulation (Percival and Constantine 2006). The temporal stability of the correlation results were evaluated by splitting the Mukteshwar climate record into two halves and repeating the analysis. We also compared the Lohkaha ring-width chronology against gridded climate variables to evaluate the spatial extent of the relations between *P. smithiana* growth and climate using KNMI Climate Explorer (Trouet and Oldenborgh 2013).

## 2.4 Palaeoclimate reconstruction

The results of our analysis comparing *P. smithiana* ring-width chronology against local and regional climate provided a basis to reconstruct past climates in the far-western Nepalese Himalaya over the last few centuries. We used a simple linear regression model to relate tree-ring width against seasonal climate, and tested the time-stability of that model by dividing the calibration period into two equal sub-periods (Snee 1997; Meko and Graybill 1995;

Touchan et al. 2011). We also tested the model through the predicted error sum-of-squares (PRESS) method (Weisberg 1985; Fritts et al. 1990; Meko 1997; Touchan et al. 2011), which is similar to the ‘leave-one-out’ cross-validation approach (Michaelsen 1987). We evaluated the model’s ability to reproduce observed changes in climate using statistical measures, including the correlation coefficient ( $r$ ), the reduction of error (RE) and the coefficient of efficiency (CE). Once the model was judged to be effective and stable, we applied it to estimate past changes in climate based on tree-ring width, and truncated the reconstruction at the point where the tree-ring chronology becomes unduly influenced by non-climatic noise (Wigley et al. 1984). We also verified the significant climatic variable to be reconstructed against gridded climate variables for the same season to evaluate its regional strength through spatial correlation. The spatial correlation was carried out in KNMI Climate Explorer (Trouet and Oldenborgh 2013).

## 3 Results and discussion

### 3.1 The Lohkaha *P. smithiana* ring-width chronology

The final set of dated ring-width measurements from Lohkaha included 101 cores collected from 52 trees. Overall, the quality of the common signal exhibited by trees at this site is quite good (Table 2). The mean between-tree correlation for the residual chronology is 0.261. Average radial growth was roughly 1.2 mm year, and there were relatively few (0.1 %) locally absent rings (Schulman 1941; St. George et al. 2013). These measurements



were detrended and combined to produce a 422-year long ring-width record for Lokhada, Nepal spanning AD 1591–2012 (Fig. 3). The expressed population signal (EPS) exceeded the arbitrary cut-off of 0.85 often used in

**Table 2** Chronology statistics of *P. smithiana* tree-ring chronology

Statistics	Standard chronology	Residual chronology
Percentage of absent ring	0.114	
Average annual radial growth	1.24	
MSL	217	
10 percentile age	113	
90 percentile age	314	
Time span	AD 1591–2012	
Cores/trees	101/52	101/52
MS	0.169	0.196
SD	0.203	0.171
AC1	0.506	−0.043
Common time period	AD 1925–2012	
$r_{ALL}$	0.132	0.266
$r_{WT}$	0.721	0.717
$r_{BT}$	0.127	0.261
SNR	12.304	29.283
EPS	0.925	0.967
EPS > 0.85	AD 1640/6	
varPC1	16.6	28.3

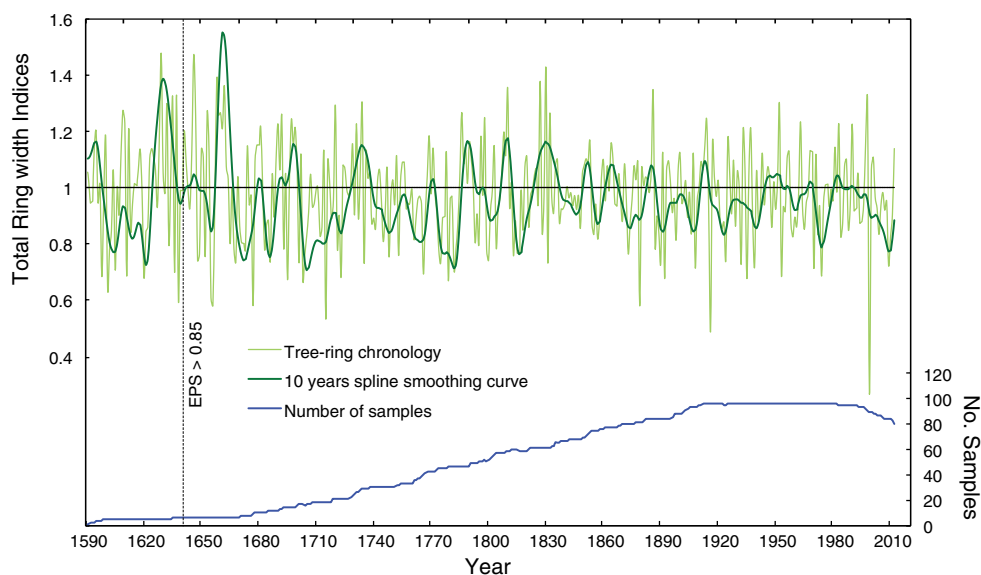
*MSL* mean segment length, *MS* mean sensitivity, *SD* standard deviation, *AC1* 1st order auto correlation,  $r_{ALL}$  all series Rbar,  $r_{BT}$  within trees Rbar,  $r_{WT}$  within trees Rbar, *SNR* signal-to-noise ratio, *EPS* expressed population signal, EPS > 0.85 indicates the year and number of trees with expressed single strength above 0.85; *varPC1* variance explained by the first principal component

