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Tree ring evidence of late summer warming in Sikkim, northeast India

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ABSTRACT

The impact of climate change in high-elevation areas is acknowledged to have wide ranging implications on environment relevant to human society. However, our understanding of climate change in the high-elevation eastern Himalayan region is hampered due to temporally and spatially limited weather records. Using ring-width chronology of larch (*Larix griffithiana)* from high-elevation North Sikkim, we developed mean late summer (July–August–September (JAS)) temperature reconstruction extending back to AD 1852. The reconstructed mean JAS temperature shows warming since the 1930s, with 1996–2005 being the warmest in context of the past ~150 years. We found that the warming trend reported here is consistent with other climate change indicators such as plant species migration to higher ranges and accelerated glacier retreats in Sikkim. Temporal and spatial extent of such annually resolved records need to be expanded for the data scarce eastern Himalayan region to understand regional variability and feedbacks in climate.

1. Introduction

The annually resolved long-term proxy climate records are important to understand climate change patterns in the pre-instrumental period. Such high-resolution long-term records developed from different regions of the Earth have helped in understanding regional and global signatures of climate change during the Medieval Warm Period (MWP) and Little Ice Age (LIA) (Mann and Jones, 2003). The high-resolution well calibrated proxy climate records from different geographic regions of the northern and southern hemispheres have provided the indispensable baseline data for placing the contemporary warming in a long-term context (Wiles et al., 2014). However, the availability of such high-resolution proxy climate records from the mid-latitude regions of Asia dominated by high-mountain orography referred to as the "Third Pole" (Qiu, 2008) has large geographic bias (Cook et al., 2010). In view of the high-spatial variability in climate under the dominant orographic influence, a dense network of data from the Third Pole region is essentially required to understand climate dynamics in global perspective. The weather records from the Himalayan region in northeast of India are very sparse and limited to the past few decades except in occasional cases where they extends to the beginning of the past century. High-resolution long-term proxy climate records from this region should help in understanding the relevance of regional forcing and feedbacks. The present study is an important step forward in fulfilling this climate data void from the eastern Himalayan region of Sikkim, northeast India.

The weather records from Sikkim are available only for Gangtok and Tadong, which extend to the late 1960s. The data show that the day temperature over the region has decreased and night temperature increased during the recorded period (Seetharam, 2008). Contrary to the trends indicated in these short term weather records, the climate change indicators such as plant phenological and species distribution changes (Telwala et al., 2013), glacier dynamics (Raina, 2009) and changes in cropping patterns over high elevation regions in Sikkim have revealed distinct signatures of unprecedented warming in the last century.

The annually resolved tree-ring-based climate records from Sikkim, a biodiversity hot spot region in northeast India, are few and do not provide low-frequency variations in reconstructed data (Bhattacharyya and Chaudhary, 2003; Shah et al., 2014). To improve our understanding of the natural variability in climate in long-term context high-resolution long-term proxy climate records are

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required. For this purpose we for the first time developed ring-width chronology of larch (*Larix griffithiana* (Lindl. *et* Gord.) Hort ex Carr.) by using a Regional Curve Standardization (RCS) method to maximize low-frequency variations in mean series. Based on a significant relationship in ring-width series and mean JAS temperature, we developed late summer temperature reconstruction extending ~150 years (AD 1852–2005).

2. Data and methods

2.1. Tree-ring data

Larch, a constituent of Northern Hemispheric flora, is the only deciduous conifer growing in Arunachal Pradesh, Darjeeling and Sikkim regions of India at elevations ranging from 2400 to 3650 m asl (Raizada and Sahni, 1960; Sahni, 1990). The tree-ring studies of this taxon from northeast India (Chaudhary and Bhattacharyya, 2000; Shah et al., 2014) have revealed the potential of developing annually resolved climate records. For the present study, we collected increment core samples in 2007 summer from 20 larch trees each growing over rocky terrains in Lachen (2660 m asl) and Lachung (2615 m asl) valleys respectively in North Sikkim (Fig. 1). Usually one core targeting the centre of stem was taken from each tree, except in cases when pith region was missed. Ecological settings of rocky terrains with thin soil make the trees experience soil moisture stress when precipitation is not homogeneously distributed throughout the growing season. The warm summers enhancing evapotranspiration also compound the soil moisture deficit over such rocky terrains.

