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Temperature variations since the mid-18th century for western Nepal, as reconstructed from tree-ring width and density of *Abies spectabilis*

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Abstract

The climate of western Nepal was reconstructed for the past 249 years using ring width and wood density of *Abies spectabilis* (D. Don) Spach from western Nepal. A total of 46 increment core samples were collected from 23 individual trees growing in an open *A. spectabilis* stand near timberline of 3850 m a.s.l. in Humla District, western Nepal. The core samples were subjected to densitometric analysis to obtain chronologies of ring width and three kinds of intra-annual bulk densities, i.e., minimum, maximum, and mean. Response analysis of tree-ring parameters with climate records revealed that the ring width was correlated negatively with March–May (pre-monsoon) temperature and positively with March–May precipitation, while the minimum density was correlated positively with March–July temperature and negatively with March–May precipitation. On the other hand, the maximum and mean densities were positively correlated with August–September and March–September temperatures, respectively. These results indicate that the ring width and minimum density are primarily controlled by the pre-monsoon temperature and precipitation, while the latewood density by the late monsoon temperature. Finally based on these results of the response analysis, a transfer function was established, with which March–September temperature was reconstructed for the past 249 years, which shows a warming trend from 1750s until approximately 1790, followed by cooling until 1810, then by a gradual warming trend extending to 1950, and a notable cold period continuing up to the present. No evidence of a consistent warming trend over the last century or two commonly appearing in higher latitudes was found in the present reconstruction, but possible factor behind the widespread glacial retreat in the Nepal Himalayas was discussed.

Keywords: Dendroclimatology; Densitometric analysis; Climate reconstruction

Introduction

Tree rings have been used as one of high-resolution proxy information on climate change. Earlier studies (Pant, 1979; Bhattacharyya and Yadav, 1990, 1992; Yadav and Bhattacharyya, 1992; Borgaonkar et al., 1999) have indicated the dendroclimatic utility of such Himalayan conifers as *Cedrus*, *Abies*, *Pinus* and *Picea* in the western Himalayas of India. Borgaonkar et al. (1999) presented tree-ring chronologies of several tree species from 11 sites covering a wide range of the Indian Himalayas, and revealed that tree growth in this region is primarily limited by moisture availability in pre-monsoon season (March–May), with a negative association with temperature and a positive association with precipitation. There have also been several reports of climate reconstruction for the Indian Himalayas from

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tree-ring data (e.g., Borgaonkar et al., 1994, 1996; Yadav et al., 1997, 1999; Yadav and Park, 2000). A 598-year (AD 1390–1987) reconstruction of pre-monsoon temperature variations using *Cedrus deodara* (D. Don) G. Don (Yadav et al., 1999) is the longest dendroclimatic series from the Himalayas. All of these studies were based on the interpretation of ring-width data. Analyses based on wood densitometry have also revealed high dendroclimatic potential of the Indian Himalayas (Hughes and Davies, 1987; Hughes, 1992; Pant et al., 2000). Hughes (1992) reconstructed April–May and August–September temperatures and April–September precipitation of Srinagar since the late 18th century from ring-width and maximum-latewood-density chronologies of *Abies pindrow* (Royle) Spach sampled from several sites in Kashmir. Pant et al. (2000) reported that pre-monsoon temperature and precipitation significantly influence mean- and minimum-earlywood densities, and ring width of *C. deodara* in two different sites around Shimla.

In contrast with quantity and quality of the above studies from the Indian Himalayas, those from the Nepal Himalayas are rather few and incomprehensive. Suzuki (1990) and Bhattacharyya et al. (1992) have indicated that several species in Nepal were promising for dendroclimatology, but did not go so far as to explicit and conclusive climatic reconstructions. More recently, based on a dense network consisting of 32 ring-width chronologies over Nepal, Cook et al. (2003) presented two reconstructions of February–June and October–February temperatures, respectively, back to AD 1546 and 1605, comprising the first report of dendroclimatic reconstruction for Nepal. However, densitometric analysis has not been systematically conducted in Nepal. In this work, not only ring width but also ring density was used in a hope to improve the quality of climate reconstruction by increasing the number of predictor variables.

