Tree ring imprints of long-term changes in climate in western Himalaya, India

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Tree-ring analyses from semi-arid to arid regions in western Himalaya show immense potential for developing millennia long climate records. Millennium and longer ring-width chronologies of Himalayan pencil juniper (*Juniperus polycarpos*), Himalayan pencil cedar (*Cedrus deodara*) and Chilgoza pine (*Pinus gerardiana*) have been developed from different sites in western Himalaya. Studies conducted so far on various conifer species indicate strong precipitation signatures in ring-width measurement series. The paucity of weather records from stations close to tree-ring sampling sites poses difficulty in calibrating tree-ring data against climate data especially precipitation for its strong spatial variability in mountain regions. However, for the existence of strong coherence in temperature, even in data from distant stations, more robust temperature reconstructions representing regional and hemispheric signatures have been developed. Tree-ring records from the region indicate multi-century warm and cool anomalies consistent with the Medieval Warm Period and Little Ice Age anomalies.

Significant relationships noted between mean premonsoon temperature over the western Himalaya and ENSO features endorse utility of climate records from western Himalayan region in understanding long-term climate variability and attribution of anthropogenic impact.

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1. Introduction

Earth's climate has been constantly changing in the geological past. However, change in atmospheric chemistry due to enhanced anthropogenic activity during the past century has added to the impact of natural forcing on climate over an order of magnitude (Jansen *et al.* 2007). Recent warming indicated in observational and proxy records from high-latitude regions is unprecedented in context of the last millennium (Mann *et al.* 1999; Osborn and Briffa 2006). However, the extent of current warming shows strong spatial heterogeneity indicating the relevance of regional forcing factors (Bradley *et al.* 2003). Such spatial heterogeneity greatly necessitates the need to develop network of long-term high-resolution proxy climate records from low-to-high latitude regions of Earth. Besides, robust climate records also provide benchmark data for the verification of climate prediction models. In the Indian context the most glaring example of our inadequate understanding of climate system is reflected by inconsistency in climate projections of increased monsoon in warmer world contrary to the observed decrease in monsoon during the last three decades of the 20th century (Kripalani *et al.* 2003). In order to develop a better understanding of climate change in long-term perspective there is urgent need to develop robust high-resolution long-term climate records from different geographic regions to assign precise time brackets to these events.

Climate records from the Himalayan region, which has hemispheric linkage for its influence on monsoon system, are few and short. The high-resolution proxy records such as tree rings, ice cores and lake deposits provide valuable proxy climate record in the region to develop annual to seasonal scale climate state parameters. The state of climate over the region during Medieval Warm Period (Lamb 1965) and Little Ice Age (Grove 1988), the multi-century warm and cold episodes recorded in high-latitude regions are not well constrained in the Himalayan region. Although, pollen

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(Chauhan 2006) and glacier proxies (Sharma and Owen 1996) from the region show long-term shifts in climate during the past millennium, dating uncertainties associated with sediments preclude the assignment of precise date to these events. Tree-ring data from the Himalayan region should provide reliable high-resolution climate records with centennial scale variations.

The climate over the western Himalaya is largely semi-arid to arid and the growth of trees is limited by moisture stress. The tree-ring data from such areas are valued proxy of precipitation. But, paucity of observational records from areas close to tree-ring sites hampers the calibration of tree-ring chronologies. However, temperature has indirect influence on tree growth in terms of evapotranspiration exacerbating the moisture stress. Temperature, for the existence of strong coherence even across the valley floors, has been reconstructed using tree-ring data from sites located even far from the meteorological stations (Yadav *et al.* 2004). The precipitation and temperature reconstructions thus far available from the western Himalayan region extend back to past few centuries (Borgaonkar *et al.* 1994, 1996; Hughes 1992, 2001) and do not cover the span of Medieval Warm (Lamb 1965). However, millennium long tree-ring chronologies of several conifer species recently developed from western Himalaya indicate potential of developing long-term climatic reconstructions. Detailed accounts of such tree-ring chronologies of different species and multi-century reconstructions of precipitation and temperature developed from different regions in western Himalaya are presented here.

2. Millennial long tree-ring chronologies

The length of tree-ring chronologies depends on the longevity of trees as well as wood materials from archaic buildings and peat deposits. So far, wood materials utilized in developing tree-ring chronologies are largely from living trees growing in climate stressed sites in western Himalaya (figure 1). The longevity of tree species in western Himalaya has been found to be considerably high, extending more than thousand years (Singh *et al.* 2004; Yadav *et al.* 2006; Singh and Yadav 2007). In western Himalaya where moisture stress is the dominant tree growth deterrent, more than two millennia old trees of *Juniperus polycarpos* have been found. The other trees attaining age longer than millennium are of *Cedrus deodara* and *Pinus gerardiana* growing in moisture stressed sites. However, tree species preferring relatively wetter sites such as *Abies pindrow, A. spectabilis, Pinus wallichiana* and *Picea smithiana* are usually younger occasionally extending as long as 500-600 years. Millennium long climate responsive tree-ring chronologies developed so far from different sites are of *Juniperus polycarpos, Cedrus deodara* and *Pinus gerardiana.*

