Varying strength of relationship between temperature and growth of high-level fir at marginal ecosystems in western Himalaya, India

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Ring-width chronologies (AD 1794–1998, 1644–1999, 1672–2000, and 1739–2002) of Abies spectabilis from four distantly located tree-line sites in western Himalaya were developed. The existence of good correlation among the site chronologies shows the influence of common forcing factor that could be climate, largely temperature. Correlation of May and mean April–May temperatures with chronologies show weakened relationship towards the later part of the 20th century.

Vegetation in the western Himalayan region ranges from tropical at lower altitudes (up to 1000 m asl) to alpine at higher elevations (4000 m asl). However, this range might vary up to a few hundred metres with change in local climatic conditions such as temperature and humidity regime. The vegetation in the region is under tremendous biotic pressure due to the recent spurt in population growth. But there are high-altitude regions in the interior of the Himalaya still uninfluenced by direct human activities. Such high-altitude mountain regions provide valuable material to evaluate the consequences of global change. Considering the importance of high-mountain regions to understand the consequences of environmental changes, the Mountain Research Initiative2 was recently launched in 2001. This programme aims to enhance global change research in the mountain regions by establishing linkages between mountain-research projects in International Geosphere Biosphere Programme (IGBP) and International Human Dimensions Programme (IHDP), and by cooperation of these programmes with the special mountain module of the Global Terrestrial Observing Systems (GTOS).

Tree-ring studies in India, aimed to develop climatic reconstructions3,4, are started towards the end of 1970s. Tree-ring studies carried out so far in the Himalayan region are mainly restricted to the lower temperate forests5–11. Tree-ring studies from the tree-line zones with a view to monitor the consequences of environmental changes on tree growth, have not been reported so far from the Himalayan region. During our recent expeditions in the high altitudes of the Himalaya, we have observed notable changes in colonization pattern of coniferous species at the upper tree-line zones. Tree rings provide a valuable parameter to understand the climatic factors responsible for such changes. In this pursuit we carried out tree-ring analyses of high-level fir (Abies spectabilis (D. Don) Spach) growing in the tree-line zones at four sites in western Himalaya.

A. spectabilis is a high-level fir growing in the subalpine forests in western Himalaya at altitudes ranging from 3000 to 3600 m or occasionally extending its upper limit by 300 m12. The trees are characterized by low branching with dense foliage. At upper limits, it is usually associated with Betula utilis D. Don and Rhododendron companulatum D. Don. We collected tree-ring samples in the form of increment cores from four sites, viz. Tola, Pithoragarh (April 1999); Ghangria near Valley of Flowers, Joshimath (May 2000); Yamnotri (September 2000); and Budhavan near Pulga in Parbat valley, Kullu (October 2002; Figure 1). All the sites constitute the treeline in respective areas at altitudes ranging from 3100 to 3600 m. The forests at all the sites have close canopy. The Tola and Ghangria sites with moderate slope have thick soil, whereas at the other two sites the sampled trees were growing on rocky substratum with thin soil cover. Details of samples collected from respective sites are shown in Table 1.

Tree-ring samples were processed for precise dating of growth-ring sequences using skeleton-plot method13. The ring widths of dated samples were measured with an accuracy of 0.01 mm. Crossdating and measurement accuracies were checked and confirmed by correlating overlapping 50-year segments of all measured series using the COFECHA software14, which identifies the samples of a core or a group of cores where dating or measurement errors may have occurred. Mean correlation of all radii with master series of respective sites as indicated by COFECHA, was 0.58 (Tola, 50 radii); 0.68 (Ghangria, 27 radii); 0.58 (Yamnotri, 26 radii) and 0.68 (Budhavan, 29 radii). Such high correlations for mesic sites at high-altitudes show good dating control among the samples as well as the presence of common signal among the samples, that is, climate.