The growth rings in larch are very distinct with clear demarcation of early and late wood cells. Such a clear anatomical distinction of early and late wood cells has allowed development of early and late wood width chronologies of larch (Shah et al., 2014). However, in our present study we considered whole ring-width measurements, as demarcation of early and late wood boundaries are occasionally very subjective especially in the case of young age trees where early and late wood transition is very gradual. The growth ring sequences in increment cores were precisely dated using the skeleton plotting method (Stokes and Smiley, 1968). The ring widths in precisely dated samples were measured to 0.01 mm resolution using the LINTAB measuring system. The dating of growth ring sequences was verified using computer assisted dating software COFECHA (Holmes, 1983) and TSAP (Rinn, 1991). Very good matching in ring-width measurement plots of cores from the same and different trees as well significant correlations among tree-ring series (mean $r = 0.46$ in all 39 series selected for this study with master series in COFECHA) revealed strong common forcing, i.e., climate affecting the radial growth of trees over different locations in North Sikkim. Due to the existence of very good cross-dating and year-to-year similarity in ring-width measurements, the tree-ring data from two sites were grouped to prepare the mean chronology.

The ring-width measurement data were processed using the signal-free Regional Curve Standardization (RCS) method to maximize low-frequency variations in the mean chronology. The signal-free approach of RCS has advantage over the traditional methods, as in this procedure loss of climatic information due to the problem of trend-in-signal is minimized (Melvin and Briffa, 2008). To produce signal-free functions used in detrending, RCS_Sig_Free software (Cook et al., 2011) was used. Under this procedure, ring-width measurement series aligned according to their biological age were averaged after applying the data adaptive power transformation (Cook and Peters, 1997). This mean series, which represents the biological growth function of population, was smoothed using a 10 year cubic spline function with a 50% frequency response cut off. This fitted curve was used to calculate residuals from individual tree sample measurements. The detrended series thus derived were averaged by applying the biweight robust mean method to develop a regional mean chronology. To obtain signal-free chronologies, the chronology construction was repeated iteratively with RCS curves built using signal-free measurement series. The iterative processes were set to stop when the robust median absolute differences between successive signal-free chronologies was ≤ 0.0001. The final RCS chronology of larch spanning from AD 1760–2006 is based on 39 series where 20 series reached the median series length of 126 years. The running correlation between all possible series in a 50-year window with 25-year overlap (rbar) and expressed population signal (eps) statistics were also