2.1 *Himalyan pencil juniper (*Juniperus polycarpos*)*

Himalayan pencil juniper is found in inner semi-arid regions of northwest Himalaya at altitudes ranging from 1500-4300 m. It is a cold and drought hardy tree growing in areas where annual rainfall is as low as around 300 mm (Raizada and Sahni 1960). Trees of this species usually grow in open stands with negligible inter-tree competition. Stem is usually lobed, resulting in wedging of growth rings. Strong wedging of growth rings results in a number of locally missing rings. The problem in dating of growth ring sequences in this species is high due to missing rings largely originating due to wedging and merging of several growth rings. However, stem discs offering larger area to track a specific ring along the tree circumference facilitates the dating of growth ring sequences. Using disc sample, chronology of this species as long as 1584 years (AD 420-2003) in length was prepared from Lahaul and Spiti region, Himachal Pradesh (Yadav *et al.* 2006). However, this chronology with strong annual-to-decadal scale variations lacked low frequency variations. To develop mean tree-ring chronology with multidecadal to centennial-scale variations, chronology using regional curve standardization (RCS) (Esper *et al.* 2003) technique has been developed from Lahaul and Spiti region, Himachal Pradesh. This chronology extends back to BC 16-AD 2006. However, due to decreasing replication of samples backward in the chronology it has been found to be suitable for climatic studies from AD 940 only (figure 2). This chronology shows centennial-scale variations with distinctly low growth in early part of the chronology from 10th-16th and high growth during 17th–19th centuries. Due to lack of meteorological data from stations close to tree ring sites, this chronology could not be calibrated with meteorological data. However, correlation with monthly precipitation and temperature data of Srinagar, Leh, Keylong, and Skardu located in similar climatic zones as the tree ring sites show direct relationship with May precipitation and indirect relationship with summer temperature (figure 3). The monthly precipitation of Keylong from May-October show direct relationship indicating that growing season precipitation plays an important role in directly influencing the growth of Himalayan pencil juniper at dry sites. However, due to a weak relationship, statistically verifiable calibrations could not be achieved for precipitation reconstruction.

2.2 *Himalayan cedar (*Cedrus deodara*)*

The Himalayan cedar grows in moist to semi-arid sites in monsoon and monsoon shadow zones in western Himalaya at altitudes ranging from 1200-3300 m asl (Raizada and Sahni 1960; Champion and Seth 1968). Good amount of winter snowpack, not too heavy summer monsoon and well drained soils are its primary ecological requirement. The