Ring-width measurement series of trees were standardized to remove the biological growth trend as well as other low-frequency variations due to stand dynamic features using ARSTAN software15. Intertree competition is a dominant factor influencing tree growth at all the four sites, as the forests are closed-canopy. To strengthen the common signal present among the samples, we used twin detrending in which the ring-width series were first detrended with linear or negative exponential growth curve fitted by least squares. The detrended series were again filtered with a spline of 20 years length with 50% frequency response cut-off. The spline length was selected so as to maximize the correlation among the site chronologies. The indices for each series were derived by taking the ratio of the measurement over the fitted value for

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Figure 1. Map showing location of tree-ring sites (filled triangles) and meteorological stations (circle with dot in the centre).

Table 1. General statistics of *Abies spectabilis* chronologies

<table>
<thead>
<tr>
<th>Site</th>
<th>ALT (m)</th>
<th>CHRONOL  year (AD)</th>
<th>C/T</th>
<th>MS</th>
<th>SD</th>
<th>ARI</th>
<th>SSS/YR</th>
<th>CIAP</th>
<th>RBT</th>
<th>S/N</th>
<th>VIEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tola</td>
<td>3400</td>
<td>205 (1794–1998)</td>
<td>50/50</td>
<td>0.11</td>
<td>0.11</td>
<td>0.20</td>
<td>9/1841</td>
<td>1928–1997</td>
<td>0.37</td>
<td>24.36</td>
<td>39.95</td>
</tr>
<tr>
<td>Ghanghria</td>
<td>3100</td>
<td>356 (1644–1999)</td>
<td>27/16</td>
<td>0.12</td>
<td>0.12</td>
<td>0.31</td>
<td>11/1830</td>
<td>1866–1998</td>
<td>0.51</td>
<td>6.87</td>
<td>35.39</td>
</tr>
<tr>
<td>Yamnotri</td>
<td>3600</td>
<td>329 (1672–2000)</td>
<td>26/15</td>
<td>0.13</td>
<td>0.14</td>
<td>0.31</td>
<td>9/1740</td>
<td>1856–2000</td>
<td>0.37</td>
<td>8.23</td>
<td>41.03</td>
</tr>
<tr>
<td>Badhavan</td>
<td>3100</td>
<td>264 (1739–2002)</td>
<td>29/16</td>
<td>0.17</td>
<td>0.15</td>
<td>−0.04</td>
<td>6/1760</td>
<td>1835–2002</td>
<td>0.46</td>
<td>11.27</td>
<td>50.13</td>
</tr>
</tbody>
</table>

ALT (m), Site altitude in metres; CHRONOL, Chronology length; C/T, Cores/trees; MS, Mean sensitivity; SD, Standard deviation; ARI, Autocorrelation-order 1; SSS/YR, Tree cores required to achieve sub-sample signal strength 0.85/and year; CIAP, Common interval analysis period; RBT, Correlation between trees; S/N, Signal/noise ratio; VIEV, Variance explained in first eigenvector.

Each year, these indices were then prewhitened using an autoregressive model selected on the basis of the minimum Akaike criterion and combined across all series in each year using biweight robust estimation of the mean to discount the influence of outliers. A set of three chronologies—a standard chronology, a residual chronology containing only the high-frequency variations, and an arstan chronology composed of the residual chronology reincorporated with the pooled autoregression, were developed. The standard chronologies along with the constituent samples are shown in Figure 2.

To understand if there is spatial coherence in growth pattern of trees at four distant sites, we computed correlations among the chronologies for 30-year periods, with a slide of 10 years (Figure 3). For this purpose, common chronology period (1841–1998) with adequate sample replication was used.