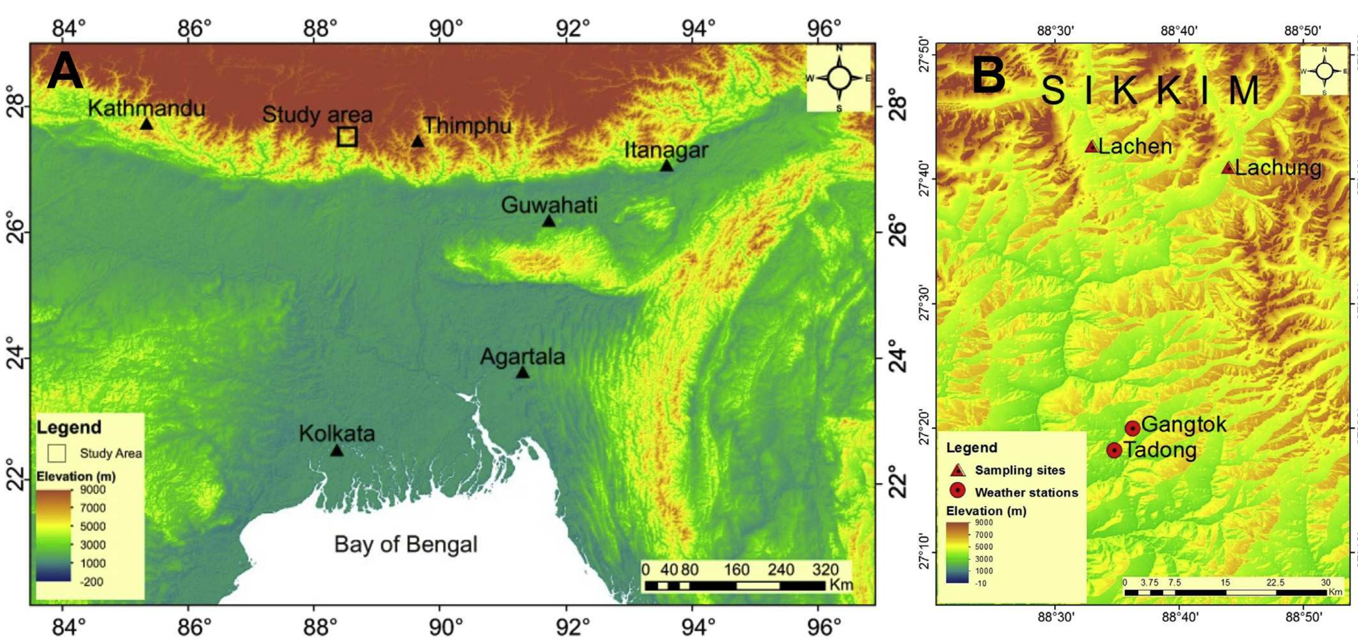

Fig. 1. Map of the study area. A. General location map of the area, B. tree-ring sampling sites and weather stations used in study.

calculated to estimate the changing common signal strength in mean chronology over time as a function of change in number of tree samples. Though the mean ring-width chronology extended to AD 1760, the eps threshold value above 0.85 (Wigley et al. 1984) reached to AD 1852 only (Fig. 2). Taking both eps and rbar statistics into account, the chronology extending to AD 1852 was taken for dendroclimatic studies.

2.2. Climate data

Sikkim in northeast India, as a function of varying orography, experiences different types of climate from sub-tropical to alpine. The weather records from Sikkim are available only for Gangtok (27°20′20″N 88°36′23″E; 1460 m asl) from 1966 and Tadong (27°18′38″N 88°35′51″E; 1321 m asl) from 1979 onwards. The mean monthly climate data of Gangtok prepared by the India Meteorological Department (1966–2000) show an extended period of summer rainfall from May to September and mean monthly temperature above 15 °C from April to October (http://www.imd.gov.in/; Fig. 3). January is the coldest month with mean temperature 8.4 °C and August the hottest with mean temperature reaching 19.5 °C. For the tree growth climate relationship study, we developed mean temperature and precipitation series developed by merging the data records from Gangtok and Tadong. We also used mean regional temperature series for the northeast Indian region prepared by the Indian Institute of Tropical Meteorology, Pune (ftp://www.tropmet.res.in/pub/data) and gridded (CRUTS3.22 (land) data available via http://climexp.knmi.nl) to understand the relationship with our tree-ring data.

2.3. Climate signal in tree-ring chronology

The signal-free RCS chronology of larch (AD 1852–2006) was correlated with mean temperature and precipitation data available for Gangtok and Tadong weather stations in northeast India. To understand the strength of climate signal in chronology bootstrapped correlation functions (Biondi and Waikul, 2004) were calculated using monthly precipitation and mean monthly temperature of the meteorological stations from September of the previous growth year to current year September from AD 1979–2003. We noted a significant negative relationship between tree-ring chronology and mean temperature of July, August, and September. However, no significant relationship was noted with precipitation data. The correlation study revealed that larch growth on rocky ecological settings is favored by cooler summers as warm temperatures could result in soil moisture deficit due to enhanced evapotranspiration. The shallow root system and very thin soil cover over the rocky sites make the trees liable to moisture stress.

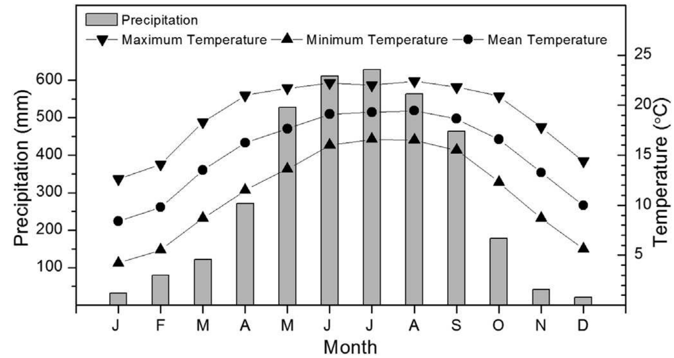

Fig. 3. Monthly precipitation and mean monthly temperature variations over Gangtok, Sikkim.