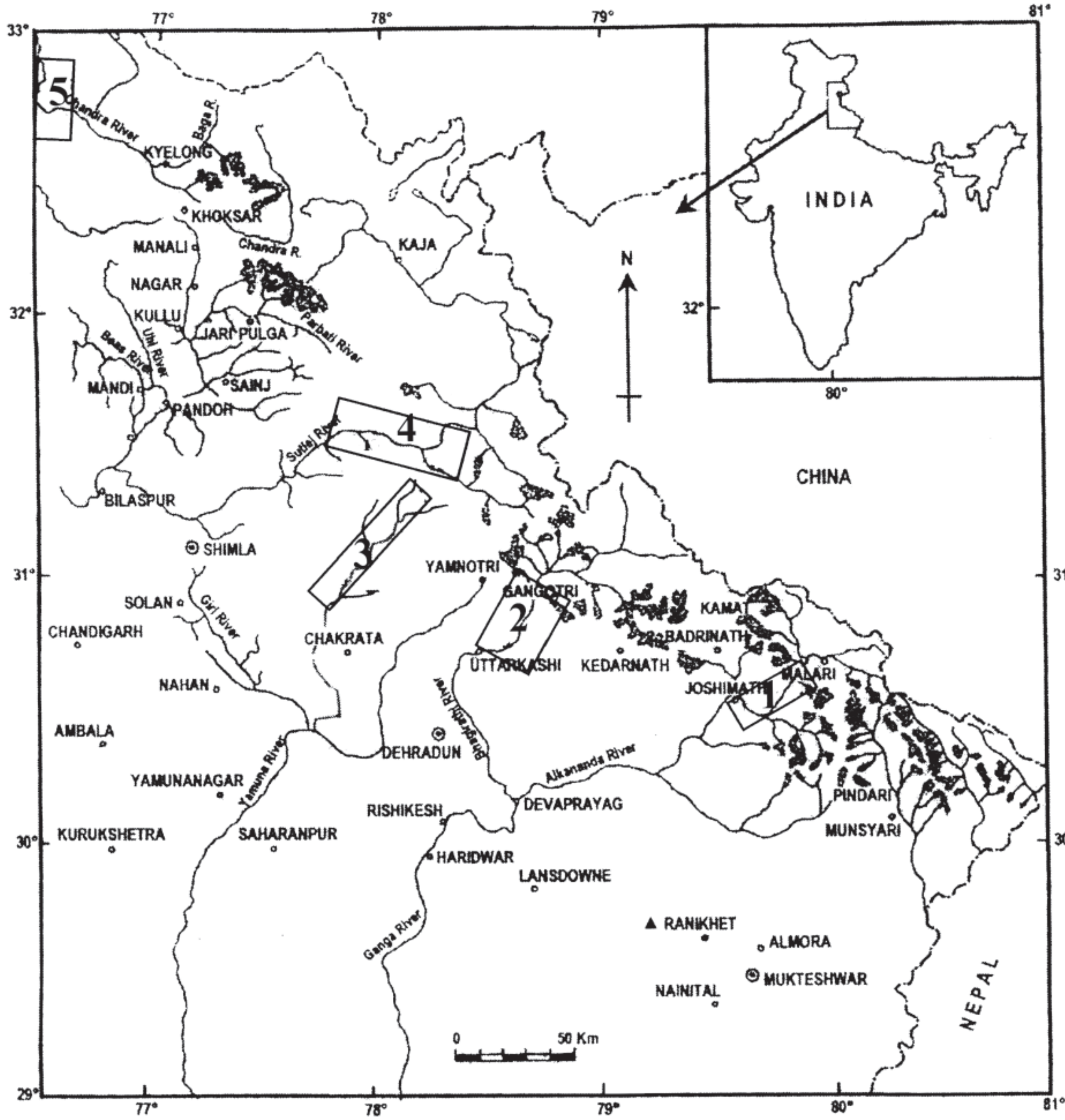

Figure 1. Map showing the location of investigated tree-ring sites. **1**. Alaknanda basin, **2.** Bhagirathi basin, **3.** Tons basin, **4.** Satluj basin, **5.** Chandra-Bhaga basin. Species utilized for developing tree-ring chronologies are Himalayan cedar, Himalayan pencil juniper and Chilgoza pine. The Himalayan cedar chronologies have been developed from all the basins, however; Himalayan pencil juniper and Chilgoza pine are from Chandra-Bhaga and Satluj basins, respectively.

trees over moist sites usually grow faster and attain huge girth in early age. Many such thick trees usually do not grow old due to wood rot and other fungal diseases. However, trees growing over semi-arid sites, where annual increment is low, attain great ages and are usually thin. Such trees growing in semi-arid sites are usually widely spaced with low inter-tree competition induced noise in the series. Due to climatic stress the number of missing rings in such tree samples is high, posing difficulty in crossdating. Successful crossdating in this species has been achieved even with missing rings as high as 4%. However, crossdating becomes unreliable with the increasing number of missing rings. Ring-width series

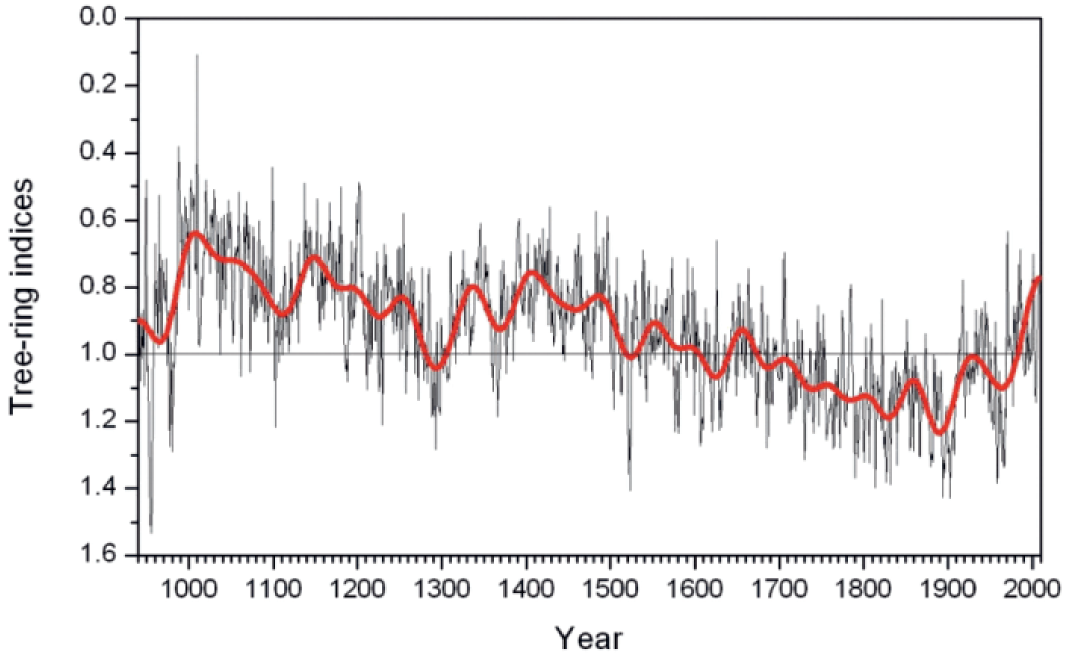

Figure 2. Tree-ring chronology of Himalayan pencil juniper for Chandra-Bhaga basin (AD 940-2006). The thick line is 50-year low pass filter.

originating from various sites in western Himalaya have been used to develop long tree-ring-width chronologies (Singh *et al.* 2004; Yadav *et al.* 2004; Singh *et al.* 2009). Longest ever chronology of this species prepared from Bhaironghati, Uttarkashi, Uttarakhand spans over 1198 years (AD 805-2002) (Singh *et al.* 2004). The calibration of tree-ring chronologies of this species from various sites in western Himalaya with monthly precipitation and temperature data from meteorological stations close to the tree-ring sampling sites have shown strong, direct relationship with precipitation and negative relationship with temperature of premonsoon months (Yadav and Singh 2002; Singh *et al.* 2004; Yadav *et al.* 2004; Singh and Yadav 2005; Singh *et al.* 2006, 2009). The close network of chronologies of this species has been used to develop premonsoon precipitation as well as temperature reconstructions.

2.3 *Chilgoza pine (*Pinus gerardiana*)*

Chilgoza is a three needle pine growing in inner semi-arid valleys of northwestern Himalaya at altitudes ranging from 1800-3000 m asl where summer monsoon rainfall is deficient and winter snowfall is abundant (Raizada and Sahni 1960). Thin silver grey bark peels out vertically in thin flakes along the stem. The leaves fall every alternate year and new ones appear in April-May. For chilgoza nuts the trees are under immense human pressure. People usually lop the branches to get the intact cones. For such heavy biotic pressure old trees are usually hard to get. However, there exists a fair possibility of getting older trees of this species in interior areas where human pressure is lower. With this understanding in mind an extensive survey of chilgoza pine forests growing over climate stressed sites in Kinnaur, Himachal Pradesh was made in 2005 and millennium old trees were sampled. Tree-ring sequences among samples were crossdated using ring-widths pattern matching. Due to moisture stress missing rings are again high in this species too reaching as high as 4.1%.

