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Dendroclimatic potential of millennium-long ring-width chronology of *Pinus gerardiana* from Himachal Pradesh, India

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We have developed a 1087-yr (AD 919–2005; so far the longest) chronology of *Pinus gerardiana* (chilgoza pine) from Kinnaur, Himachal Pradesh using 15,083 annual ring-width measurements from 35 increment cores. The tree growth–climate relationship using response-function analyses indicated that precipitation, except for the months of January, February and October, has a direct relationship with growth. However, this relationship was significant for previous year's October and current year's February, March, May and June. Mean monthly temperature showed largely negative relationship with growth, except for June and August–October. The longevity and climate sensitivity of this species shows its potential in developing millennium-long climatic reconstructions needed for understanding the long-term climate variability in the Himalayan region.

Keywords: Climate variability, dendroclimatic potential, *Pinus gerardiana*, ring-width chronology.

PROXY climate records from high-latitude regions[1,2] and climate models[3] have shown that the level of warming during the past few decades has been unprecedented in the context of the past two millennia. With global warming there is a growing notion that the frequency and/or severity in weather extremes in recent decades is increasing. The unusual heat wave in April 1999 in northwest and central India[4] in the context of the observed data of the 20th century, might provide proof of the impact of global warming in the country. Any potential increase in intensity or frequency of such extremes would have serious implications as agriculture, contributing about 50% of the national economy, is highly sensitive to weather and climate. However, one should be cautious about attributing the effect to any such individual event or making assumptions about the likelihood of future events from observed data, unless such events are placed in longer palaeoperspective.

Tree-ring records from the Himalayan region with annual and seasonal resolution have proven potential to extend instrumental climate records back to several centuries[5,6]. However, tree species covering the Little Ice Age and

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Medieval Warm Period are still poorly known. So far only two species, *Cedrus deodara* and *Juniperus macropoda* are known to grow for more than millennia in the western Himalayan region[7,8]. Such tree-ring records are highly valuable for long-term climate reconstruction needed to understand climate variability in long-term perspective. In this context the present study is an attempt to develop millennium-long ring-width chronology of chilgoza pine from Purbani, Kinnaur, Himachal Pradesh. The tree-ring chronology of this species developed from the region could provide valuable data to reconstruct long-term climate needed to understand the intricacies of climate pattern under the background influence of greenhouse gases.

Pinus gerardiana (Wall. ex. Lamb) is found in the inner semi-arid valleys of northwestern Himalaya at an altitude ranging from 1800 to 3000 m asl, where summer monsoon rainfall is deficient and winter snowfall is abundant[9,10]. Earlier tree-ring study of this species from the western Himalayan region yielded around 401-yr chronology[11]. Older trees of this species are expected as it grows over high climate-stressed sites. With this understanding an extensive survey of chilgoza pine forest growing over climate-stressed sites in Kinnaur was made in 2005 (Figure 1). Old chilgoza pine trees occasionally mixed with *Cedrus deodara* (Himalayan cedar) trees were found growing on steep rocky slopes with thin soil cover. The ecological setting shows the vulnerability of tree growth to fluctuations in rainfall and soil moisture stress accentuated by hot weather conditions.

Healthy old trees growing in open canopy forest without any visible mark of injury were selected for sampling using increment borers. The lopping of branches for harvesting chilgoza pine nuts was noticed in many trees and these were avoided for sampling. Tree-ring samples were processed in the laboratory using standard dendrochronological techniques[12]. Ring-widths of samples were

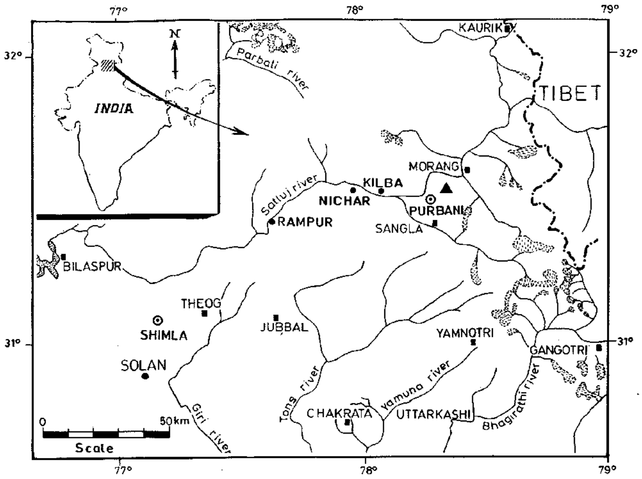

Figure 1. Map showing tree-ring sampling site (filled triangle) and meteorological stations used in the study (circle with dot at the centre).

measured with 0.01 mm accuracy using linear encoder interfaced with personal computer. The ring-width measurement sequences were used for dating of annual growth rings to the level of calendar year of their formation using the TSAP program[13]. Dating accuracy and measurement errors were cross-checked and confirmed using dating quality check program, COFECHA[14]. A total of 35 chilgoza pine cores were dated and used in chronology preparation. As samples for the present study originated from a highly moisture-stressed site, missing rings were found to be common (4.1% missing rings in an ensemble of 15,083 rings from 35 tree samples).