Meteorological stations in the Himalayan region with long, homogeneous records are usually located far from the tree-ring sites and comparatively at lower elevations. The meteorological records from any such single station could not be assumed to be representative of regional
climate and may not provide ideal data for tree growth-climate relationship. Therefore, averaged series derived from two or more station records, which avoid many problems associated with record inhomogeneities and also differing station microclimates, provide potentially more reliable data to calibrate tree-ring chronologies.\textsuperscript{16,17}

It has been found that there is large-scale coherence in temperature records unlike precipitation, which shows great variation over relatively short distances depending upon slope, aspect and direction of the hills.\textsuperscript{18} For this reason only temperature records provide ideal data to study tree growth-climate relationship, even for the chronologies prepared from remote highland sites where meteorological records do not exist. We prepared regional temperature series by merging two homogeneous data sets from Mukteswar (29°28'N, 79°39'E; 2311 m asl; 1897–2000) and Shimla (31°18'N, 77°17'E; 2311 m asl; 1897–2000) in western Himalaya (Figure 1). The existence of strong coherence in temperature variations at two distant sites (around 300 km apart) as measured by correlation between temperature records of the respective months ($r = 0.58–0.95$, $p < 0.0001$) allowed us to prepare average temperature series by merging the two station data sets. The temperature correlations during the monsoon months (July–September) compared to non-monsoon months are weaker. High spatial variability in precipitation, which has moderating influence on temperature, could be the important reason for such a weak correlation for monsoon months. The mean temperature series show that January is the coldest month with average of 5.7°C and June the warmest month with an average of 19.2°C.

The correlation between the monthly precipitation of the above two stations was weak in comparison to temperature, and was statistically not significant during the monsoon months (July–September) due to high spatial variability\textsuperscript{19}. For high spatial variability in precipitation, we could not prepare the mean series for the present study.

We used response function analysis\textsuperscript{20} to identify the influence of temperature on tree growth. The residual chronologies and the mean monthly temperature beginning in September of the previous growth year and ending in October of the current growth year over the period 1897–1998 were used for this purpose (Figure 4a–d). Temperature data during months prior to the growing season were included in the response function study, because growing-season ring widths can integrate climate over longer periods.

We have developed four ring-width site chronologies (AD 1794–1998, 1644–1999, 1672–2000 and 1739–2002 respectively) of A. spectabilis growing at distantly located upper tree-line zones in western Himalaya. A com-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Tree-ring chronologies (standard) with number of tree cores used. \textit{a}, Tola (AD 1794–1998); \textit{b}, Gharghoria (AD 1644–1999); \textit{c}, Yamoshi (AD 1672–2000), and \textit{d}, Budhavan (AD 1739–2002).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Correlation among chronologies in different 30-year blocks from 1841 to 1998 with slide of 10 years. Dotted line represents 95\% confidence limit. \textit{a–d}, Same as in Figure 2.}
\end{figure}
Table 2. Correlation between ring-width site chronologies (residual) and May and mean spring
(>April–May) temperature with \( p \) values given in brackets

<table>
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<tbody>
<tr>
<td>Tola</td>
<td>May</td>
<td>−0.23 (0.02)</td>
<td>−0.41 (0.02)</td>
<td>−0.03 (0.9)</td>
<td>−0.28 (0.14)</td>
</tr>
<tr>
<td></td>
<td>April–May</td>
<td>−0.11 (0.3)</td>
<td>−0.15 (0.41)</td>
<td>−0.06 (0.77)</td>
<td>−0.19 (0.30)</td>
</tr>
<tr>
<td>Ghangria</td>
<td>May</td>
<td>−0.42 (0.0001)</td>
<td>−0.55 (0.0007)</td>
<td>−0.40 (0.03)</td>
<td>−0.36 (0.05)</td>
</tr>
<tr>
<td></td>
<td>April–May</td>
<td>−0.37 (0.0001)</td>
<td>−0.55 (0.0006)</td>
<td>−0.30 (0.11)</td>
<td>−0.31 (0.09)</td>
</tr>
<tr>
<td>Yamnotri</td>
<td>May</td>
<td>−0.24 (0.01)</td>
<td>−0.31 (0.07)</td>
<td>−0.23 (0.21)</td>
<td>−0.12 (0.50)</td>
</tr>
<tr>
<td></td>
<td>April–May</td>
<td>−0.26 (0.008)</td>
<td>−0.36 (0.04)</td>
<td>−0.18 (0.33)</td>
<td>−0.09 (0.60)</td>
</tr>
<tr>
<td>Budhavan</td>
<td>May</td>
<td>−0.31 (0.004)</td>
<td>−0.45 (0.007)</td>
<td>−0.09 (0.60)</td>
<td>−0.34 (0.07)</td>
</tr>
<tr>
<td></td>
<td>April–May</td>
<td>−0.33 (0.0006)</td>
<td>−0.43 (0.01)</td>
<td>−0.28 (0.13)</td>
<td>−0.32 (0.09)</td>
</tr>
</tbody>
</table>