In view of the existence of similar relationship between tree-ring indices and climate data, the correlations were also calculated with mean climate data series prepared after merging the Gangtok and Tadong data sets. The mean climate series of the two stations (precipitation and temperature) showed the existence of a significant negative relationship with July–August–September temperature. However, no significant relationship was noted with precipitation (Fig. 4). We prepared mean July–August–September temperature series of two stations after normalizing the two series relative to the common period 1979–2003 for further studies. The regional mean temperature series of northeast India also indicated a similar relationship with ring-width chronology during 1979–2003, as noted independently with Gangtok and Tadong temperature series. However, the gridded weather data for this region (CRUTS3.22 did not reveal a significant relationship with the ring-width chronology of larch. In view of the significant relationship noted between ring-width chronology and mean JAS temperature series ($r = -0.63$, $p < 0.001$, 1979–2003) we developed a reconstruction back to AD 1852.

2.4. Reconstruction of mean late summer (JAS) temperature

After establishing a significant relationship between ring-width chronology of larch and mean JAS temperature, we adopted a linear regression approach to develop temperature reconstruction. The predictor chronology variables of t0 and t+1 were tested for their relationship with mean summer temperature. t0 and t+1 chronology variables showed significant correlations with the target mean JAS temperature series ($p < 0.05$, 1979–2003). The principal component analysis of the two chronology variables (t0, t+1) using

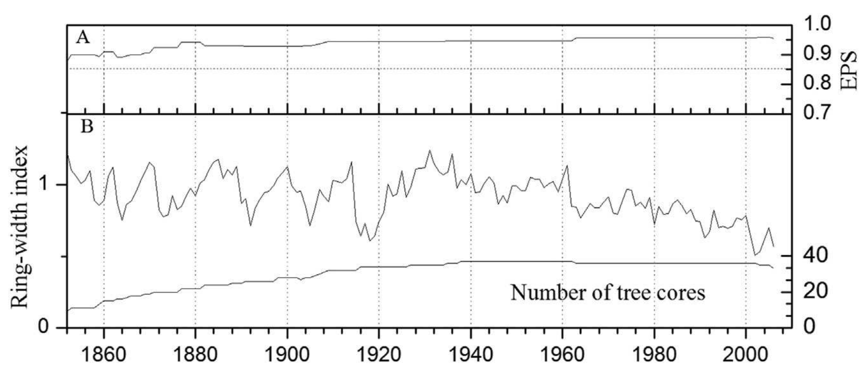

Fig. 2. Ring-width chronology of larch (AD 1852–2006) used in reconstruction of mean late summer temperature. A. EPS variation over the chronology period, B. Ring-width chronology with the number of tree core samples used.

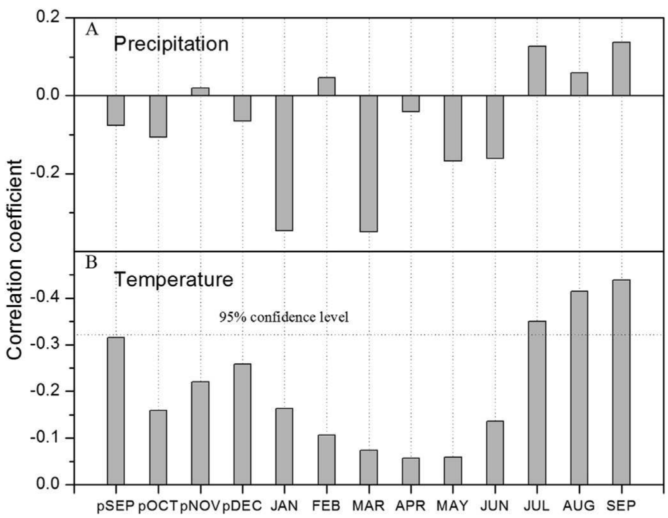

Fig. 4. Correlation functions of ring-width chronology with monthly precipitation (A) and mean monthly temperature (B) (bars above dotted lines are significant at 95% confidence level).