The ring-width chronology of this species from Kinnaur, Himachal Pradesh extends from AD 919-2005. This chronology was found to have direct relationship with precipitation of March-July and negative with premonsoon temperature (Singh and Yadav 2007; Singh *et al.* 2009).

3. Climatic reconstructions

3.1 *Precipitation*

Tree-ring chronologies of different species have been used to develop premonsoon precipitation reconstruction. However, such reconstructions are usually based on limited replication of tree samples from a few sites in a restricted area (Borgaonkar *et al.* 1994; Yadav and Park 2000). Singh and Yadav (2005) first used a network of 15 ring-width chronologies from homogeneous semi-arid sites in western Himalaya to develop premonsoon precipitation back to AD 1731 (figure 4a). This

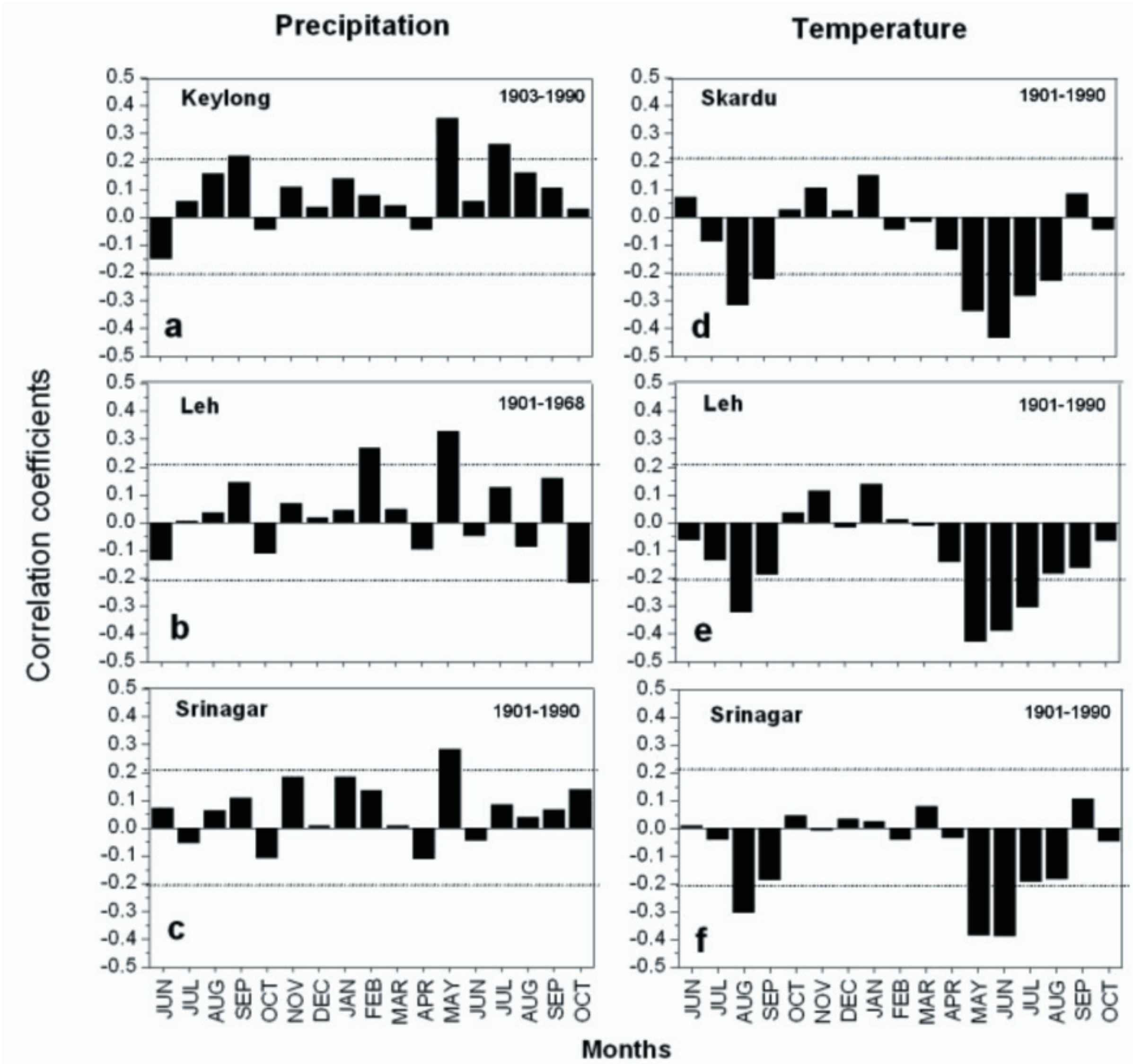

Figure 3. Correlation between Himalayan pencil juniper ring-width chronology (residual) and monthly climate variables (precipitation and temperature). Left panel precipitation, (**a**) Keylong, (**b**) Leh, and (**c**) Srinagar. Right panel temperature (**d**) Skardu, (**e**) Leh, and (**f**). Srinagar. The dotted lines represent the 95% confidence level.