Figure 4. Response function of the residual chronologies with mean monthly temperature (1897–1998). Vertical bars are 95% confidence limits. a–d, Same as in Figure 2.

Comparison of site chronology statistics such as mean sensitivity, standard deviation and autocorrelation shows that trees growing on rocky sites are more sensitive to environmental changes (Table 1). The general statistics of the chronologies prepared by us are similar to ring-width chronologies of A. spectabilis prepared from Nepal Himalaya \(^2\,\,\,^2\). The chronology features indicate that relatively fewer samples are required from rocky sites with thin soil cover, to obtain chronology suitable for climatic studies (subsample signal strength 0.85, measured by combination of mean interseries correlation and the number of tree-core samples represented in the chronology)\(^3\). Good correlation among the chronologies from distant locations (Figure 3) demonstrates the existence of spatially coherent modes in tree ring-width variation that could possibly be due to climate, largely temperature, forcing on tree growth. However, records of weaker correlations during some periods show the existence of site-specific variations.

The response function analyses have indicated that the tree growth at almost all the sites, irrespective of altitude, has indirect relationship with April–May temperature, except at Tola where only May temperature is significant (Figure 4 a). The Yamnotri site chronology showed significant relation for longer season (April–July; Figure 4 c). The differences in response function features at different sites show that edaphic factors play an important role in modulating the influence of temperature on growth of trees. Indirect relationship with temperature of spring months shows that warm springs, causing increased evapotranspiration, lead to soil-moisture deficit. Thus, reduced soil-moisture availability during the onset of growing season is deterrent for tree growth. At such heights, due to thin air and clear atmosphere, the solar insolation is also high. Intense insolation during warm springs further accelerates the evapotranspiration.

Mean April–May temperature series (1897–1998) showed significant correlation with ring-width chronologies, except for the Tola series where only May temperature has significant relationship. The correlations were again computed during three sub-periods; 1897–1930, 1931–60, and 1961–90, to see the temporal stability in tree growth and temperature relationship. These sub-periods were selected on the basis of temperature trend present in the series. The analyses of mean April–May and May temperature series showed cooling during 1897–1930 (April–May 0.09, and May 0.18°C per decade), warming during 1931–60 (April–May 0.06, and May 0.32°C per decade)
and again cooling during 1961–90 (April–May 0.1, and May 0.05°C per decade) respectively; none being statistically significant. The 1990s showed resilience of warming, but still the 1940s was the warmest decade of the 20th century in the region.

However, the mean annual temperature series show that the 20th century warmed up by 0.6°C. Seasonal differences are noted in temperature trend with winters (December–February) showing maximum warming in the 20th century (1°C). During the three sub-periods, strongest correlation was seen during 1897–1930, which declined in the other two sub-periods (Table 2). Similar weakening in tree growth and temperature (April–June) relationship was earlier noted in Taxus baccata chronology prepared from subalpine forest in Yamnotri. Studies from elsewhere in the high-latitude northern hemisphere regions have also indicated a decline in tree growth and temperature relationship towards the later part of the 20th century. This has been attributed to increasing winter precipitation on the starting date of the growing season. However, to arrive at any definitive conclusion, more tree-ring and climate data are required. For climate data from tree-line areas of the Himalayan region, where it is not feasible to man the weather observatories, automated weather stations are needed to be set up. Such data would be useful for better understanding of tree growth–climate relationship at climatically sensitive high-altitude regions.


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