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## Basin specificity of climate change in western Himalaya, India: Tree-ring evidences

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**Tree-ring-width chronologies of Himalayan cedar (*Cedrus deodara*) from moisture-stressed sites in Alaknanda, Bhagirathi, Tons, Satluj (lower) and Chandra-Bhaga river basins in western Himalaya were studied to understand the basin-specific as well as synoptic-scale features of climate change. In the past 325 years, extreme cool and wet climate during 1734 and 1803 and extreme hot and dry climate during 1705, 1707, 1767, 1774, 1782, 1873, 1887, 1890, 1892 and 1974, common in all the basins, reflect synoptic-scale features. However, in 1816, extreme low growth in trees over all the basins could have resulted due to reduced photosynthesis caused by impaired solar radiation reaching the ground**

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**because of aerosol load in the stratosphere ejected by the Tambora volcanic eruption. The cool and wet extremes are more basin-specific compared to the hot and dry ones. Basin-specific cool and wet climates are due to strong orography-influenced variability in precipitation.**

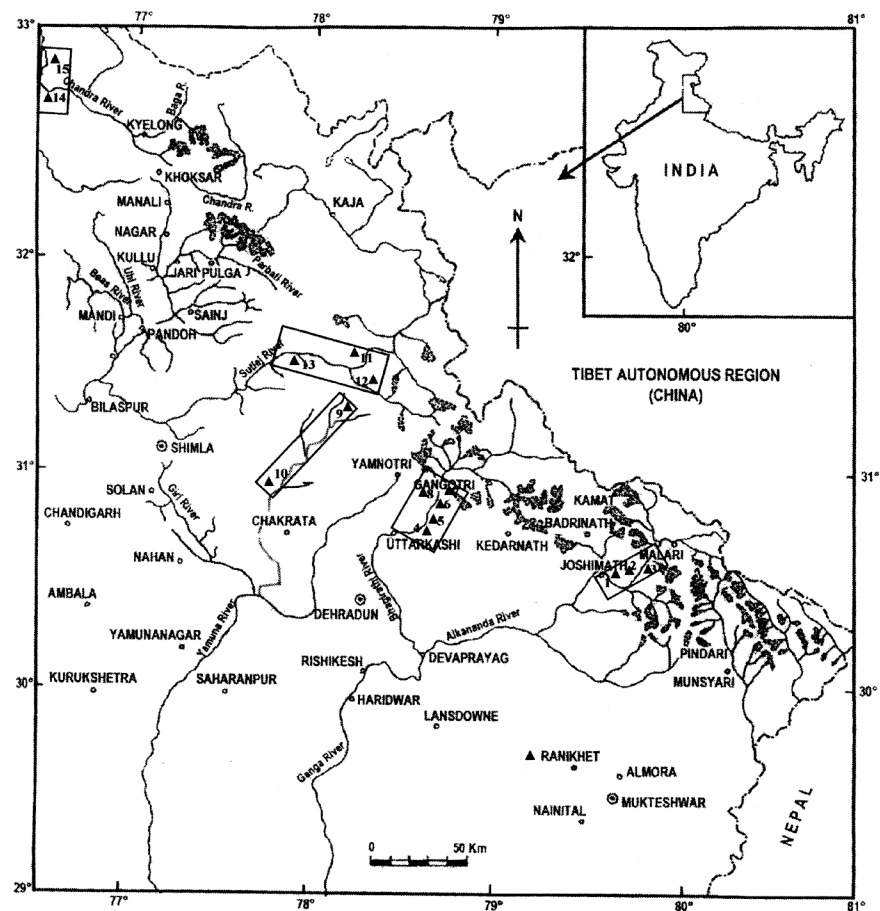
**Keywords:** Climate change, Himalayan cedar, tree rings, volcanic eruption.