reconstruction was further updated and extended back to AD 1560 using longer tree-ring series from 13 homogeneous sites in western Himalaya (Singh *et al.* 2006) (figure 4b). Though the reconstruction captured interdcadal scale features, the most striking feature of these are the increase in precipitation during last few decades of the 20th century (figure. 4a, b). The δ^{18}O records in tree rings from Karakoram, northern Pakistan also indicate unprecedented pluvial conditions in the 20th century (Treydte *et al.* 2006). The premonsoon precipitation in western Himalaya is brought by westerly disturbances originating in North Atlantic and Mediterranean region. The observational records show decreasing number of wetserlies during recent decades (Das *et al.* 2002). However, tree-ring based premonsoon precipitation reconstructions show increased values in recent decades (Singh and Yadav 2005; Singh *et al.* 2006). To understand if the increasing trend in reconstruction, consistent with the observational records from Shimla, Mukteswar and Dehradun, is of restricted geographical extent or the artifact of detrending methods applied to tree-ring series, data from different climatic zones are required to be analysed. Another premonsoon precipitation reconstruction extending back to AD 1310-2004 (Singh *et al.* 2009) developed from the Kinnaur region, Himachal Pradesh (figure 5) indicates considerable interannual to decadal scale variability. A 50-year running mean indicated dry periods during 1773–1822 (179.1 mm), 1471-1520 (187 mm), and

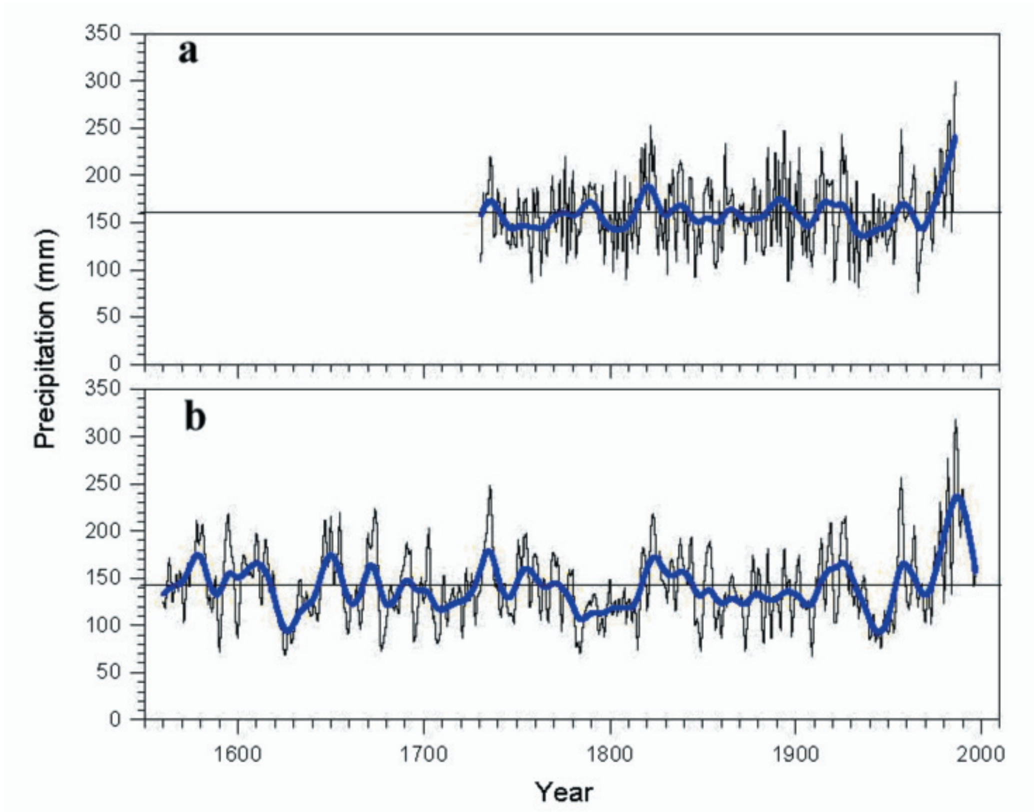

Figure 4. Premonsoon (March-April-May) precipitation reconstruction developed using tree-ring data network of Himalayan cedar from Bhagirathi and Tons basins. (**a)** 1731-1986 –reconstruction developed using network of 15 ring-width chronologies, (**b)** 1560-1997-reconstruction developed using network of longer series from 13 sites in Bhagirathi and Tons basins. The smooth line is 20-year low pass filter.

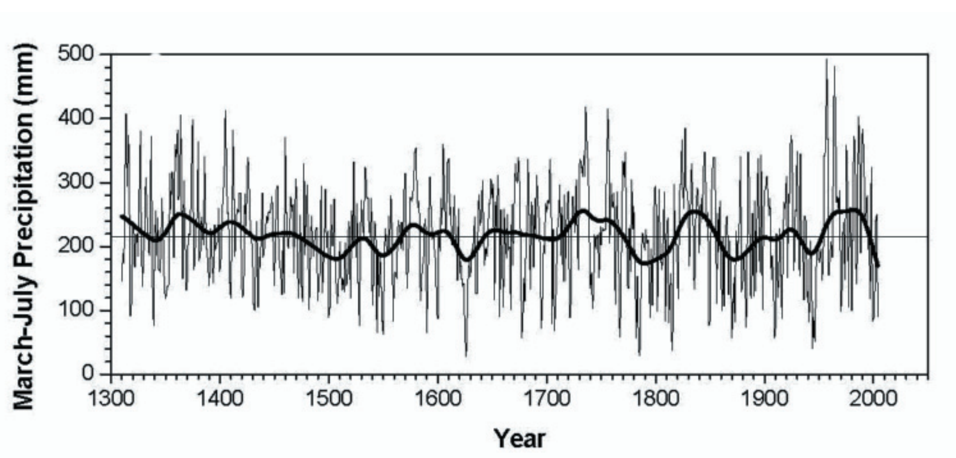

Figure 5. March-July precipitation reconstruction developed using ring-width chronologies of Chilgoza pine and Himalayan cedar from Satluj basin, Kinnaur, Himachal Pradesh. The smooth line is the 20-year low pass filter.