varimax method showed 88% common variance in the first principal component (PC#1) with eigenvalue 1.772. The PC#1 showing significant correlation with the mean JAS temperature series (−0.68, $p = 0.0002$, 1979–2003) was first attempted to develop a temperature reconstruction using a linear regression approach. However, due to the short length of available weather data, the leave-one-out approach (Michaelsen, 1987) was adopted in calibration and verification studies. Under this method, the linear regression models for each year were successively calibrated from remaining observations and then used to estimate the mean JAS temperature value for the year omitted at each step. This resulted in 25 predicted mean JAS temperature values, which were compared to the observed temperature data to compute validation statistics of model accuracy and error (Table 1). The significant statistics obtained in leave-one-out calibration approach denoted statistical skill in mean JAS temperature reconstruction. The reconstructed mean JAS temperature series developed this way revealed close similarity and significant correlation with the observed mean JAS temperature ($r = 0.59$, $p < 0.0019$, 1979–2003). On establishing the fidelity of this calibration-verification model, we used a full period linear regression model (1979–2003) to develop the mean JAS temperature reconstruction.

Table 1
Calibration verification statistics.

Calibration		Verification				
Period	ar^2 [%]	Period	R	T-value	Sign test	RE
1979–2003 L1	32	1979–2003L1	0.59	3.06	$19^+/6^-$	0.33
1979–2003	61		[0.0019]	[0.0095]	[0.0146]	

$ar^2 - r^2$ adjusted after degrees of freedom, R- Pearson correlation, Sign test, T-value (Product mean T value) and RE (reduction of error), L1-cross-validation using Leave-one-out method (Fritts, 1976). The p values are in brackets.

The calibration and verification statistics, such as the reduction of error (RE), Sign test, and Pearson correlation coefficient (Fritts, 1976) were used to test the significance and fidelity of the reconstruction (Table 1). However, in this process we noted that the residuals had significant first order autocorrelation ($r = 0.46$, $p = 0.04$). Such a heteroscedastic nature of the residuals violated the assumption that in a classical linear regression model the residuals should be independent of each other. When the ordinary regression residuals are not independent, they contain information that could be used to improve the predictions. To overcome this problem in reconstruction, we applied an autoregressive error correction model that takes the heteroscedasticity into account. For this, we used generalized autoregressive conditional heteroscedasticity (GARCH) model of maximum likelihood method to correct for autocorrelation (Bollerslev, 1986). The GARCH model at lag 1 with significant p values capturing 61% variance in the instrumental mean JAS temperature data (1979–2003) was used in reconstruction. This reconstructed mean JAS temperature was compared with regional temperature series of northeast India for additional validation of the reconstruction model. The reconstructed mean JAS temperature series showed a significant relationship with the regional mean JAS temperature series of northeast India ($r = 0.71$, 1973–2005). However, the correlations were very weak back to 1973, indicating the use of limited station data in regional temperature series, which do not reflect the regional signatures of mean JAS temperature over Sikkim.

3. Results and discussion

3.1. Analyses of reconstructed mean JAS temperature

The reconstructed mean JAS temperature extending back to AD 1852 (Fig. 5) superimposed with 10 year low pass filter revealed decadal-scale warm and cool epochs. The data presented here provide the first tree-ring-based reconstruction showing low-frequency variations in mean JAS temperature. The mean JAS temperature reconstruction reported earlier for this region of India (Bhattacharyya and Chaudhary, 2003) did not reveal low-frequency variations as tree-ring data were processed using methods to focus on high-frequency variations. However, the decadal-scale warm and cool episodes recorded in our data are consistent with the mean JAS temperature reconstruction reported earlier by Bhattacharyya and Chaudhary (2003).

The temperature reconstruction revealed warm JAS in 1915–1919, after which the temperatures dipped for around a decade and warming gained momentum since the 1930s (Fig. 5, Table 2). The 10-year running mean of the mean JAS temperature reconstruction revealed 1996–2005 being the warmest (mean anomaly 0.56 °C) and 1927–1936, the coolest (mean anomaly −2.57 °C). The rapid pace of warming revealed in our data is also consistent with the rate of warming recorded in mean JAS temperature (0.05 °C/year) over Sikkim, the highest in the Indian region (Rathore et al., 2013). Such a rapid pace of warming revealed in weather data from Sikkim consistent with the mean JAS temperature reconstruction is also supported by other environmental change indicators during the last century (Raina, 2009; Telwala et al., 2013). Nearly 90% of the endemic plant species of alpine Sikkim Himalaya are reported to have shifted to higher elevation ranges in the last century and this shift is assumed to be driven by rise in temperature (Telwala et al., 2013). The glaciers in Sikkim region have also retreated at considerably high rate (~13.02 m/year) during 1976–2005 (Raina, 2009). The observational records of Zemu glacier over the 20th century indicate an alarming retreat of ~863 m during 1909–2005 (Raina, 2009). The trend in warming reported here could be a regional feature as most of the glaciers in humid regions of Nepal, sensitive to temperature fluctuation, are also showing accelerated wastage over the last few decades (Fujita and Nuimura, 2011). The presence of such strong regional climatic signatures in our data reported here show that high-resolution