IN mountain regions, climate varies at short distances due to strong topographic forcing, and also the amplitude of such changes is high at high elevations due to the relatively greater sensitivity to climate change<sup>1,2</sup>. Concerns were raised for such a high climate variability in the mountains and its societal relevance during the 1992 Earth Summit at Rio de Janeiro<sup>3</sup>. In the Himalayan region, climate, especially precipitation, varies at local and mesoscale levels owing to complicated relief, direction of ridges, degree of slope, sunny or shady aspects of slope and forest cover<sup>4</sup>. Instrumental weather records from the western Himalayan region for the past century show increasing trend in temperature at the rate of around 0.6°C/100 years. However, no such long-term trend has been noted in precipitation. The severity of temperature effect on vegetation is moderated by precipitation, which is highly location-specific under strong topographic influence. The rising temperature, even if the total precipitation remains around the long-term mean, will perturb the equilibrium state of vegetation. The magnitude of the impact of climate change would be relatively high at marginal ecosystem sites where vegetation is at its threshold limit of climate. Many of the plant species growing at upper elevation limits in the western Himalaya have been found shifting to higher elevations, though the rate was species- and site-specific<sup>5</sup>. The lower limits of apple orchards in western Himalaya have significantly extended upwards during the last few decades of the 20th century. However, the impact of climate change on vegetation and cropping system is expected to vary over basins depending on the basin-specific orographic influence on climate.

Our understanding of the local and synoptic-scale climate features in the Himalayan region is limited due to lack of sufficient weather records from low- and high-elevation regions of orographically separated basins. Long-term high-resolution proxy climate records offer valuable data to understand climatic sensitivity of different orographically separated basins. Though a network of tree-ring chronologies from the western Himalayan region has been used to infer the long-term regional climate features<sup>6-9</sup>, no attempt has been made to understand the climatic features of orographically separated basins. The overarching goal of the present study was to investigate the specificity of climate in Alaknanda, Bhagirathi, Tons, Satluj (henceforth used for lower Satluj basin) and Chandra-Bhaga basins in western Himalaya using high-resolution tree-ring records.

Tree-ring-width chronologies of Himalayan cedar prepared from tree-ring samples in the moisture stressed sites at Alaknanda, Bhagirathi, Tons, Satluj and Chandra-Bhaga river basins in western Himalaya (Figure 1), collected during various field trips in western Himalaya from 1996 to 2005, were used in the present study. Details about the collection of tree-ring materials, methodology used in dating of tree-ring sequences in samples and chronology preparation have been described elsewhere<sup>6-9</sup>. Computer programs COFECHA<sup>10</sup> and ARSTAN<sup>11,12</sup> were used for verification of dating and chronology preparation respectively. Tree-ring measurements were standardized to remove the biological growth trend as well as other low-frequency variations due to stand dynamics features and maximize the common signal among individual tree-ring chronologies. For this, double detrending using negative exponential or linear growth curves fitted by least squares and cubic spline with two-third of the series length and 50% frequency response cut-off, were applied. Residual chronologies containing high-frequency variations in series were taken for further analyses. Chronology details are given in Table 1. The expressed population signal (eps), which considers inter-series correlation and sample size to estimate how well a finite number of samples represent the theoretical population average<sup>13</sup>, exceeding the threshold value of 0.85 was used to select the chronology length for further studies. The common chronology period with sufficient sample replication (eps > 0.85) in the respective basins was selected for principal-component analyses. The principal components of the series from a basin represent per cent common variance in the chronologies used. The first principal component derived from chronologies in the respective basins showing per cent common variance always higher than 90% represents common forcing on tree growth, i.e. climate. The principal components from different basins (1675–1996, 1675–1999, 1675–2002, 1675–2005 and 1675–2003) plotted together are shown in Figure 2. Positive scores between 1, 2 and >2 and negative scores between –1, –2 and <–2 standard deviation were considered as extreme and very extreme growth years (Figure 3).

The Alaknanda, Bhagirathi and Tons basins on the southern slope of the Himalayan divide are under the influence of a strong southwest summer monsoon and receive summer rains from the mid-June to mid-September. Winter depressions from January to March cause snowfall. April and May are marked by thundershowers and hailstorms. Usually in May and during the first half of June, before the break of the monsoon, convectional rains occur commonly in the afternoon every third to fourth day often at high elevations<sup>14</sup>. The average annual precipitation in this region as reflected from Shimla weather station is around 1460 mm. The lower Satluj basin receives summer monsoon, whereas upper Satluj basin falls under the monsoon shadow zone. Tree-ring sites used in the present study are in the lower Satluj basin which experiences feeble



**Figure 1.** Map showing location of tree-ring sites. Alaknanda basin: 1, Juma; 2, Kosa; 3, Tolma; Bhagirathi basin: 4, Dharali III; 5, Dharali IV; 6, Gangotri IV; 7, Jangla; 8, Mukhaba; Tons basin: 9, Balcha; 10, Devata; Satluj basin: 11, Roghi; 12, Purbani; 13, Ralli; Chandra-Bhaga basin: 14, Madgram; 15, Ratoli.