Materials and methods

Study site and sample trees

Sampling for the present study was carried out in October 2000 in an *Abies spectabilis* dominated stand (29°51′N and 81°56′E) near timberline of 3850 m a.s.l. on the northeast-facing slope in Humla District, western Nepal (Fig. 1). In contrast with the north-facing slope where the present samples were taken, the south-facing slope was devoid of trees but shrubs were present due partly to drier soil conditions induced by stronger sunshine and partly to clearance for grazing by local people. The subsidiary ridges, where the sampling was conducted, were occupied by relatively old *A. spectabilis* as compared with valleys where mixed stands of young *A. spectabilis* and *Betula utilis* D. Don dominated. Paired increment cores were taken at breast height (1.3 m above ground) from each of 23 individual trees, totaling in 46 core samples. The mean diameter at breast height for the sampled trees was 77 cm. The length of tree-ring chronologies was limited by butt rot in most of the oldest trees.

Sample preparation and chronology development

The increment cores were sawn into strips of 1.8 mm in thickness with a twin-bladed saw. After moisture control, the strips were subjected to X-ray irradiation for radiograph. To determine the absolute year each ring was formed, cross-dating was performed by matching ring-width variations for all series on the radiograph as well as with the original increment strips. Subsequently the radiographs were scanned into a personal computer at a resolution of 16 μm (1600 dots per inch) for densitometry analysis. Ring widths and bulk densities of minimum earlywood, maximum latewood and mean intra-annual were obtained using the software DendroScan (Varem-Sanders and Campbell, 1996). In some of the cores blurred X-ray images hindered reliable measurement of ring width and density. In such cases, densitometry was abandoned but ring width was measured alternatively on the original cores using a micrometer equipped with moving stage under an ocular microscope, resulting in a total of nine cores devoid of density measurement. In order to counter-check for possible measurement and dating errors, individual ring-width series were tested against a master series derived by averaging all series on the basis of correlation computed using the program COFECHA developed by Holmes (1983).

The mean ring width and density chronologies for each tree were obtained by averaging the two series from a given tree. Then each raw tree chronology was standardized to detrend the long-term individual growth pattern induced by aging while minimizing the removal of variance due to climate as much as possible. The standardization was conducted by fitting either a negative exponential curve or a straight line for ring-width series and a straight line for minimum-, maximum- and mean-density series, and then by dividing each measured value by its calculated expectation. Finally, the site chronologies of ring width and densities were obtained by averaging the individual standardized series.

Response analysis

In order to identify the response of tree growth to climate, response analysis was performed. For this

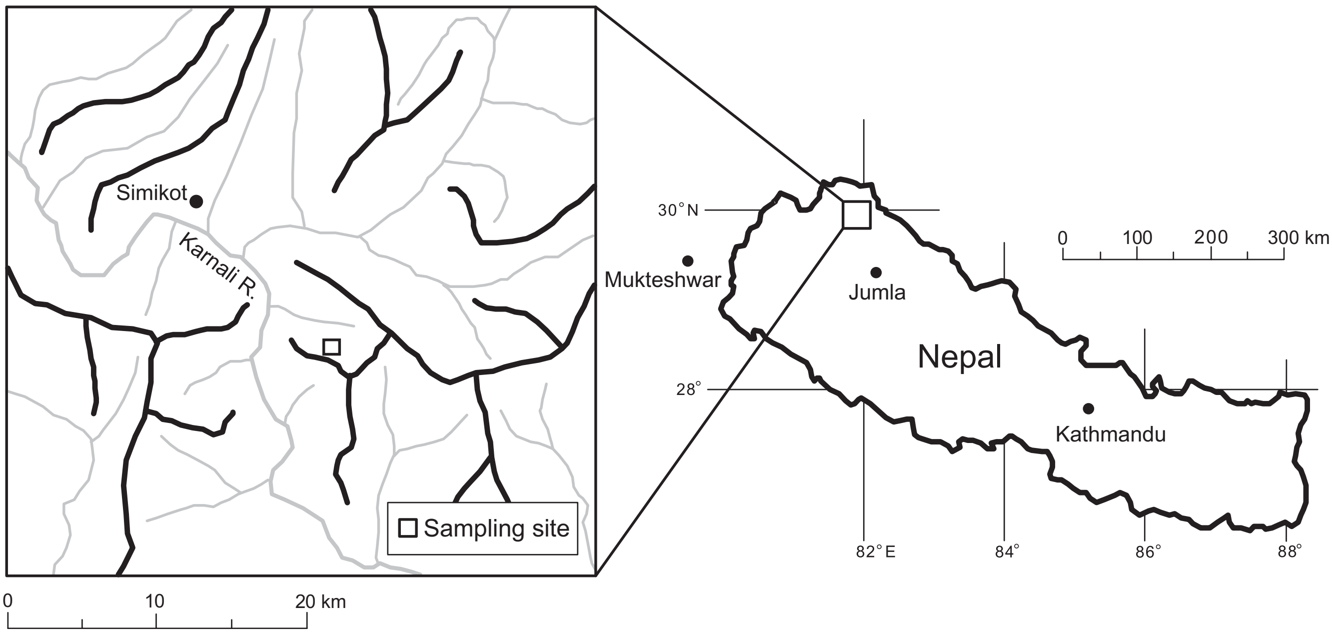

Fig. 1. Location of the sampling site.