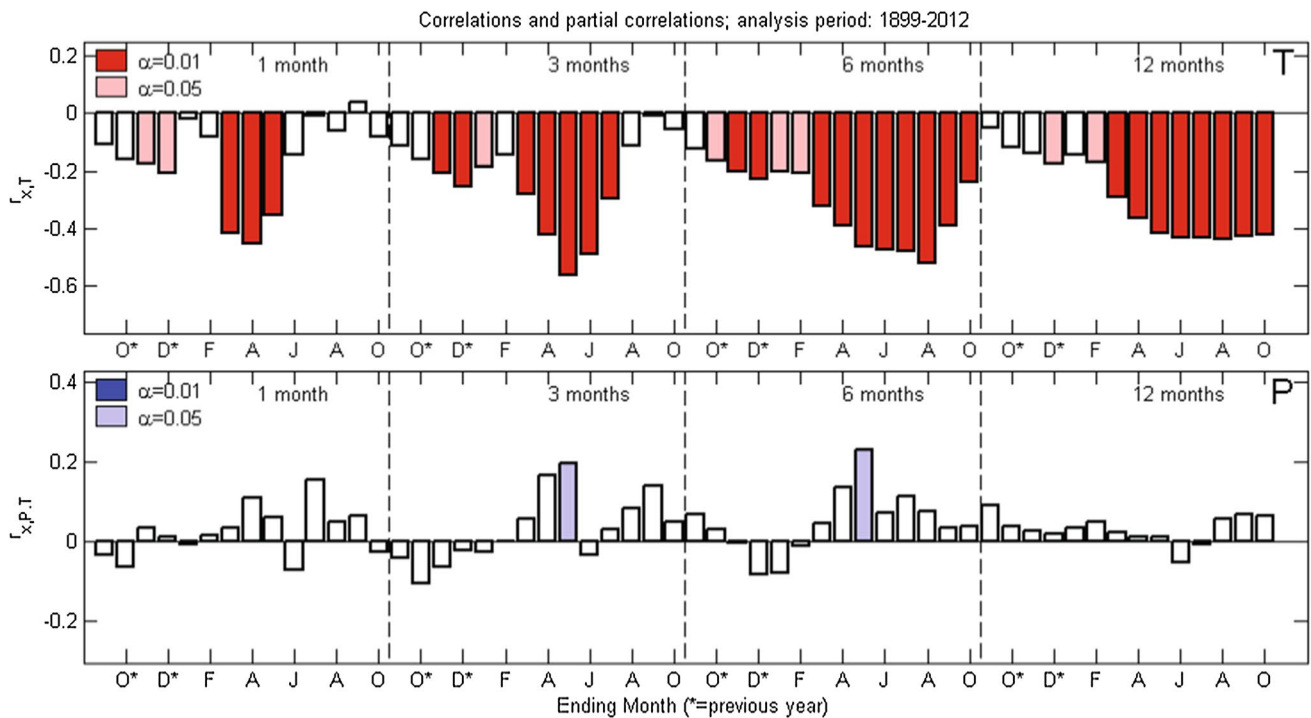
dendroclimatology (Wigley et al. 1984) and, based on the EPS criterion, we judged the Lokhada chronology to be reliable back to AD 1640, although its between-tree agreement is somewhat lower during a brief period centered around AD 1680. The characteristics of the Lokhada chronology are generally comparable to results obtained by other studies of the same species (Borgaonkar et al. 1994; Yadav et al. 1997; Ahmed and Naqvi 2005; Ahmed et al. 2009, 2011, 2012; Khan et al. 2008; Zafar et al. 2010; Borgaonkar et al. 2011; Ram 2012).

### 3.2 Tree–climate relations

The seasonal correlation analysis showed that radial growth of *P. smithiana* is most strongly associated with spring temperatures (Fig. 4). Over the full period (1899–2012), the Lokhada ring-width chronology is negatively correlated with mean March to May temperatures ( $r = -0.56$ ), with similar results obtained from both the early (1899–1955) and late (1956–2012) sub periods ( $r = -0.51$  and  $-0.62$ , respectively). The Lokhada ring-width record when compared against gridded climate data shows that tree growth at this location is significantly correlated with mean March–May temperatures across much of the western Himalaya, north central and northeastern India (supplementary material, Figure 2). The inverse relationship between tree growth and spring temperatures might be due to increased evapo-transpiration and inadequate soil moisture at the onset of radial growth (Pant et al. 2000; Yadav and Singh 2002; Cook et al. 2003; Sano et al. 2005; Liang et al. 2008; Dawadi et al. 2013). Tree-ring records from several other species in the Nepalese Himalaya have shown similar negative responses to early-season temperatures (Cook et al. 2003; Sano et al. 2005;

**Fig. 3** Tree-ring chronology of *P. smithiana* extending from AD 1591 to 2012 along with sample depth and EPS threshold cut off. The thick line represents the 10 years spline-smoothing curve





**Fig. 4** SEASCORR results summary of seasonal climatic signals in tree-ring data of *P. smithiana*. (*Top*) correlation of tree-ring variable with monthly, 3-month total, 6-month total and 12-month mean temperature for ending months from September preceding the growth

year through October of the growth year. (*Bottom*) partial correlations between tree-ring chronology with monthly total precipitation. Monte-Carlo-derived significance of correlation or partial correlation is shown in colors (Meko et al. 2011) for levels 0.01 and 0.05

Chhetri and Thapa 2010; Gaire et al. 2011; Thapa et al. 2013). Outside of Nepal, studies in the western Himalayan region of India (Borgaonkar et al. 1994, 1996; Pant et al. 2000; Yadav and Singh 2002; Yadav et al. 2004; Singh and Yadav 2005) and Pakistan's Karakoram range (Ahmed et al. 2012) also reported that the growth of conifer species is inhibited by anomalous spring warmth. Although Borgaonkar et al. (2011) showed that *P. smithiana* at high-altitude sites near Kinnor, India exhibited a strong positive relationship with mean annual and winter (December–February) temperatures, that behavior is not present in the Lohkada chronology.

### 3.3 Spring temperature reconstruction

Based on the seasonal correlation results, we identified mean spring (March–May) temperatures as the most promising candidate for palaeoclimate reconstruction. We constructed a linear regression model with spring temperature as the predictand and the Lohkada ring-width chronology as the sole predictor. Over the full calibration period, the regression model explained 32 % of the total variance in spring temperatures, and had positive values for both RE and CE, indicating that the model