**Table 1.** Ring-width chronologies of Himalayan cedar from different western Himalayan sites used in study

Basin	Site	Altitude (m asl)	Chronology length (years)	Chronology cut-off year with eps >0.85
Alaknanda	Juma	2770	1339–1996	AD 1590
	Kosa	3040	1560–1996	AD 1585
	Tolma	2630	1339–1996	AD 1390
Bhagirathi	Dharali III	2790	1558–1999	AD 1610
	Dharali IV	3060	1560–1999	AD 1645
	Gangotri IV	3200	1584–1999	AD 1640
	Jangla	2980	1086–2002	AD 1315
	Mukhaba III	2820	1558–1999	AD 1610
Tons	Balcha	2630	1274–2002	AD 1355
	Devata	2770	1491–2002	AD 1675
Satluj	Roghi	2900	1389–2005	AD 1440
	Purbani	3000	1286–2005	AD 1415
	Ralli	2700	1456–2005	AD 1510
Chandra-Bhaga	Madgram	2650	1276–2003	AD 1430
	Ratoli	2700	1217–2003	AD 1470

summer monsoon. Weather records for Kalpa in Kinnaur (lower Satluj basin; AD 1951–2004) show around 584 mm annual precipitation. The Chandra-Bhaga valley falls in the trans Himalayan region with very little summer monsoon

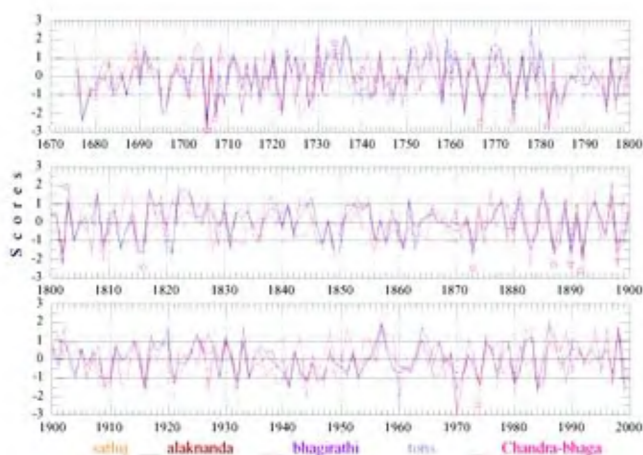
rainfall. Most of the precipitation occurs in winter. Precipitation records for Keylong in Chandra-Bhaga basin show around 648 mm of annual precipitation. Climate reconstruction for the above specific basins could not be

attempted due to lack of sufficient weather records required to calibrate tree-ring data.