purpose it is desirable to use climatic records from the nearest weather stations. However, at only 18 years for temperature and 39 years for precipitation the records from Jumla, some 70 km south of the sampling site, were too short for meaningful response analysis and therefore Indian climate data from Mukteshwar (29°28′N, 79°39′E) at a height of 2311 m a.s.l., some 200 km southwest of the sampling site, were used instead. Another possibility was to use regional mean temperature rather than that from a single station. As a matter of fact, the north–central India average temperature (Rupa Kumar et al., 1994; Pant and Rupa Kumar, 1997) revealed reasonable agreement with our tree-ring chronologies in short-term fluctuations, but showed apparent inconsistency in long-term trends. This is possibly because the Indian average temperature is based mostly on data from low elevation stations which may well differ from temperature trends in high altitudes as Shrestha et al. (1999) demonstrated in their analysis with all Nepal station data. On the other hand, precipitation of Mukteshwar did not agree very well with our tree-ring chronologies probably due to strong locality of precipitation pattern. Thus for precipitation the regional average for East Uttar Pradesh (Parthasarathy et al., 1987; Pant and Rupa Kumar, 1997) was used. Mukteshwar station data were obtained from online data sets of the Global Historical Climatology Network version 2 (Peterson and Vose, 1997) and Indian regional average data from those of the Indian Institute of Tropical Meteorology. To confirm the validity of this substitution, correlations between Jumla and the respective Indian data were examined. A significant correlation ($p<0.001$, $n = 37$) was obtained in annual precipitation. Although no such statistical significance ($p = 0.06$, $n = 14$) was established in annual mean temperature due to the short span of comparison, the Mukteshwar temperature data were concluded valid in view of its similarity in the trend of fluctuation with Jumla counterpart.

Before proceeding to response analysis of tree growth and climate, the most suitable growth year for timing annual cyclic nature of tree growth was defined to distinguish it from the calendar year. Judging from the field experience and the temperature records, tree growth at our sampling site was considered to shut down for the year by the end of October when the local mean temperature is estimated to plunge below 5 °C. Thus the growth year was tentatively defined as to begin in November of a given year and to end in October of the next calendar year. Then as a preliminary response analysis, simple correlation between tree-ring chronologies and monthly climatic variables (temperature and precipitation) of the current and previous years was calculated. It turned out, first of all, that current growth was significantly correlated with at least one of the climatic variables until as late as current September but not beyond. This means that September is more suitable for marking off a growth year than October as tentatively defined above, and this new definition was adopted in the following analysis. Any significant correlation was neither found with any climatic variables of the previous growth year. Lastly, though it depends upon the climatic factor the majority of significant correlations appeared as a seasonal cluster, indicating better correspondence of tree growth with seasonal climate than with monthly counterpart which is more likely to be subjected to random fluctuations. Accordingly the growth year was divided into four seasons beginning with winter (October–February) followed successively by pre-monsoon (March–May), early monsoon (June–July) and late monsoon (August–September), and only the current growth year was taken into account for the following analysis.

Response analysis was conducted in two ways, i.e., simple correlation analysis and multiple correlation analysis. In the latter, however, the response function of Fritts (1976) was used, in which rather than seasonal climatic variables themselves, their principal components were used as independent variables to explain variability in tree-ring parameters. This procedure can provide more consistent result since somewhat correlated raw climatic data are orthogonalized with less degrees of freedom. A set of resulting regression coefficients of principal components was finally converted back to a new set of coefficients corresponding to the original seasonal climatic variables.