1584-1633 (196.8 mm). Humid periods occurred in 1949-1998 (253.9 mm), 1723-1772 (249.5 mm), 1359-1408 (243.4 mm) and 1817-1866 (241.1 mm). Dry conditions in the late eighteenth century and wet conditions in the twentieth century are consistent with those recorded in Karakoram, Pakistan (Treydte *et al.* 2006). The reconstruction also mirrors dry and wet conditions during the span of the Little Ice Age (LIA). The dry and wet conditions recorded in this reconstruction closely match the earlier precipitation reconstructions developed from the eastern part of the western Himalaya (Uttaranchal Himalaya) under the influence of the southwest Asian monsoon (Singh and Yadav 2005; Singh *et al.* 2006). However, the unprecedented increase in precipitation during last few decades of the twentieth century noted in the Karakoram, Pakistan (Treydte *et al.* 2006), and in the Uttaranchal Himalayan region (Singh and Yadav 2005; Singh *et al.* 2006), is not observed in the reconstruction from Kinnaur region. A similar trend in precipitation has also been noted in another reconstruction from western Himalayan region from a tree-ring chronology developed using the Regional Curve Standardization (RCS), the method known to retain low frequency variations in the mean chronology (R R Yadav, unpublished data). The precipitation reconstruction reveals a pronounced trend of decreasing rainfall since 1990s, which if continues would have serious socioeconomic implications for the local inhabitants. The spatial extent of this valley specific feature in the monsoon shadow zone needs to be investigated further with the help of more tree-ring data from orographically separated basins.

3.2 *Temperature*

As is the case with precipitation reconstructions, the temperature reconstruction from the western Himalayan region are also few and largely limited to past few centuries only (Borgaonkar *et al.* 1996; Hughes 2001; Yadav *et al.* 1997). The long-term reconstructions even covering the entire span of Little Ice Age are few (Yadav *et al.* 1999; 2004). Besides, these multicentury long temperature reconstructions are devoid of low frequency variations. The temperature reconstruction spanning over the past 800 years (Yadav *et al.* 2004) shows strong consistency with temperature records from Nepal Himalaya (figure 6a, b) (Cook *et al.* 2003) indicating regional representativeness of temperature records derived from tree rings.

The premonsoon (March-April-May) temperature reconstruction derived using network of tree-ring data from western Himalaya (Yadav *et al.* 2004) shows inter-decadal variability superimposed over strong inter-annual variability (figure 6b). The mean premonsoon temperatures from the western Himalayan region indicate higher variability in reconstructed data since 16th century AD as compared to the early period of reconstruction. The cool episodes recorded during 1573–1622, 1731–1780, 1817–1846 represent the interdecadal variability during LIA cooling in western Himalaya. Mean summer temperature responsive tree-ring-width chronology recently developed from the western Himalayan region (figure 2) independently supports the earlier findings (Yadav *et al.* 2004).

The decreasing temperature trend in late 20th century is consistent with trends noted in Nepal (Cook *et al.* 2003), Tibet (Briffa *et al.* 2001) and Central Asia (Briffa *et al.* 2001). The cooling trend in late 20th century mean temperature has been found to be due to cooling trend noted in minimum temperature during the second half of the 20th century in semi-

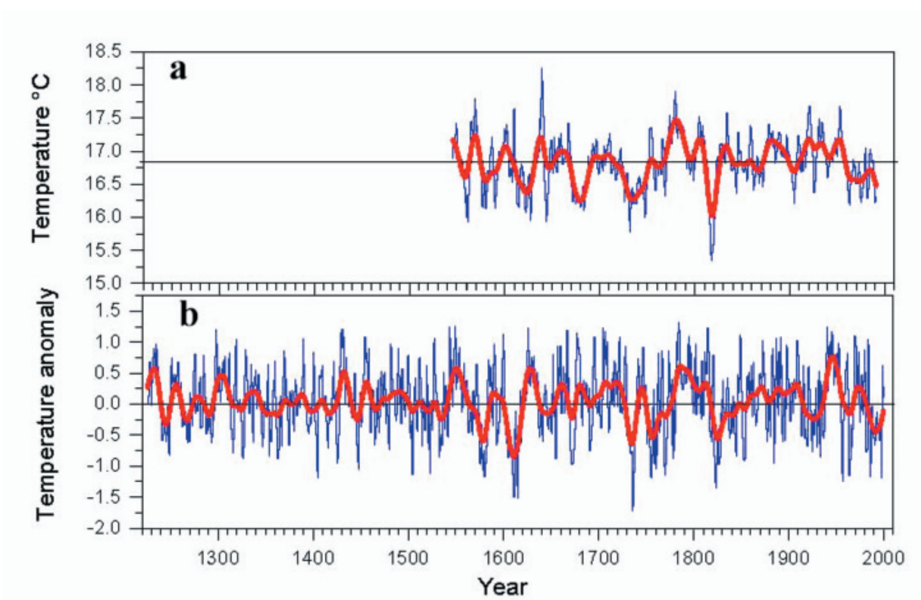

Figure 6. Mean temperature reconstruction from the Himalayan region using network of tree-ring chronologies. (**a**) February-June temperature reconstruction for Nepal (AD 1546-1991) developed using network of 32 ring-width chronologies (Cook *et al*. 2003), (**b**) Mean premonsoon (March-April-May) temperature reconstruction for western Himalaya (AD 1226-2000) developed using ring-width data from Bhagirathi and Tons basins. Smooth lines are 20-year low pass filter.