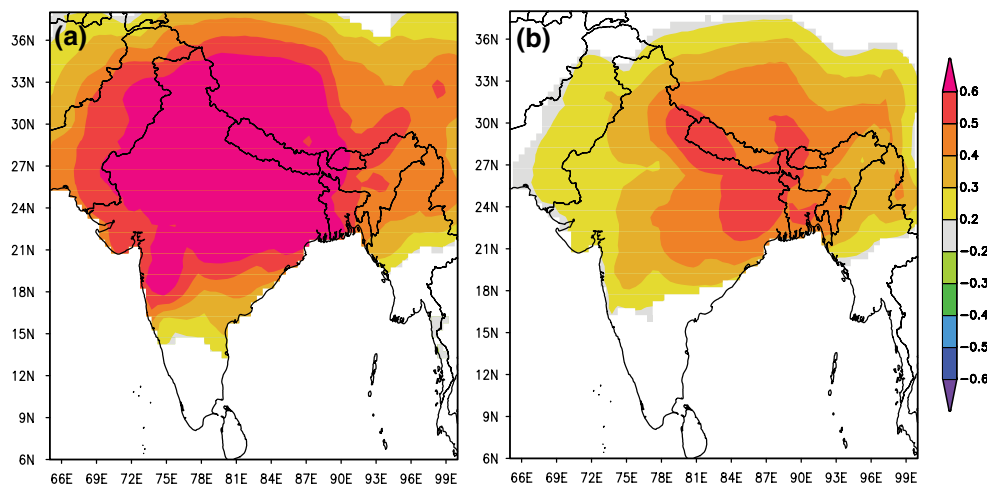
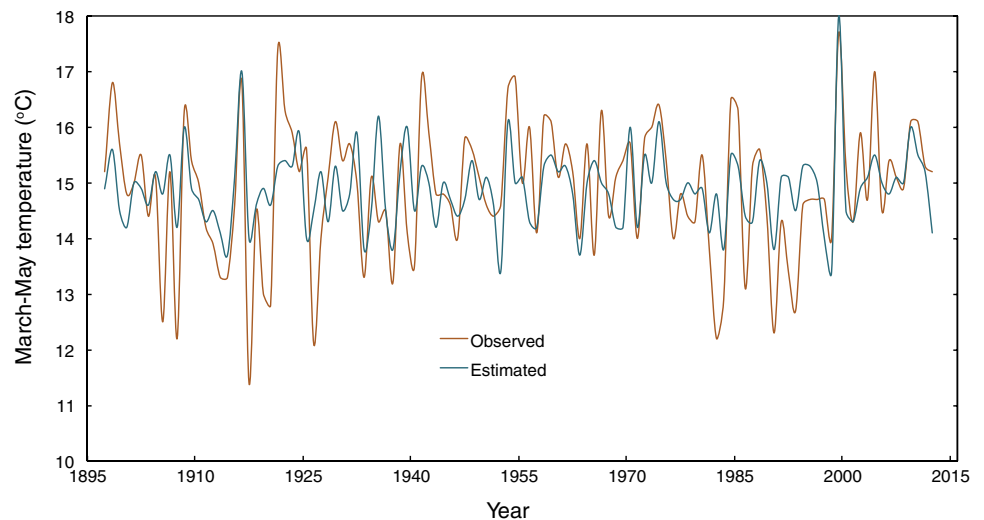
has skill in reproducing the observed variability in temperature (Table 3). Our cross-validation tests, which split the calibration into two equal sub-periods and the PRESS procedure, indicate the model was stable over the period of comparison. The observed and estimated spring temperatures when compared over the period of calibration indicated that the linear regression model is skillful for reconstructing spring temperature variability (Fig. 5). But comparing smoothed versions of the observed and estimated temperatures indicated that the model is also applicable in recovering low-frequency variations (supplementary material, Figure 3). The low frequency variability in estimated temperature generally follows pattern similar to the low frequency variability of observed data but lack resemblance in trends in some periods. This might be due to the low temperature variance captured in the reconstruction. The observed and estimated spring temperature when compared against average gridded spring temperature data showed significant positive spatial correlation across much of the western Himalaya, north central and northeastern India (Fig. 6). This showed that the reconstruction produced roughly the same spatial correlation pattern with regional temperatures as the observed record.

**Table 3** Calibration verification statistics for March–May temperature reconstructions

	Calibration (1897–1954)	Verification (1955–2012)	Calibration (1955–2012)	Verification (1897–1954)	Calibration (1897–2012)
$r^2$	0.28		0.39		0.32
Adjusted- $r^2$	0.26		0.38		0.32
$r^2$ - verification		0.39		0.28	
RE		0.38		0.28	
CE		0.37		0.27	
PRESS					0.30

RE reduction of error, CE coefficient of efficiency, PRESS predicted error sum-of-square

**Fig. 5** Observed mean spring (March–May) temperatures at Mukteshwar, India and temperature estimated from the Lokhada *P. smithiana* tree-ring width chronology. The time period for both the data is AD 1897–2012



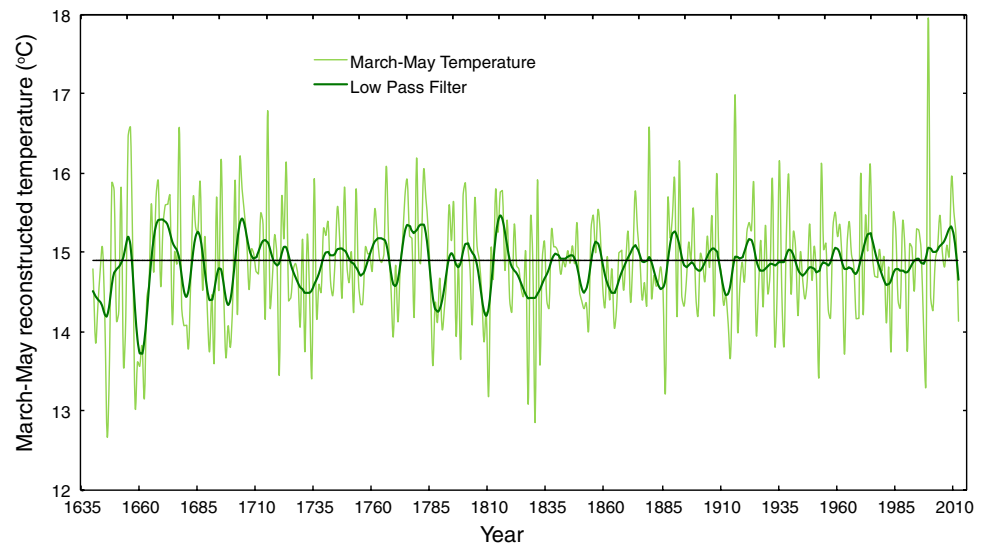
**Fig. 6** Spatial correlations between **a** observed and **b** estimated temperature with gridded average March–May CRU TS 3.21 temperature records. Spatial correlation was carried out for the common period of AD 1901–2012

### 3.4 Analysis and comparison of reconstructed temperature

We applied the regression model to reconstruct spring (March–May) temperatures back to AD 1640 (Fig. 7).