Results and discussion

Chronology

Of the 46 cores sampled, 40 from 20 trees were successfully cross-dated. Cross-dating was relatively easy since pointer years in which some characteristic rings common to the majority of the cores appear, were recognized in every 2 or 3 decades. Statistical characteristics of the tree-ring series are shown in Table 1. Reduction in mean among-tree correlation from 0.54 in the raw ring-width series to 0.26 in the standardized series is due mainly to removal of declining growth trend with age. On the other hand, the density series did not show such a notable change in correlation by standardization, indicating lack of common source of variation due to aging. In the standardized chronologies, mean correlation was higher in ring-width (0.26) than in density series (0.12–0.23) with the minimum correlation consistently appearing in minimum density series. The resulting site chronologies extending back to AD 1717 are presented in Fig. 2. Mean sensitivity (mean relative changes found between adjacent ring measurements), first-order autocorrelation and standard deviation for the site chronologies were also obviously higher in ring-width than in density series. Expressed population signal (EPS), an indication of how well the site chronology estimates the population chronology (Wigley et al., 1984), was lower in minimum-density series (0.72) than in the three other series (0.83–0.87). Subsample signal strength (SSS), expressing how well a chronology constructed using a subset of individual tree series estimates the site chronology (Wigley et al., 1984), was also calculated to clarify uncertainty arising from decreasing sample size back into the past. It turned out that for ring width, and minimum, maximum and mean densities, respectively, 7, 10, 7 and 8 individual tree series were needed to maintain the reliability of SSS $\geqslant 0.8$, i.e., to retain 80% of the signal. These sample sizes correspond to the starting years of AD 1752, 1790, 1780 and 1781 in respective site chronologies. Accordingly in climate reconstruction, the earliest portion of chronology data prior to 1752 was disregarded on the

Table 1. Statistical characteristics of tree-ring series

	Ring width	Minimum density	Maximum density	Mean density
Measurements				
Number of trees (cores)	20 (40)	19 (31)	19 (31)	19 (31)
Width (mm) or density (g/cm^3)	1.22	0.25	0.60	0.36
Overall-mean sensitivity	0.14	0.07	0.07	0.05
Mean correlation within tree[a]	0.74	0.36	0.32	0.46
Mean correlation among trees[a]	0.54	0.14	0.23	0.19
Standardized chronologies				
Fitting curves for detrending	Neg. exp. or linear	Linear	Linear	Linear
Mean correlation among trees[a]	0.26	0.12	0.23	0.21
Site chronology				
Time span	1717–2000	1717–2000	1717–2000	1717–2000
Standard deviation	0.13	0.04	0.05	0.04
Mean sensitivity	0.09	0.04	0.04	0.03
First-order autocorrelation	0.62	0.35	0.44	0.26
Expected population signal (EPS)	0.87	0.72	0.86	0.83
No. of trees for subsample signal strength (SSS) $\geqslant 0.8$	7	10	7	8
Period where SSS $\geqslant 0.8$	1752–2000	1790–2000	1780–2000	1781–2000

[a]Calculated for the common interval of 1840–2000.

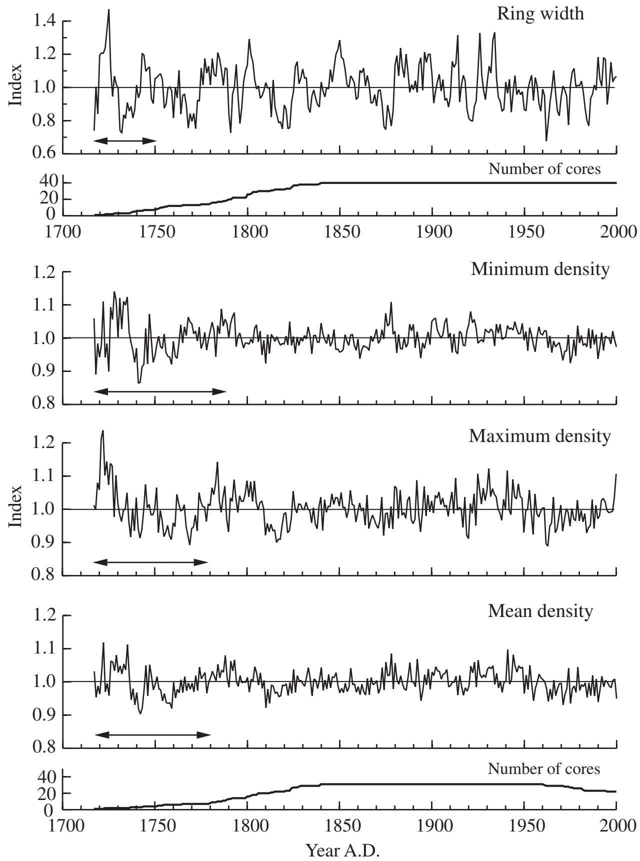

Fig. 2. Site chronologies of *Abies spectabilis*. The periods where subsample signal strength (SSS) <0.8 are indicated by arrows.