arid western Himalaya. The cooling in minimum temperature has been hypothesized to be largely anthropogenic in origin due to large-scale deforestation and soil degradation/erosion. Due to reduction of forest cover, soil water infiltration is greatly reduced and surface run-off increased. The reduced soil moisture content decreases the soil thermal inertia causing rapid radiation loss at night. This results in increased diurnal temperature range. The observational temperature records from Dehradun, Shimla and Mukteswar show high correlation coefficients for premonsoon minimum temperatures during 1901-1959 (r=0.85-90), which decreases considerably during 1960-1998 (r=0.46-0.58). However, the maximum temperature of above three stations showed strong correlations during both the sub-period (r=0.84-0.91). This reflects that the degree of nocturnal cooling is largely dependent on local site conditions reinforcing the conclusion that large-scale deforestation coupled with heavy soil degradation could be responsible for the decrease in minimum temperature in the western Himalaya. However, the subdued late 20th century warming noted in reconstruction could also have resulted from the lack of low frequency variations in the reconstruction. The ring-width chronology prepared from Lahaul-Spiti region, developed using techniques to preserve in the low frequency variations in the mean ring-width chronology, has indicated warming in late 20th century mean summer temperature in the Himalayan region. However, the amplitude of warming could be subdued partly due to decrease in strength of correlations with instrumental temperature records towards the latter part of the 20th century.

Mean premonsoon temperature records developed from western Himalaya have been found to have significant relationship with ENSO features (Yadav *et al.* 1997, 1999). This reflects that long-term climate records should be useful in understanding climate change over regional to hemispheric scale.

4. Wood density and isotope studies

In addition to ring-width, wood density and stable isotope composition of carbon, oxygen and hydrogen in annual rings are potential proxies of environmental variables. However, such variables have not been studied adequately in the context of India as a whole. Hughes (1992) first demonstrated the potential of late wood density of *Abies pindrow* from sub-alpine forests in Kashmir to develop temperature and precipitation reconstructions. However, later studies on wood density of other species viz. *Abies pindrow*, *Cedrus deodara*, *Picea smithiana and Pinus roxburghii* demonstrated stronger climatic signal in early wood density as compared to the late wood (Pant *et al.* 2000; Borgaonkar *et al.* 2001). The analyses of stable isotope ratios of hydrogen, oxygen and carbon in annual rings of *Abies pindrow* from Kashmir (Ramesh *et al.* 1985, 1986) have demonstrated potential applicability in developing long-term records of climatic variables affecting tree growth. These preliminary studies show that the wood density and isotope variables along with conventional ring-width parameter should provide reliable climatic estimates to understand long-term climate variability.

5. Conclusions

Tree-ring analyses so far carried out in the western Himalayan region of India have indicated that the region has treasure of natural archives to develop long-term environmental information. The oldest living trees known from the region are Himalayan pencil juniper (*Juniperus polycarpos*), Himalayan pencil cedar (*Cedrus deodara*) and Chilgoza pine (*Pinus gerardiana*), all growing in semi-arid to arid sites.

The network of chronologies from samples collected from homogeneous ecological settings has been utilized to develop premonsoon precipitation and temperature reconstructions. The reconstructed precipitation data show large-scale spatial heterogeneity. Late 20th century increase in tree-ring inferred premonsoon precipitation is noted in Garhwal region. However, reconstructions from Kinnaur, Himachal Pradesh show decrease in precipitation in last few decades of the 20th century. Such spatial heterogeneity in precipitation has high ecological and hydrological implications.

The temperature reconstructions from different regions in Himalaya show strong consistency. The late 20th century warming in western Himalaya, as reported in high-latitude northern Hemisphere, is subdued. This has been attributed partly to decrease in the strength of relationship between tree-ring-width chronologies and temperature records as well as decrease in mean temperature due to decreasing trend in minimum temperature in western Himalaya.

Pilot studies on wood density and stable isotope parameters in annual rings carried out on some western Himalayan conifer species show that these predictor variables along with ring-widths should provide robust estimates of climate.

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References

Borgaonkar H P, Pant G B and Rupa Kumar K 1994 Dendroclimatic reconstruction of summer precipitation at Srinagar, Kashmir, India, since the late-eighteenth century; *Holocene* **4** 299–306

Borgaonkar H P, Pant G B and Rupa Kumar K 1996 Ring-width variations in *Cedrus deodara* and its climatic response over the western Himalaya; *Int. J. Climatol*. **16** 1409–1422

Borgaonkar H P, Rupa Kumar K, Pant G B, Okada N, Fujiwara T and Yamashita K 2001 Climatic implications of tree-ring density variations in Himalayan conifers; *Palaeobotanist* **50** 27–34

Bradley R S, Hughes M K and Diaz H F 2003 Climate in Medieval time; *Science* **302** 404–405

Briffa K R, Osborn T J, Schweingruber F H, Harris I C, Jones P D, Shiyatov S G and Vaganov E A 2001 Low frequency temperature variations from northern tree ring density network; *J. Geophys*. *Res*. **106** 2929–2941

Champion H G and Seth S K 1968 *A revised survey of the forest types of India* (Delhi: Manager of Publications)

Chauhan M S 2006 Late Holocene vegetation and climate change in the alpine belt of Himachal Pradesh; *Curr*. *Sci*. **91** 1562–1567