We chose not to extend the reconstruction over the entire length of the Lokhada record because the earlier portion is comprised of fewer tree-ring specimens and has a weaker common signal. Comparing the reconstructed temperatures

**Fig. 7** The reconstructed March–May temperature data filtered with a smoothing spline with a 50 % frequency cut off of 10 years



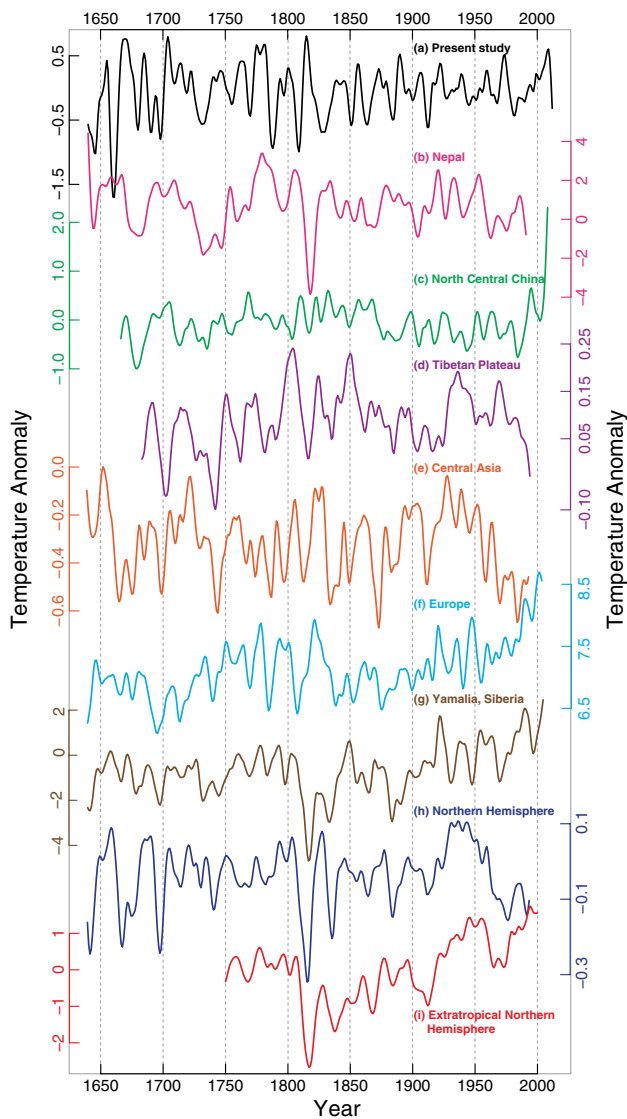
to the mean of the calibration period (AD 1897–2012) identified several cool and warm periods. If we consider lower-frequency variations, the reconstruction exhibits cooling trends during its earlier portion and warming in the recent few decades (Fig. 7). The longest cool period extended from the latter part of the eighteenth century to the late nineteenth century. Working in the western Himalayan region of India, Borgaonkar et al. (2011) identified an unprecedented enhancement in growth during the last few decades in the tree-ring chronologies based on the same taxa which is absent in our record. This may be due to the different standardization approach applied on the tree-ring data based on local site characteristics.

Three other tree-ring based temperature reconstruction for Nepal are available viz., February–June (Cook et al. 2003), October–February (Cook et al. 2003) and March–September (Sano et al. 2005). We compared the temperature reconstruction from present study with temperature reconstruction of February–June (Cook et al. 2003). The February–June temperature reconstruction of Cook et al. (2003) is based on the dense tree-ring network covering Nepal. Our reconstruction does not perfectly matches with Cook et al. (2003) February–June temperature reconstruction, which could be due to the difference in season and methodology involved in chronology development. However, the multi-decadal scales of warming and cooling trends are shared and we observed appearance of warming trends has comparable coherency (Fig. 8). Cook et al. (2003) recorded sharp cold period centered in 1810s, which they considered as cooling trend due to the eruption of Tambora in 1815–1816, and another unknown eruption in 1809 (Dai et al. 1991; Cole-Dai et al. 2009). However, we did not noticed such sharp cold period during the 1810s but AD 1815–1823 cooling trends are observed in low frequency smoothing of 30 and 50 years (supplementary

material, Figure 4). The March–September temperature reconstruction based on *A. spectabilis* tree-ring data from western Nepal Himalaya (Sano et al. 2005) is not compared directly with the present temperature reconstruction because there is absence of cool and warm periods description in their record. Further Sano et al. (2005) also compared their reconstruction with February–June temperature reconstruction (Cook et al. 2003). Sano et al. (2005) also reported that their temperature reconstruction does not perfectly matches with temperature reconstruction of Cook et al. (2003) but shared multi-decadal to century-scale warming and cooling trends.

The spring temperature reconstruction from present study is also compared with other regional temperature reconstructions (Briffa et al. 1998, 2001, 2013; Xoplaki et al. 2005; Wilson et al. 2007; Chen and Yuan 2014) along with records from Nepal (Cook et al. 2003) (Fig. 8). For comparison all the reconstructed temperature anomalies were filtered using smoothing spline with a 50 % frequency cut-off of 10 years. There are similar cooling trends observed during the early eighteenth century temperature reconstruction records from Nepal (Cook et al. 2003), North central China (Chen and Yuan 2014) and Tibetan Plateau (Briffa et al. 2001) (Fig. 8a–d). Increasing trends in the spring temperature reconstruction of present study during recent few decades are also observed in the temperature reconstructions from North central China (Chen and Yuan 2014), Europe (Xoplaki et al. 2005), Siberia (Briffa et al. 2013) and extratropical northern Hemisphere (Wilson et al. 2007) (Fig. 8c, f, g, i). From the Mid eighteenth century towards recent there is a close resemblance between the spring (March–May) temperatures of Europe (Xoplaki et al. 2005) and the present study. Both these spring temperature reconstructions do not show cooling trends for few years after Tambora eruption that is witnessed in all other





**Fig. 8** Reconstructed temperature anomalies filtered using smoothing spline with a 50 % frequency cut off of 10 years: *a* spring (March–May) temperature reconstruction for far western Nepal Himalaya (present study), *b* February–June temperature reconstruction for Nepal (Cook et al. 2003), *c* May–June maximum temperature for north central China (Chen and Yuan 2014), *d* April–September for Tibet (Briffa et al. 2001), *e* April–September for Central Asia (Briffa et al. 2001), *f* seasonal March–May temperature for Europe (Xoplaki et al. 2005), *g* summer (June–July) temperature for Yamalia, north-west Siberia (Briffa et al. 2013), *h* growing-season, April–September temperature for northern Hemisphere (Briffa et al. 1998) and *i* annual temperature for extra-tropical northern Hemisphere (Wilson et al. 2007)

records considered. Thus it was observed that the present study has closest relationship with records of spring temperature from Europe (Xoplaki et al. 2005). However, there were comparable instances in the given period of all the records (Fig. 8) where there are similar trends as obtained in present study. At the end of 1940s i.e., mid twentieth

century the records including the present study showed a peculiar rise in temperature, even including records from cold and arid regions such as North central China, Central Asia and Siberia (Fig. 8c, e, g). However, temperature in Central Asia and northern Hemisphere revert back towards cooling trends in the late twentieth century. Thus looking at all the records we observed that our present study is following patterns of temperature variations observed in surrounding regions. Probably all these records have slight variation amongst each other and with present study due to regional climate factors, species and parameters used for tree-ring based temperature reconstruction.