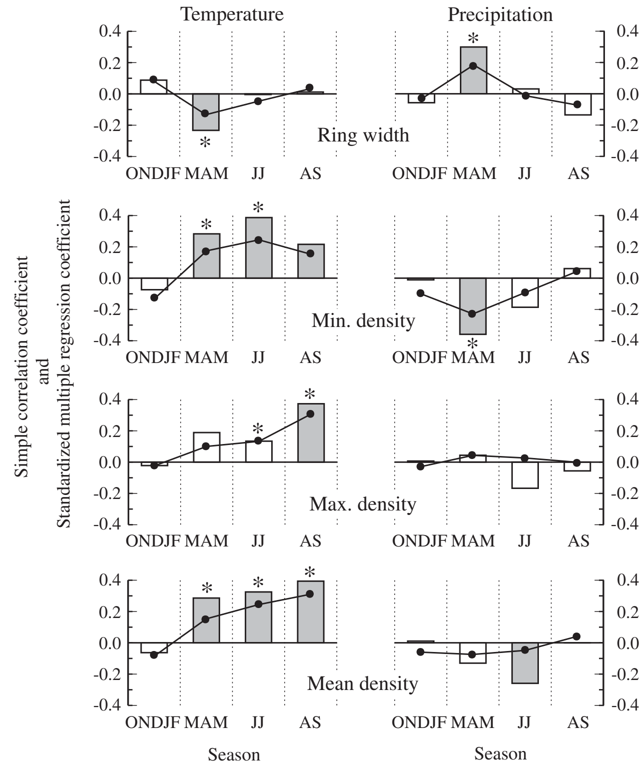

Fig. 3. Response of tree growth to seasonal temperature and precipitation. Columns indicate simple correlation coefficients with shade representing significance at 5%. Lines indicate orthogonalized multiple regression coefficients converted back so as to correspond with the original season. Asterisks indicate significance also at 5%. Seasons as follows: ONDJF, winter; MAM, pre-monsoon; JJ, early monsoon; AS, late monsoon.

basis of SSS<0.8 in ring-width chronology. The uncertainty at the first year of reconstruction, i.e., 1752, in terms of SSS was 0.56, 0.71 and 0.68, respectively, for minimum, maximum and mean densities.

Response analysis

Fig. 3 shows response of the four tree-ring parameters to seasonal temperature and precipitation in terms of simple correlation and standardized multiple regression coefficients. Simple correlation is represented by columns with shade indicating significance at the 5% level, while multiple regression coefficients by lines with asterisks indicating significance also at the 5% level. As a whole, tree growth is influenced in one way or another by the climate of growing season, i.e., of March to September, but not by that of winter. More specifically, the ring width is influenced by the climate of only pre-monsoon (March–May) season, while the wood densities are collectively influenced by that of the entire growing season.

Tree-ring width controlled solely by pre-monsoon climate was correlated negatively with temperature and positively with precipitation, indicating that moisture availability in this season limits tree growth as shown in Fig. 4. This figure represents mean monthly temperature at sampling site as estimated by applying the lapse rate of air temperature (i.e., −0.5 °C per 100 m) to Mukteshwar records and monthly precipitation of East Uttar Pradesh, India. While the temperature rises sharply from March through May, the rainfall lags behind by some months causing water deficit, and suppressing tree growth. Similar response of ring width was also found in several coniferous species from the Indian Himalayans farther west (Borgaonkar et al., 1994, 1999). In view of another fact that the minimum density of the earlywood was correlated positively with March–July temperature and negatively with March–May precipitation, moisture deficit in early stage of growing season probably suppressed cell enlargement resulting in increased density as Fritts (1976) reasoned. More specifically, the suppression of cell enlargement in earlywood corresponds to reduction in lumen size of earlywood cells, resulting in higher density since the proportion of cell