To remove the non-climatic signal and long-term growth trends mainly due to increasing age and tree size, ring-width measurement series were standardized. We used negative exponential or straight-line curves to ring-width measurement series of individual tree-cores. However, in case of 13 chilgoza pine samples, where growth dynamics appeared to be influenced by other stand dynamics features, cubic smoothing splines with a 50% frequency-response cut-off width equal to two-thirds of the series length were used. In these series spline length varying from 205 to 637 yrs was used. A set of three chronologies standard, residual containing only the high-frequency variations and arstan composed of residual chronology with the pooled autoregression reincorporated, were developed using the computer program ARSTAN[15,16].

For dendroclimatic studies climate records from stations close to the sampling site are required, which is rarely available in the Himalayan region. However, in the present case, unlike many other tree-ring sites, precipitation records are available from the station close to the tree-ring sampling site. However, the temperature records are not available for this region. Due to strong coherence in temperature over distant regions, temperature data of Shimla were used in the present study (Figure 1). Response function, which is a multiple regression analysis, was used to understand the tree growth–climate relationship. As precipitation records for the region were available from AD 1951 to 1994, the residual site chronology and climate (temperature and precipitation) records for the common period from 1951 to 1994 were used in response-function analysis.

Study of growth ring sequences in chilgoza pine from the moisture-stressed site in Kinnaur, showed strong interannual variability in ring-width pattern among various trees. Cross-dating among the samples showed frequent occurrence of missing rings (4.1%). An earlier study on this species from Kishtwar, Jammu and Kashmir[11] also indicated frequent occurrence of missing rings (2.66%). The occurrence of frequent missing rings reflects the sensitivity of the tree to extreme climatic conditions. Mean ring-width chronology (AD 919–2005) from 15,089 measurements in 35 tree samples is the longest so far for this species (Figure 2). This extends the previous record of 401-yr (AD 1583–1983) long chronology of this species

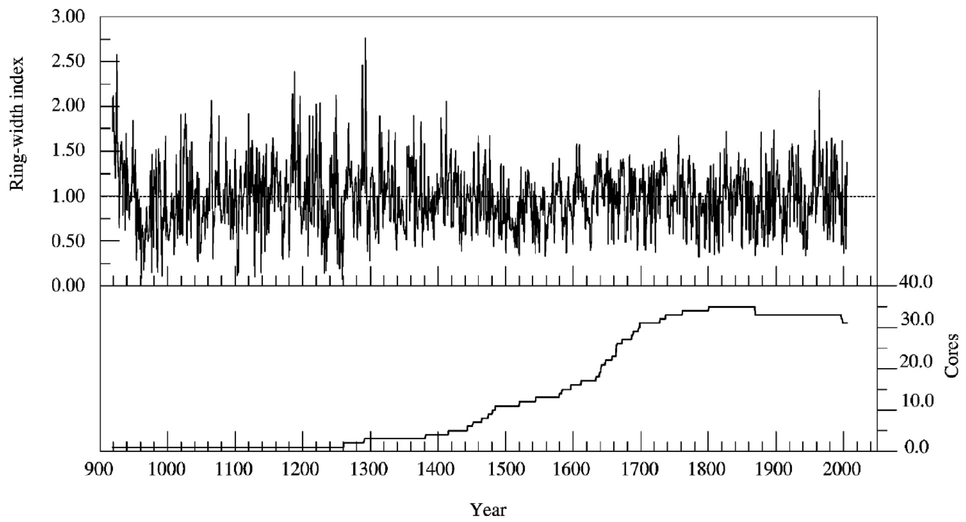

Figure 2. Ring-width chronology of *Pinus geradiana* from Purbani, Himachal Pradesh (upper panel), and number of samples used in the chronology (lower panel).

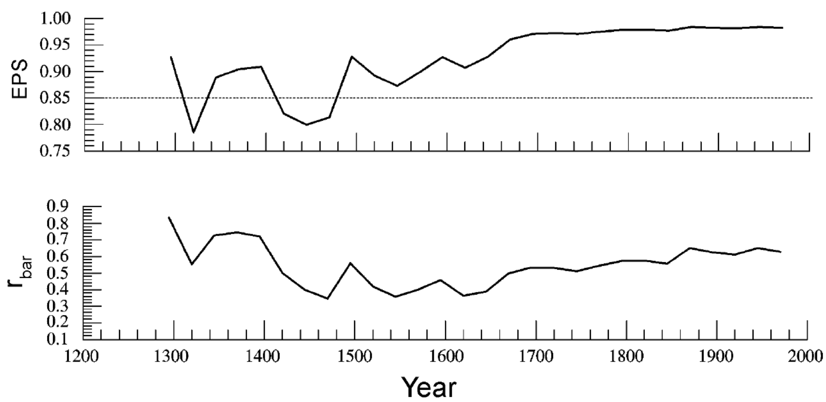

Figure 3. Standard chronology: EPS (upper panel) and r_{bar} (lower panel).