The reconstruction did not show the significant pattern of cooling during the Little Ice Age but there were few cold episodes recorded. The millennium-long reconstruction of mean summer (May–August) temperature extending back to AD 940 derived from tree-ring width data of Himalayan Pencil Juniper (*Juniperus polycarpos* C. Koch) from the monsoon-shadow zone in the western Himalaya, India revealed medieval warm period and little ice age cooling and again warming since the nineteenth century (Yadav et al. 2011). The cool episodes noted in their reconstruction around AD 1537–1622, 1731–1780, 1817–1846 represent the LIA was widely observed in many regions (PAGES 2K Consortium 2013), however, there exist regional to local temporal offsets and differences in the magnitude of cooling (Cook et al. 2003, 2013; Yadav et al. 2004, 2011; PAGES 2K Consortium 2013). Some tree-ring based summer temperature reconstructions from Asian mountain regions like Tibet and central Asia (Briffa et al. 2001), Nepal (Cook et al. 2003) and India (Yadav et al. 2004) document cooling during the last decades of the twentieth century. However, other high-resolution climate proxies from high-latitudes of the northern and southern Hemispheres indicated warming in the twentieth century (Mann and Jones 2003; Yadav et al. 2011; Cook et al. 2013; PAGES Consortium 2013).

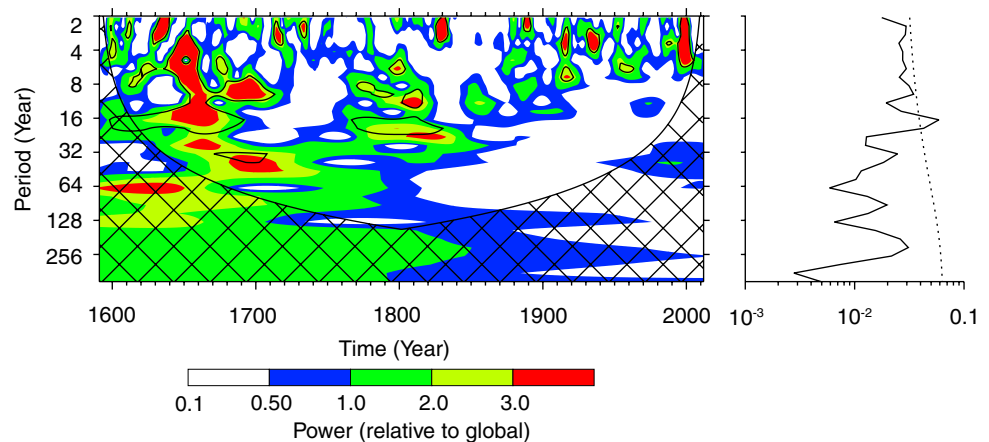
### 3.5 Regional tele-connections

The average March–May observed and estimated temperature was compared with average March–May temperature of All-India and homogenous regions, viz., Western Himalaya, Northwest, North Central, Northeast, West Coast, East Coast and Interior Peninsula temperature records (<http://tropmet.res.in>) for the common time period of AD 1901–2007. Except West coast region, all other six region including all India showed significant correlation at  $p < 0.05$  with reconstructed temperature series (Table 4). This observed positive correlation shows the large-scale regional coherency pattern and also the validation of the reconstructed data. However, the observed average March–May temperature showed higher correlation with all these

**Table 4** Correlation of observed and estimated March–May temperature with different climatic zone of India ([www.tropmet.res.in](http://www.tropmet.res.in)). The correlation analysis was carried out for the time period of AD 1901–2007

Climate zones	Correlation	
	Observed March–May temperature	Estimated March–May temperature
All India	0.853	0.466
Western Himalaya	0.679	0.273
North-west India	0.786	0.330
North-central India	0.888	0.503
North-east India	0.739	0.547
Interior Peninsular India	0.559	0.351
East-coast India	0.399	0.313
West-coast India	0.510	0.189

**Fig. 9** Wavelet power spectrum of reconstructed temperature data for AD 1640–2012. The power has been scaled by the global wavelet spectrum. The *cross-hatched region* is the cone of influence, where zero padding has reduced the variance. *Black contour* is the 10 % significance level, using a red-noise background spectrum. The global wavelet power spectrum (*black line*) and 10 % significance level global wavelet spectrum (*dashed line*) shown at right



regions wise Indian temperature as compare to the estimated temperature.