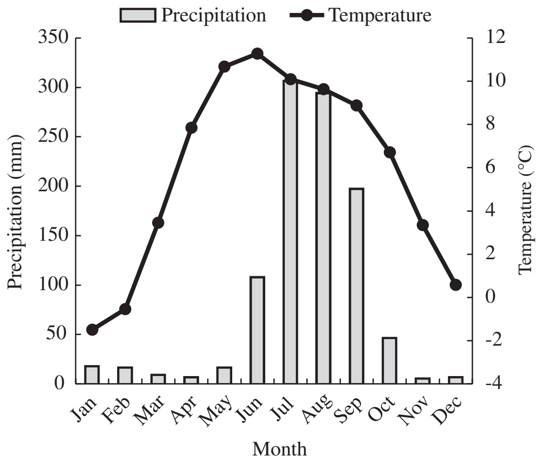

Fig. 4. Mean monthly temperature at sampling site as estimated by applying the lapse rate of temperature to Mukteshwar records and monthly precipitation for East Uttar Pradesh, India.

wall increases. On the other hand, the suppression results in narrower width of annual ring since the sum of cell diameters in the radial direction represents ring width. Pant et al. (2000) also indicated a similar mechanism of interaction among pre-monsoon climate, ring width and minimum density in *C. deodara* from the western Himalayas by presenting a micrograph of narrow and normal rings.

The maximum density showed a positive association with temperature of late monsoon (August–September) period when latewood is formed but no association with precipitation. This can also be explained as an increase in density due to inhibited growth in cell size as was the case with the earlywood. However, reduction in cell size is not the only way of increasing density, which can also occur by simple thickening of cell wall without any alteration in cell size. As a matter of fact, Yasue et al. (2000) reported that variations in maximum density of *Picea glehnii* Mast. growing in Hokkaido, northern Japan, were due largely to differences in cell-wall thickness of last-formed tracheids of the year, which is positively correlated with temperature in summer when the cell wall is thickening. Whichever the case, this point is unsettled in the present study. Significantly correlated with the climate of the entire growing season, i.e., with March–September temperature and June–July precipitation, the mean density makes a good indicator for reconstructing climate throughout the growing season.

In closing this section, it can be concluded that the growing season (March–September) temperature and March–July precipitation are well represented by at least one of the tree-ring parameters, and thus suitable for reconstruction.

Climate reconstruction

In accordance with the discussion in the preceding section, March–September temperature and March–July precipitation can be theoretically reconstructed. More specifically, March–September temperature can be represented as a function of ring width, and minimum, maximum and mean densities. On the other hand, there are two alternatives for precipitation reconstruction, i.e., March–July precipitation taking all the significant correlations into account, or March–May precipitation dropping the rather weak correlation of June–July precipitation with the mean density. Thus three transfer functions of the form:

$$T_{3-9} = a\mathrm{RW} + b\mathrm{MND} + c\mathrm{MXD} + d\mathrm{MAD} + e, \quad (1)$$

$$P_{3-7} = f\mathrm{RW} + g\mathrm{MND} + h\mathrm{MAD} + i, \quad (2)$$

$$P_{3-5} = j\mathrm{RW} + k\mathrm{MND} + l, \quad (3)$$

where T_{3-9} the March–September temperature, P_{3-7} the March–July precipitation, P_{3-5} the March–May precipitation, RW, MND, MXD, MAD the ring width, and minimum, maximum and mean densities, and *a*–*l* the multiple regression coefficients, were subjected to the *F*-test of significance using the entire climate records available, i.e., of 1898–1991. It turned out that Eqs. (1) and (3) significantly represented tree ring–climate relationship at the 0.1% level, while Eq. (2) did so at only the 5% level. Thus in the following analysis Eq. (2) was dropped and only Eqs. (1) and (3) were considered to represent temperature and precipitation, respectively.

For a more rigorous calibration, the entire period of the climate records was divided into early and late halves, and *F*-tests of significance were conducted individually for each section. It turned out that the temperature transfer function was highly significant at 1% for the early half of the calibration period and at 0.1% for the late half (Table 2). On the other hand, the precipitation transfer function was highly significant at 0.1% for the early half, but turned out to be non-significant for the late half, indicating inadequacy of the transfer function for precipitation reconstruction for the entire period, forcing us to abandon precipitation reconstruction.

Then the temperature transfer function was further scrutinized, in which temperature reconstructed by the transfer function calibrated with tree-ring parameters of the calibration period was tested against the observed temperature of the verification period. Following the normal procedure of dendroclimatology, exactly half the period of available climatic records was assigned as the calibration period, and the remaining half as the verification period. The test was repeated switching the calibration and verification periods around. This verification test was conducted in three ways, i.e., test of

Table 2. *F*-tests of significance on transfer functions

Climatic variable and season	Calibration period	*F*-value	Multiple correlation coef.
Mar.–Sep. temperature	Entire period	7.94***	0.51
	Early half	5.61**	0.59
	Late half	7.99***	0.66
Mar.–May precipitation	Entire period	9.33***	0.41
	Early half	8.27***	0.52
	Late half	1.94^{ns}	0.28

Entire period: 1898–1991, early half: 1898–1944, and late half: 1945–1991.
*$p<0.05$, **$p<0.01$, ***$p<0.001$, and ns: non-significant.