Cook E R, Krusic P J and Jones P D 2003 Dendroclimatic signals in long tree-ring chronologies from the Himalayas of Nepal; *Int*. *J*. *Climatol.* **23** 707–732

Das M R, Mukhopadhyay R K, Dandekar M M and Kshirsagar S R 2002 Pre-monsoon western disturbances in relation to monsoon rainfall, its advancement over NW India and their trends; *Curr*. *Sci*. **82** 1320–1321

Esper J, Cook E R, Krusic P, Peters K and Schweingruber F H 2003 Tests of the RCS method for preserving low-frequency variability in long tree-ring chronologies; *Tree-Ring Res*. **59** 81–98

Grove J M 1988 *The Little Ice Age* (New York: Methuen)

Hughes M K 1992 Dendroclimatic evidence from the western Himalaya; in *Climate since 1500* AD (eds) R S Bradley and P D Jones (London: Routledge) pp 415–431

Hughes M K 2001 An improved reconstruction of summer temperature at Srinagar, Kashmir since 1660 *A D*, based on tree-ring width and maximum latewood density of *Abies pindrow* [Royle] Spach; *Palaeobotanist* **50** 13–19

Jansen E, Overpeck J, Briffa K R, Duplessy J C Joos F, Masson-Delmotte V, Olago D, Otto-Bliesner B, *et al.* 2007 Palaeoclimate; in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds) S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Averyt, M Tignor and H L Miller (Cambridge: Cambridge University Press) pp 433–497

Kripalani R H, Kulkarni A, Sabade S S and Khandekar M L 2003 Indian monsoon variability in a global warming scenario; *Nat. Hazards* **29** 189–206

Lamb H H 1965 The Early Medieval Warm Epoch and its Sequel; *Palaeogeogr. Palaeoclimatol*. *Palaeoecol*. **37** 1–13

Mann M E, Bradley R S and Hughes M K 1999 Northern Hemisphere temperature during the past millennium: inferences, uncertainties, and limitations; *Geophys*. *Res*. *Lett*. **26** 759–762

Osborn T J and Briffa K R 2006 The spatial extent of 20th-century warmth in the context of the past 1200 years; *Science* **311** 841–844

Pant G B, Rupa Kumar K, Borgaonkar H P, Okada N, Fujiwara T and 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

Ramesh R, Bhattacharya S K and Gopalan K 1985 Dendrochronological implications of isotope coherence in trees from Kashmir, India; *Nature (London)* **317** 802–804

Ramesh R, Bhattacharya S K and Gopalan K 1986 Climatic correlations in the stable isotope records of silver fir (*Abies pindrow*) trees from Kashmir, India; *Earth Planet*. *Sci*. *Lett*. **79** 66–74

Raizada M B and Sahni K C 1960 Living Indian gymnosperms. Part 1 (Cycades, Ginkgoales and Coniferales); *Indian For*. *Rec*. **5** 1–150

Sharma M C and Owen L A 1996 Quaternary glacial history of NW Garhwal, central Himalaya; *Q. Sci. Rev*. **15** 335–365

Singh J, Yadav R R, Dubey B and Chaturvedi R 2004 Millennium-long ring-width chronology of Himalayan cedar from Garhwal Himalaya and its potential in climate change studies; *Curr*. *Sci*. **86** 590–593

Singh J and Yadav R R 2005 Spring precipitation variations over the western Himalaya, India since AD 1731 as deduced from tree rings; *J. Geophys*. *Res*. 110 D01110. DOI 10.1029/2004JD004855

Singh J, Park W K and Yadav R R 2006 Tree-ring-based hydrological records for western Himalaya, India, since AD 1560; *Clim. Dyn*. **26** 295–303

Singh J and Yadav R R 2007 Dendroclimatic potential of millennium-long ring-width chronology of *Pinus gerardiana* from Himachal Pradesh, India; *Curr. Sci*. **93** 833–836

Singh J, Yadav R R and Wilmking M 2009 A 694-year tree-ring based rainfall reconstruction from Himachal Pradesh, India; *Clim*. *Dyn*. doi, 10.1007/s00382-009-0528-5

Treydte K S, Schleser G H, Helle G, Frank D C, Winiger M, Haug G H and Esper J 2006 The twentieth century was the wettest period in northern Pakistan over the past millennium; *Nature (London)* **440** 1179–1182

Yadav R R, Park W K and Bhattacharyya A 1997 Dendroclimatic reconstruction of April-May temperature fluctuations in the western Himalaya of India since A.D. 1698; *Q*. *Res*. **48** 87–191

Yadav R R, Park W K and Bhattacharyya A 1999 Spring temperature variations in western Himalaya, India, as reconstructed from tree-rings: A.D. 1390–1987; *Holocene* **9** 85–90

Yadav R R, and Park W K 2000 Precipitation reconstruction using ring-width chronology of Himalayan cedar from western Himalaya: preliminary results; *Proc*. *Indian Acad*. *Sci*. *(Earth Planet. Sci*.*)* **109** 339–345

Yadav R R and Singh J 2002 Tree-ring-based spring temperature patterns over the past four centuries in western Himalaya; *Q*. *Res*. **57** 299–305

Yadav R R., Park W-K, Singh J and Dubey B 2004 Do the western Himalayas defy global warming?; *Geophys. Res. Lett.* **31** L17201. doi 0.1029/2004GL020201

Yadav R R, Singh J, Dubey B and Mishra K G 2006 A 1584-year ring-width chronology of juniper from Lahul, Himachal Pradesh: Prospects of developing millennia long climate records; *Curr*. *Sci*. **90** 1122–1126

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