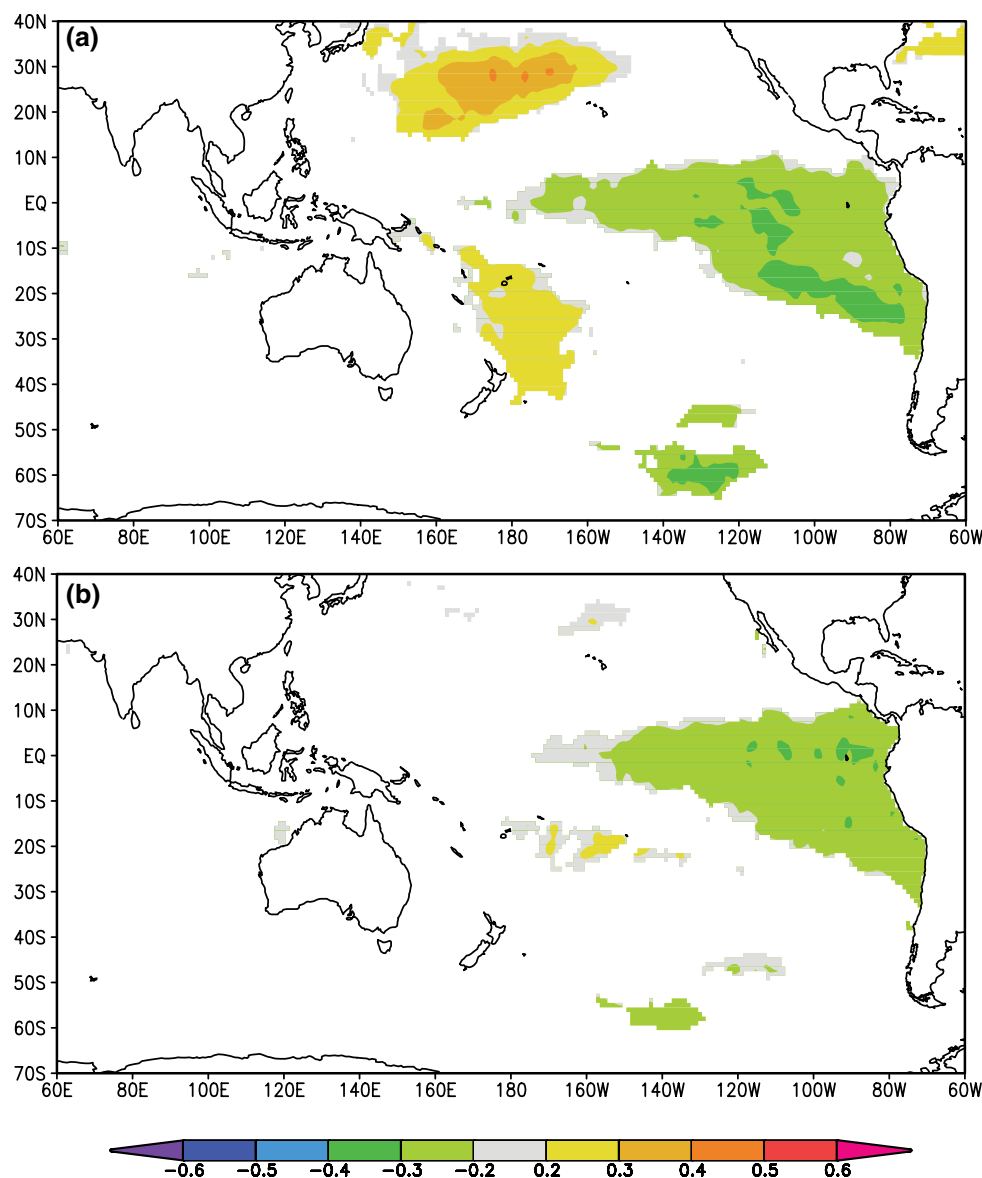
Applying wavelet analysis (Torrence and Compo 1998) to the Loxhada reconstructions shows that most of its variance is concentrated at higher frequencies (Fig. 9). The higher frequency bands of less than 7 years observed may be linked with ENSO activity. The periodicity of this high frequency variability was dominant during mid seventeenth century, early eighteenth, nineteenth and twentieth century and late period of twentieth century. Based on this result we performed correlation analysis of both observed and estimated average March–May temperature with Sea Surface Temperature (SST) index of different region of the equatorial Pacific viz., NINO1.2, NINO3, NINO3.4 and NINO4 (Kaplan et al. 1998) and extended multivariate ENSO Index (MEI) (Wolter and Timlin 2011). Both observed and estimated March–May temperatures had significant negative correlations with SSTs index and MEI for monsoon and post monsoons seasons (supplementary material, Table 1). These negative relationships suggest that warm (cool) spring season over the western Nepal Himalaya region are associated with cool (warm) SSTs in the following seasons. Similar observation between spring temperature reconstruction and SST are also noted in Yadav et al. (1997). We also carried out spatial correlation of observed

and estimated temperature with Sea Surface Temperature (Kaplan et al. 1998) and observed similar negative correlation in the equatorial belt of the Pacific Ocean (Fig. 10) for monsoon months. However the relationship is stronger in case of observed data as compare to the estimated. But this tele-connection showed temperature reconstruction based on the high-resolution proxy from the high altitude region of the western Nepal Himalaya has linkages with climatic variability in a global scale.

#### 4 Conclusions

The study presents the longest dendroclimatic temperature reconstruction for the Far-western Nepal Himalayan region of Nepal. This new reconstruction provides a basis for studying past temperature variability in this region where very short period of the instrumental data is available. The long term climate management planning and climate modeling work of the region shall be possible with the available long-term records of temperature. The relationship of Nepal Himalayan climate with ENSO indicated climate records based on high-resolution proxy such as tree-ring from this region help to understand climate change linkages and coherency pattern in global terms. In the future,

**Fig. 10** Spatial correlations between **a** observed and **b** estimated temperature with Kaplan Sea Surface Temperature in global scale. The spatial correlation was carried out for monsoon months (June–September) covering a time span from AD 1897 to 2012



combination additional tree-ring records from *P. smithiana* with tree-ring data from other species should help study the temporal and spatial structure of temperature variability in Nepal.

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## References

- Ahmed M, Naqvi SH (2005) Tree-ring chronologies of *Picea smithiana* (wall.) Boiss., and its quantitative vegetational description from Himalayan range of Pakistan. *Pak J Bot* 37:697–707
- Ahmed M, Wahab M, Khan N (2009) Dendroclimatic investigation in Pakistan using *Picea smithiana* (Wall.) Boiss.—preliminary results. *Pakistan J Bot* 41:2427–2435
- Ahmed M, Palmer J, Khan N, Wahab M, Fenwick P, Esper J, Cook ER (2011) The dendroclimatic potential of conifers from the northern Pakistan. *Dendrochronologia* 29:77–78