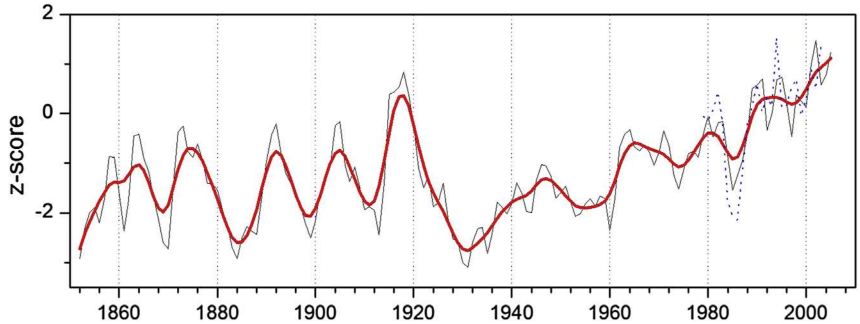

Fig. 5. Mean late summer (July–August–September) temperature reconstruction (AD 1852–2005) for North Sikkim, eastern Himalaya overlaid with 10-year low pass filtered version (thick line).

proxy records developed from a close network of sites in the eastern Himalayan region should be very useful to understand spatial and temporal features of current warming.

Table 2
5- and 10-year mean JAS temperature anomalies

5-year mean anomaly				10-year mean anomaly			
Cool		Warm		Cool		Warm	
1852–1856	−2.26	1915–1919	0.51	1852–1861	−1.87	1914–1923	−0.29
1883–1887	−2.55	1991–1995	0.36	1880–1889	−2.26	1975–1984	−0.58
1928–1932	−2.55	1996–2000	0.10	1927–1936	−2.57	1985–1994	−0.20
1933–1937	−2.33	2001–2005	1.02	1951–1960	−1.84	1996–2005	0.56

4. Conclusions

We developed ring-width chronology of larch (*L. griffithiana* (Lindl. *et* Gord.) Hort ex Carr.) extending back to AD 1760 using increment core samples collected from trees growing over two homogeneous ecological settings in North Sikkim in the eastern Himalayan region of India. The ring-width measurement data were processed using a signal-free Regional Curve Standardization (RCS) method to maximize the low-frequency variations in the mean chronology. Though the larch chronology reported here extended back to AD 1760, statistically sufficient sample replication was available to 1852 only. Tree-growth climate relationship study revealed that mean JAS temperature adversely affected the growth of larch trees over the rocky ecological settings in North Sikkim. In view of the significant relationship noted between ring-width chronology and mean JAS temperature series of Gangtok and Tadong, we developed temperature reconstruction extending back to AD 1852 using a non-linear regression approach that took autoregressive error correction into account. The reconstruction model accounting 61% of the variance in observational data is the strongest so far from northeast India. This also provides the first tree-ring-based reconstruction from North Sikkim, showing low-frequency variations in mean JAS temperature.

The most revealing feature in the mean JAS temperature reconstruction presented here is the increasing trend in temperature since the early 1930s. The 10-year running mean of the temperature reconstruction revealed 1996–2005 as the warmest period (mean anomaly 0.56 °C) in past ~150 years. The warming trend revealed in JAS temperature reconstruction is consistent with the upward shift in ecological range of alpine plant species and retreat of glaciers in Sikkim. We are optimistic that the present report should catalyze efforts to develop a network of climate responsive tree-ring chronologies from difficult terrains of the eastern Himalayan region of India. Such annually resolved long-term records should provide benchmark data for the data scarce eastern Himalayan region to improve our understanding of spatial and temporal features of current warming.