Table 3. Verification statistics on temperature transfer functions

Verification period	Correlation coefficient	Reduction of error	Sign test (±)
1961–1991	0.52**	0.26[a]	22/9*
1898–1928	0.53**	0.23[a]	22/9*

*$p<0.05$, **$p<0.01$.
[a]RE>0.

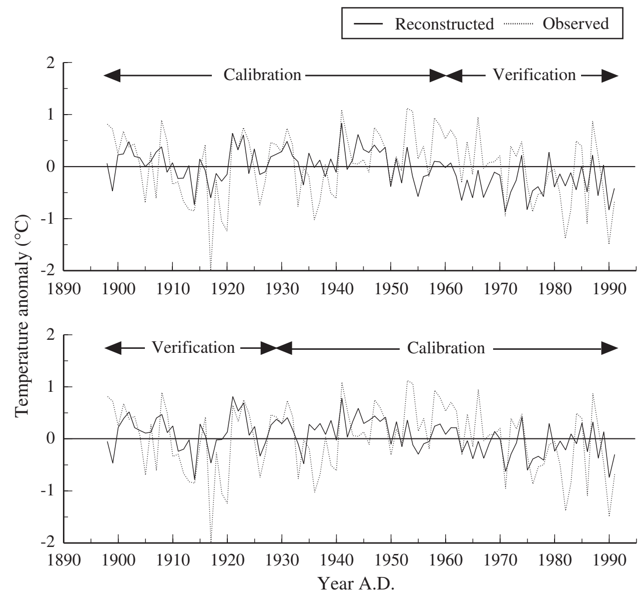

Fig. 5. Observed and reconstructed mean March–September temperature, as deviations from the 1898 to 1991 observed mean.

correlation between reconstructed temperature and its observed counterpart, in terms of reduction of error (RE) and sign test. Further details of these tests are given in Fritts (1976). Although both the test of correlation and sign test turned out to be significant, only the RE statistics came up with negative values and failed to qualify. Alternatively, the calibration period was increased to 2/3 of the period of available climatic records at an expense of the verification period, resulting in two calibration periods of 1898–1960 and 1929–1991 with respective verification periods of 1961–1991 and 1898–1928.

For these altered periods of calibration and verification, the temperature transfer function turned out to be significant with the multiple correlation coefficient of 0.49 (1%) for the first calibration period, and of 0.52 (0.1%) for the second period. Using these two transfer functions, verification of temperature reconstruction was conducted with the result given numerically in Table 3 and graphically in Fig. 5 as a comparison between observed and estimated growing season temperatures. All the verification statistics turned out to be significant, indicating the validity of the transfer function for temperature reconstruction for the entire period of tree-ring chronologies.

The resultant March–September temperature reconstructed for the period from 2000 back to 1752 is shown in Fig. 6a. It shows a warming trend from 1750s until approximately 1790, followed by cooling until 1810, then by a gradual warming trend extending to 1950, and a notable cold period continuing up to the present.

This reconstruction was compared with the one of Cook et al. (2003), which represents February–June temperature derived from a dense tree-ring network covering Nepal (Fig. 6b), though they are not perfectly matched with respect to reconstructed season and method of chronology development. As a whole, the multi-decadal to century-scale warming and cooling trends appearing in our reconstruction are shared. Another common feature appearing in both reconstructions is a sharp cold period centered in 1810s, which according to Cook et al. (2003) is attributable to the eruption of Tambora in 1815–1816 and another unknown eruption in 1809–1810 (Dai et al., 1991).

These two reconstructions also share the cool period of the last half of the 20th century with other climate reconstructions in the Himalayas, i.e., that of Hughes (1992) in Kashmir and of Yadav et al. (1999) in Garhwal. Another common feature in all these reconstructions in the Himalayan region is lack of consistent warming trend over the last century or two appearing in many dendroclimatic reconstructions in higher latitudes (e.g., Jacoby and D'Arrigo, 1989; Sweda, 1994; Briffa et al., 1995; MacDonald et al., 1998; Hughes et al., 1999).