- Ahmed M, Khan N, Wahab M, Zafar MU, Palmer J (2012) Climate/growth correlations of tree species in the Indus basin of the Karakoram range, north Pakistan. *IAWA J* 33:51–61
- Bhattacharyya A, Lamarche VC Jr, Telewski FW (1988) Dendrochronological reconnaissance of the conifers of northwest India. *Tree-Ring Bull* 48:21–30
- Bhattacharyya A, Lamarche VC Jr, Hughes MK (1992) Tree-ring chronologies from Nepal. *Tree-Ring Bull* 52:59–66
- Bhuju UR, Shakya PR, Basnet TB, Shrestha S (2007) Nepal biodiversity resource book: protected areas, Ramsar sites, and world heritage sites. ICIMOD and Ministry of Environment, Science and Technology, Kathmandu
- Bhuju DR, Career M, Gaire NP, Soraruf L, Riondato R, Salerno F, Maharjan SR (2010) Dendroecological study of high altitude forest at Sagarmatha National Park, Nepal. In: Jha PK, Khanal IP (eds) Contemporary research in Sagarmatha (Mt. Everest) region, Nepal. Nepal Academy of Science and Technology, Lalitpur, pp 119–130
- Borgaonkar HP, Pant GB, Kumar KR (1994) Dendroclimatic reconstruction of summer precipitation at Srinagar, Kashmir, India, since the late-eighteenth century. *Holocene* 4:299–306
- Borgaonkar HP, Pant GB, Kumar KR (1996) Ring-width variations in *Cedrus deodora* and its climatic response over the western Himalaya. *Int J Climatol* 16:1409–1422
- Borgaonkar HP, Sidker AB, Ram S (2011) High altitude forest sensitivity to the recent warming: a tree-ring analysis of conifers from western Himalaya, India. *Quatern Int* 236:158–166
- Briffa KR, Jones PD, Schweingruber FH, Osborn TJ (1998) Influence of volcanic eruptions on Northern Hemisphere summer temperature over the past 600 years. *Nature* 393:450–455
- Briffa KR, Osborn TJ, Schweingruber FH, Harris IC, Jones PD, Shiyatov SG, Vaganov EA (2001) Low frequency temperature variations from northern tree ring density network. *J Geophys Res* 106:2929–2941
- Briffa KR, Melvin TM, Osborn TJ, Hantemirov RM, Kirilyanov AV, Mazepa VS, Shiyatov SG, Esper J (2013) Reassessing the evidence for tree-growth and inferred temperature change during the Common Era in Yamalia, northwest Siberia. *Quat Sci Rev* 72:83–107
- Chen F, Yuan Y (2014) May–June maximum temperature reconstruction from mean earlywood density in north central China and its linkages to the summer monsoon activities. *PLoS One*. doi:10.1371/journal.pone.0107501
- Chhetri PK, Thapa S (2010) Tree ring and climate change in Langtang National Park, central Nepal. *Our Nat* 8:139–143
- Cole-Dai J, Ferris D, Lanciki A, Savarino J, Baroni M (2009) Cold decade (AD 1810–1819) caused by Tambora (1815) and another (1809) stratospheric volcanic eruption. *Geophys Res Lett*. doi:10.1029/2009gl040882
- Cook ER (1985) A time-series analysis approach to tree-ring standardization. PhD Dissertation. Department of Geosciences, The University of Arizona, Tucson
- Cook ER, Holmes RL (1986) Users manual for program ARSTAN. In: Holmes RL, Adams RK, Fritts HC (eds) Tree-ring chronologies of western North America: California, eastern Oregon and northern Great Britain. University of Arizona, Arizona
- Cook ER, Kairiukstis LA (1990) Methods of dendrochronology: applications in the environmental sciences. Kluwer Academic, Dordrecht
- Cook ER, Krusic PJ, Jones PD (2003) Dendroclimatic signals in long-tree chronologies from the Himalayas of Nepal. *Int J Climatol* 23:707–732
- Cook ER, Anchukaitis KJ, Buckley BM, D'arrigo R, Jacoby GC, Wright WE (2010) Asian monsoon failure and mega drought during the last millennium. *Science* 328:486–489
- Cook ER, Krusic PJ, Anchukaitis KJ, Buckley BM, Nakatsuka T, Sano M, Pages Asia2k members (2013) Tree-ring reconstructed summer temperature anomalies for temperate east Asia since 800 C. E. *Clim Dyn* 41:2957–2972
- Dai J, Mosley-Thompson E, Thompson LG (1991) Ice core evidence for an explosive tropical volcanic eruption 6 years preceding Tambora. *J Geophys Res* 96(17):361–366
- Dawadi B, Liang E, Tian L, Devkota LP, Yao TS (2013) Pre-monsoon precipitation signal in tree rings of timberline *Betula utilis* in the central Himalayas. *Quatern Int* 283:72–77
- Fritts HC, Guiot J, Gordon JG (1990) Verification. In: Cook ER, Kairiukstis LA (eds) Methods of dendrochronology: applications in the environmental sciences, International Institute for Applied Systems Analysis. Kluwer Academic, Boston, pp 178–184
- Gaire NP, Dhakal YR, Lekhak HC, Bhuju DR, Shah SK (2011) Dynamics of *Abies spectabilis* in relation to climate change at the treeline ecotone in Langtang National Park. *Nepal J Sci Technol* 12:220–229
- Gou X, Chen F, Jacoby GC, Cook ER, Yang M, Peng J, Zhang Y (2007) Rapid tree growth with respect to the last 400 years in response to climate warming, northeastern Tibetan Plateau. *Int J Climatol* 27:1497–1503
- Harris I, Jones PD, Osborn TJ, Lister DH (2014) Updated high-resolution grids of monthly climatic observations—the CRU TS 3.10. *Int J Climatol* 34:623–642
- Holmes RL (1983) Computer assisted quality control in tree ring dating and measuring. *Tree-Ring Bull* 43:69–78
- Huang JG, Zhang QB (2007) Tree rings and climate for the last 680 years in Wulan area of northeastern Qinghai-Tibetan Plateau. *Clim Change* 80:369–377
- IPCC (2007) IPCC: climate change: the physical sciences basis. Summary for policy makers, Geneva
- Junger W, Ponce de A (2012) mtsdi: multivariate time series data imputation. <http://cran.r-project.org/web/packages/mtsvdi>
- Kaplan AM, Kushnir CY, Clement A, Blumenthal M, Rajagopalan B (1998) Analyses of global sea surface temperature 1856–1991. *J Geophys Res* 103(9):18567–18589
- Khan N, Ahmend M, Wahab M (2008) Dendrochronological potential of *Picea smithiana* (Wall.) Boiss from Afghanistan. *Pak J Bot* 40:1063–1070
- Li ZS, Zhang QB, Ma K (2012) Tree-ring reconstruction of summer temperature for AD 1475–2003 in the central Hengduan mountains, northwestern Yunnan, China. *Clim Change* 110:455–467
- Liang E, Shao X, Qin N (2008) Tree-ring based summer temperature reconstruction for the source region of the Yangtze river on the Tibetan Plateau. *Glob Planet Change* 61:313–320
- Liang E, Diwadi B, Pederson N, Eckstein D (2014) Is the growth of birch at the upper timberline in the Himalayas limited by moisture or by temperature? *Ecology* 95(9):2453–2465
- Mann ME, Jones PD (2003) Global surface temperatures over the past two millennia. *Geophys Res Lett* 30(15):1820. doi:10.1029/2003GL017814
- Meko DM (1997) Dendroclimatic reconstruction with time varying subsets of tree ring indices. *J Clim* 10:687–696
- Meko DM, Graybill DA (1995) Tree-ring reconstruction of upper Gila River discharge. *J Am Water Resour Assoc* 31:605–616
- Meko DM, Touchan R, Anchukaitis KJ (2011) Seacorr: a MATLAB program for identifying the seasonal climate signal in an annual tree-ring time series. *Comput Geosci* 37:1234–1241
- Michaelsen J (1987) Cross-validation in statistical climate forecast models. *J Clim Appl Meteorol* 26:1589–1600
- Pages 2k Consortium (2013) Continental-scale temperature variability during the past two millennia. *Nat Geosci* 6:339–346
- Pant GB, Kumar KR, Borgaonkar HP, Okada N, Fujiwara T, Yamashita K (2000) Climatic response of *Cedrus deodara* tree-ring