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References

Bhattacharyya, A., Chaudhary, V., 2003. Late-summer temperature reconstruction of the eastern Himalayan region based on tree-ring data of *Abies densa*. Arctic Antarctic Alpine Research 35, 196–2002.
Biondi, F., Waikul, K., 2004. DendroClim2002: a C++ program for statistical calibration of climate signals in tree-ring chronologies. Computers Geosciences 30, 303–311.
Bollerslev, T., 1986. Generalized autoregressive conditional heteroscedasticity. Journal Econometrics 31, 307–327.
Chaudhary, V., Bhattacharyya, A., 2000. Tree ring analysis of *Larix griffithiana* from the Eastern Himalayas in the reconstruction of past temperature. Current Science 79, 1712–1716.
Cook, E.R., Anchukaitis, K.J., Buckley, B.M., D'Arrigo, R., Jacoby, G.C., Wright, W.E., 2010. Asian Monsoon failure and megadrought during the last Millennium. Science 328, 486–489.
Cook, E.R., Krusic, P.J., Holmes, R.H., Peters, K., 2011. Program ARSTAN Ver.44a, 2011. www.ldeo.columbia.edu/tree-ring-laboratory.
Cook, E.R., Peters, K., 1997. Calculating unbiased tree-ring indices for the study of climatic and environmental change. The Holocene 7, 361–370.
Fritts, H.C., 1976. Tree Rings and Climate. Academic Press, London.
Fujita, K., Nuimura, T., 2011. Spatially heterogeneous wastage of Himalayan glaciers. Proceeding National Academy of Sciences, USA 108, 14011–14014.
Holmes, R.L., 1983. A computer-assisted quality control program. Tree-Ring Bulletin 43, 69–78.
Mann, M.E., Jones, P.D., 2003. Global surface temperatures over the past two millennia. Geophysical Research Letters 30. http://dx.doi.org/10.1029/2003GL017814.
Melvin, T.M., Briffa, K.R., 2008. A "Signal-Free" approach to dendroclimatic standardisation. Dendrochronologia 26, 71–86.
Michaelsen, J., 1987. Cross-validation in statistical climate forecast models. Journal of Climate and Applied Meteorology 26, 1589–1600.
Qiu, J., 2008. The third pole. Nature 454, 393–396.
Raina, V.K., 2009. Discussion Paper on Himalayan Glaciers: a State-of-Art Review of Glacial Studies, Glacial Retreat and Climate Change. Ministry of Environment and Forests, Govt. of India, New Delhi.
Raizada, M.B., Sahni, K.C., 1960. Living Indian Gymnosperms. Part 1 (Cycades, Ginkgoales and Coniferales). Indian Forest Records 5, 1–150.
Rathore, L.S., Attri, S.D., Jaswal, A.K., 2013. State Level Climate Change Trends in India: Meteorological Monograph No. ESSO/IMD/EMRC/02/2013. India Meteorological Department, Ministry of Earth Sciences, Government of India, p. 147.

Rinn, F., 1991. TSAP-win Time Series Analysis and Presentation for Dendrochronology and Related Applications. Version 0.53 for Microsoft Windows. Rinn Tech, Heidelberg, Germany.

Sahni, K.C., 1990. Gymnosperms of India and Adjacent Countries. Bishen Singh Mahendra Pal Singh, Dehradun, p. 169.

Seetharam, K., 2008. Climate change scenario over Gangtok. Mausam 59, 361–366.

Shah, S.K., Bhattacharyya, A., Chaudhary, V., 2014. Streamflow reconstruction of Eastern Himalaya River, Lachen 'Chhu', North Sikkim, based on tree-ring data of *Larix griffithiana* from Zemu Glacier basin. Dendrochronologia 32, 97–106.

Stokes, M.A., Smiley, T.L., 1968. An Introduction to Tree-ring Dating. The University of Chicago Press, Chicago.

Telwala, Y., Brook, B.W., Manish, K., Pandit, M.K., 2013. Climate induced elevational range shifts and increase in plant species richness in a Himalayan biodiversity. PLoS One 8, 1–8.

Wigley, T., Briffa, K.R., Jones, P.D., 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. Journal of Climate and Applied Meteorology 23, 201–213.

Wiles, G.C., D'Arrigo, R.D., Barclay, D., Wilson, R.S., Jarvis, S.K., Vargo, L., Frank, D., 2014. Surface air temperature variability reconstructed with tree rings for the Gulf of Alaska over the past 1200 years. The Holocene 24, 198–208.