The present climate reconstruction helps to narrow down the possible cause of glacial retreat widely observed throughout the Nepal Himalayas (e.g., Yamada et al., 1992; Fujita et al., 1997; Naito, 2001; Asahi, 2001). Generally speaking, it is either a significant

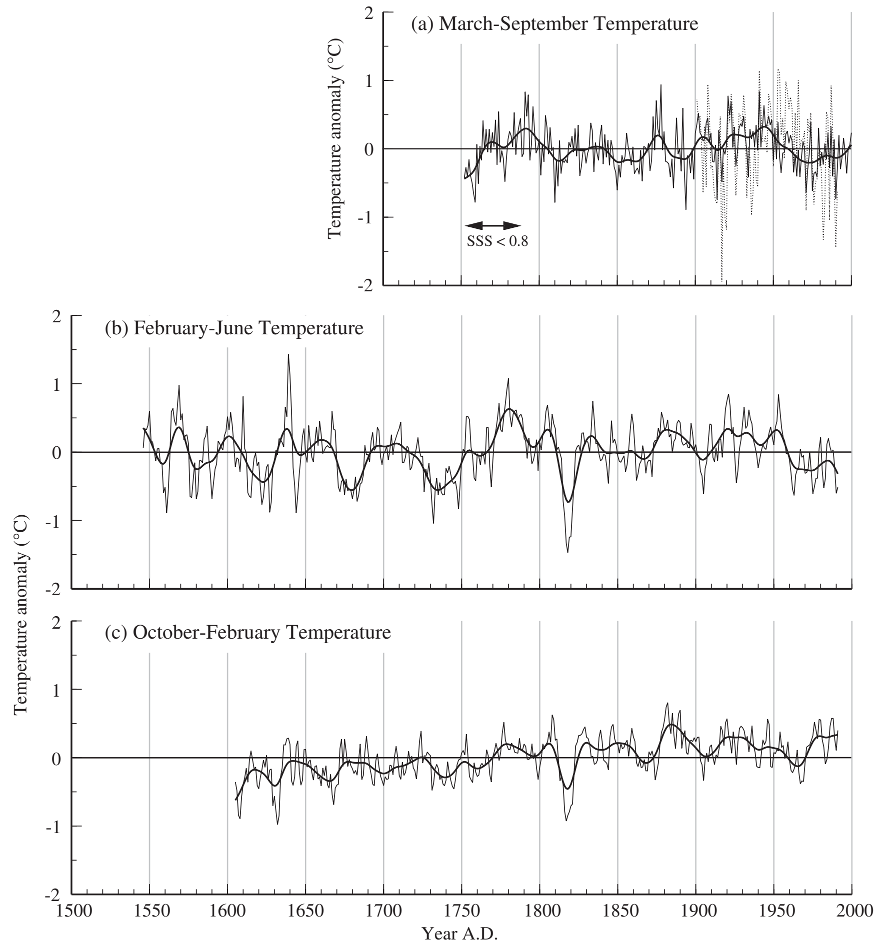

Fig. 6. Reconstructed mean temperatures, as deviations from the long-term means: (a) March–September with observed data (dotted line) in this study; (b) February–June and (c) October–February in Cook et al. (2003); (http://www.ncdc.noaa.gov/paleo/pubs/cook2003/cook2003.html). Thick curves show low-pass filtered values.

rise in temperature or decline in precipitation that can cause such massive and widespread glacial retreat. The present result eliminates the possibility of rise in summer temperature, while the all-India rainfall data (Parthasarathy et al., 1995) neither show any significant decline in both summer and winter precipitation over the last century. This leaves warming winter as the most likely cause of retreating glaciers. As a matter of fact, another reconstruction of October–February temperature by Cook et al. (2003) for Nepal shows general warming trend over the past 400 years (Fig. 6c). Additionally, observation-based temperature analysis over the Indian subcontinent (Hingane et al., 1985) also supports this inference of warming winter provided that it also applies to Nepal.

Conclusion

Continued effort toward the development of a tree-ring network consisting of not only ring width but also intra-annual density across the Nepal Himalayas would lead us to reconstruction of regional climate of higher quality, and help us to understand the mechanism of climate variability in the Himalayan region including the one of glacial retreat. In the present study, *A. spectabilis* turned out to be suitable for climate reconstruction since each tree-ring parameter showed strong association with climatic factors. More intensive search for undisturbed old forests of *A. spectabilis* deep into the foothills of the Himalayas may well result in an extension of climate reconstruction by a few hundred years.

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