- parameters from two sites in the western Himalaya. *Can J For Res* 30:1127–1135
- Percival DB, Constantine WLB (2006) Exact simulation of Gaussian time series from nonparametric spectral estimates with application to bootstrapping. *Stat Comput* 16:25–35
- R Development Core Team (2014) R: a language and environment for statistical computing. R foundation for statistical computing, Vienna, Austria. ISBN 3-900051-07-0. <http://www.R-project.org>
- Ram S (2012) Tree growth/climate relationships of conifer trees and reconstruction of summer season Palmer Drought Severity Index (PDSI) at Pahalgam in Srinagar, India. *Quatern Int* 254:152–158
- Sano M, Furuta F, Kobayashi O, Sweda T (2005) Temperature variations since the mid-18th century for western Nepal, as reconstructed from tree-ring width and density of *Abies spectabilis*. *Dendrochronologia* 23:83–92
- Sano M, Sheshshayee MS, Managave S (2010) Climatic potential of  $\delta^{18}\text{O}$  of *Abies spectabilis* from the Nepal Himalaya. *Dendrochronologia* 28:93–98
- Sano M, Ramesh R, Sheshayee MS, Sukumar R (2011) Increasing aridity over the past 223 years in the Nepal Himalaya inferred from a tree ring  $\delta^{18}\text{O}$  chronology. *Holocene* 22(7):809–817
- Schulman E (1941) Some propositions in tree-ring analysis. *Ecology* 22:193–195
- Shrestha AB, Aryal R (2011) Climate change in Nepal and its impact on Himalayan glaciers. *Reg Env Change* 11:65–77
- Shrestha AB, Wake CA, Mayewski PA, Dibb JE (1999) Maximum temperature trends in the Himalaya and its vicinity: an analysis based on temperature records from Nepal for the period 1971–94. *J Clim* 12:2775–2786
- Shrestha AB, Wake CP, Dibb JE, Mayewski PA (2000) Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatological parameters. *Int J Climatol* 20(3):317–327
- Shrestha UB, Gautam S, Bawa KS (2012) Widespread climate change in the Himalayas and associated changes in local ecosystems. *PLoS One* 7(5):e36741. doi:10.1371/journal.pone.0036741
- Singh J, Yadav RR (2005) Spring precipitation variations over the western Himalaya, India, since AD 1731 as deduced from tree rings. *J Geophys Res*. doi:10.1029/2004jd004855
- Singh J, Yadav RR, Wilmking M (2009) A 694-year tree-ring based rainfall reconstruction from Himachal Pradesh, India. *Clim Dyn* 33:1149–1158
- Snee RD (1997) Validation of regression models: methods and examples. *Technometrics* 19:415–428
- St. George S, Ault TR, Torbenson MCA (2013) The rarity of absent growth rings in Northern Hemisphere forests outside the American Southwest. *Geophys Res Lett* 35:L14707. doi:10.1029/2008GL034074
- Stokes MA, Smiley TL (1968) An introduction to tree ring dating. University of Chicago Press, Chicago
- Thapa UK, Shah SK, Gaire NP, Bhuju DR, Bhattacharyya A, Thaguna GS (2013) Influence of climate on radial growth of *Abies pindrow* in Western Nepal Himalaya. *Banko Janakari* 23(2):14–19
- Torrence C, Compo GP (1998) A practical guide to wavelet analysis. *Bull Am Meteorol Soc* 79:61–78
- Touchan R, Woodhouse C, Meko DM, Allen C (2011) Millennial precipitation reconstruction for the Jemez Mountains, New Mexico, reveals changing drought signal. *Int J Climatol* 31:896–906
- Trouet V, Oldenborgh GJV (2013) KNMI climate explorer: a web based research tool for high-resolution paleoclimatology. *Tree-Ring Res* 69(1):3–13
- Weisberg R (1985) Applied linear regression. Wiley, New York
- Wigley TML, Briffa KR, Jones PD (1984) On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *J Clim App Meteorol* 23:201–213
- Wilson R, D'arrigo R, Buckley B, Buntgen U, Esper J, Frank D, Luckman B, Payette S, Vose R, Youngblut D (2007) A matter of divergence: tracking recent warming at hemispheric scales using tree ring data. *J Geophys Res* 112:D17103. doi:10.1029/2006JD008318
- Wolter K, Timlin MS (2011) El Nino/Southern Oscillation behaviour since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext). *Int J Climatol* 31:1074–1087
- Xoplaki E, Luterbacher J, Paeth H, Dietrich D, Steiner N, Grosjean M, Wanner H (2005) European spring and autumn temperature variability and change of extremes over the last half millennium. *Geophys Res Lett* 32:L15713
- Yadav RR (2010) Long-term hydroclimatic variability in monsoon shadow zone of western Himalaya, India. *Clim Dyn* 36:1453–1462
- Yadav RR, Singh J (2002) Tree-ring analysis of *Taxus baccata* from the western Himalaya, India, and its dendroclimatic potential. *Tree-Ring Res* 58:23–29
- Yadav RR, Park WK, Bhattacharyya A (1997) Dendroclimatic reconstruction of April–May temperature fluctuations in the western Himalaya of India since AD 1698. *Quatern Res* 48:187–191
- Yadav RR, Park WK, Bhattacharyya A (1999) Spring-temperature variations in western Himalaya, India, as reconstructed from tree-rings: AD 1390–1987. *Holocene* 9:85–90
- Yadav RR, Park WK, Singh J, Dubey B (2004) Do the western Himalayas defy global warming? *Geophys Res Lett* 31:L17201. doi:10.1029/2004gl020201
- Yadav RR, Braeuning A, Singh J (2011) Tree ring inferred summer temperature variations over the last millennium in western Himalaya, India. *Clim Dyn* 36:1545–1554
- Yu L, Zhisheng A, Haizhou M, Qiufang C, Zhengyu L, Kutzbach JK, Jjiangfeng S, Huiming S, Junyan S, Liang Y, Qiang L, Yinke Y, Lei W (2006) Precipitation variation in the north-eastern Tibetan Plateau recorded by the tree rings since 850 AD and its relevance to the northern hemisphere temperature. *Sci China Ser D Earth Sci* 49:408
- Zafar MU, Ahmed M, Farooq MA, Akbar M, Hussain A (2010) Standardized tree ring chronologies of *Piceasmithiana* from two new sites of northern area Pakistan. *World Appl Sci J* 11(12):1531–1536