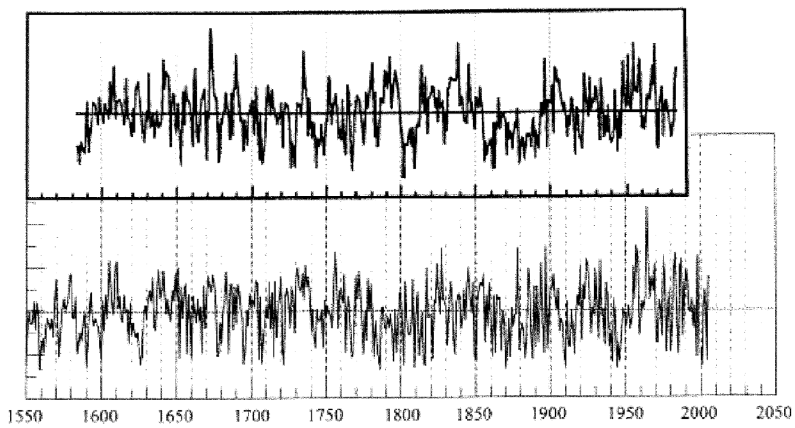

Figure 4. Ring-width chronology from Kishtawar, Jammu and Kashmir (upper panel; after Bhattacharyya *et al.*[11]) and part of present ring-width chronology (lower panel) showing interannual to decadal-scale similarity.

to 1087-yrs (AD 919–2005). Chronology details such as expressed population signal (EPS; 0.93) and r_{bar} (0.56), a measure of signal strength[16,17], indicate its suitability in climate studies back to AD 1495 (Figure 3). The EPS value of 0.85 or above is taken as a cut-off of series length suitable for climate reconstruction.

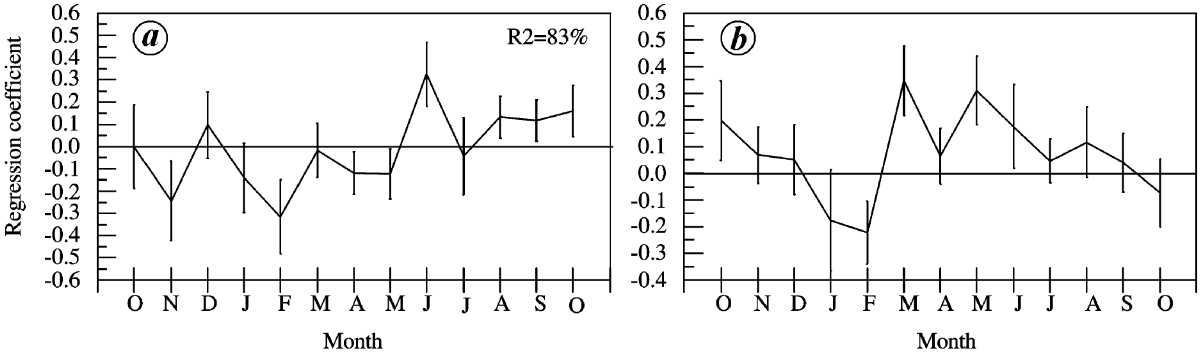

Figure 5. Response function of residual chronology of *P. geradiana* with mean monthly temperature (***a***) and monthly precipitation (***b***). Vertical bars are the 95% confidence limits.

We compared the present chronology with earlier chronology[11] of this species from Kishtawar. Both the chronologies showed close resemblance at interannual to decadal-scale level (Figure 4). This indicates that a common forcing factor (i.e. climate) affects the tree growth dynamics at two distant sites. Existence of such a close similarity in chronologies from distant locations clearly indicates the potential of developing the reconstructions representing the synoptic-scale climate features. However, dissimilarities in 1790s and 1810s could be due to different microclimatic conditions prevailing in the two regions.

Response-function analysis showed that temperatures of November of the previous growth year and current year's February, April and May have significant negative, and current growth year's June, August–October have a positive relationship. Precipitation of previous year's October and current year's March, May and June has positive and current year's February significant negative relationship with the growth of chilgoza pine trees (Figure 5). Tree growth–climate relationship shows that cool and wet March–May and July are of vital importance for the growth of trees at the moisture-stressed site in Purbani. Significant positive relationship of tree growth with temperature and precipitation during June indicated that wet and warm conditions favour the growth of trees.

Reconstruction of pre-monsoon precipitation (March–June), though showing strong correlation with the chronology, could not be presented here as calibrations using one chronology could not be statistically verified. However, robust millennium-long climatic reconstruction is expected to be developed after increasing the replication of more tree samples (especially those around 1000 years) in the chronology or by adding more predictor chronologies in the calibration model.

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