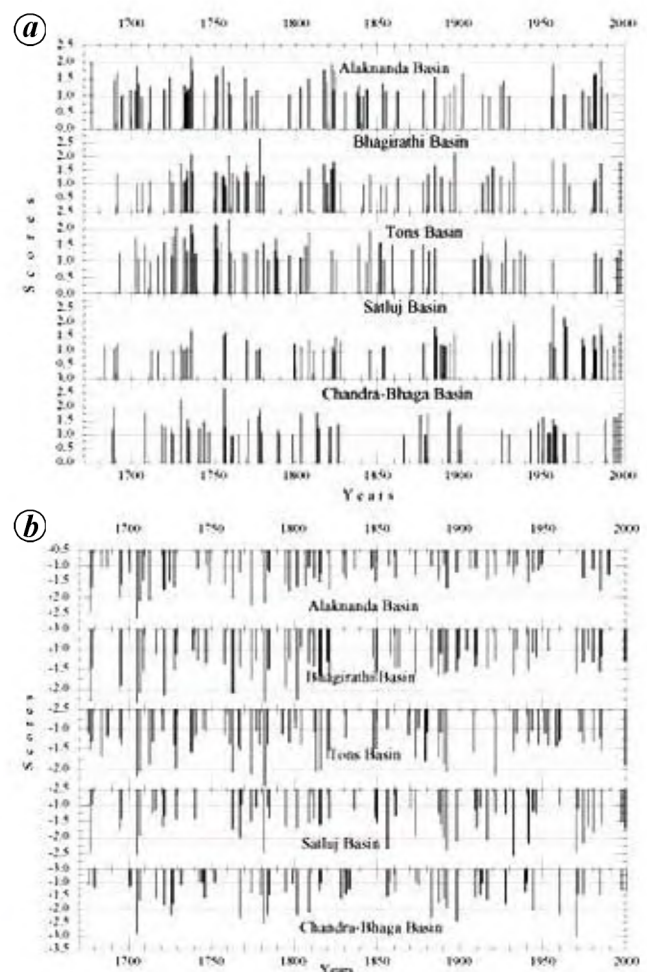
Previous studies on the relationship between tree-ring-width chronologies prepared from various moisture-stressed sites under the summer monsoon zone in the western Himalaya have indicated that growth of Himalayan cedar, *Cedrus deodara* (Roxb.) D. Don is favoured by cool and wet climate during non-monsoon months, the relationship being stronger during premonsoon<sup>6-9,15</sup>. However, the chronologies from Chandra-Bhaga basin showed direct relationship with precipitation over the full dendrochronological year (October of the previous year to September of the current year)<sup>16</sup>. Therefore, positive scores in first principal components from different basins reflect cool and wet climate whereas negative scores reflect warm and dry climate during the respective years. Annual fluctuations in principal components in basins on the southern slope of the Himalaya under the influence of summer monsoon are strongly correlated, except for the Tons basin which showed weaker relationship with others (Table 2). However, in the trans Himalayan region, the Chandra-Bhaga basin stands out for its weak relationship with other basins, the weakest being with Tons basin. The cool and wet years are far less common among the basins compared to the warm and dry years. Poor coherence in cool and wet years in different basins shows that the precipitation is strongly affected by orographic conditions specific to basins. The high growth scores recorded during 1734 and 1803 indicating cool and wet climate, and low growth scores during 1705, 1707, 1767, 1774, 1782, 1873, 1887, 1890, 1892 and 1974 indicating warm and dry climate represent synoptic-scale features. However, the cause of extreme growth reduction in trees over all the basins during 1815 and 1816 coinciding with the Tambora eruption deserves special mention here. Growth rings of 1815 and 1816 in Himalayan cedar trees over all the basins were narrow. In many cases, the 1816 ring was missing in tree samples and occasionally

had traumatic resin ducts in the late wood portion, both features indicating extreme environmental stress on trees. It is hypothesized that extreme low growth in trees in 1816 over all the basins could have resulted due to reduced photosynthesis caused by impaired solar radiation reaching the ground because of aerosol load in the stratosphere ejected by the Tambora volcanic eruption, and not hot and dry weather as implicit from previous tree growth and climate relationship studies<sup>6-9,15</sup>.

The Tambora volcano in Indonesia erupted on 10 April 1815, sending a massive cloud of aerosols into the stratosphere. The volcanic soot drifted around the earth and reduced solar radiation reaching the ground the following year, i.e. 1816, causing dramatic weather changes. Volcanic sulphates in ice cores from Greenland associated with the Tambora eruption<sup>17</sup> endorse high explosivity of the eruption. The year 1816, known as the 'year without summer' in Europe, experienced extreme weather conditions in the northern hemisphere due to impaired solar radiation reaching the ground<sup>18</sup>. India had crop failure following



**Figure 2.** Principal component series (derived from tree-ring-width chronologies in the respective sites). Horizontal lines above and below zero value are one standard deviation.



**Figure 3.** Principal components (above one standard deviation) from different basins plotted to show years with extreme growth under cool and wet ((a) positive scores), and hot and dry ((b) negative scores). Horizontal lines are one and two standard deviations.

**Table 2.** Correlation between principal component series from different basins

Period		Bhagirathi	Tons	Satluj	Chandra-Bhaga
1675–1996	Alaknanda	0.83 (0.0001)	0.57 (0.0001)	0.71 (0.0001)	0.30 (0.0001)
1675–1699		0.86 (0.0001)	0.54 (0.0057)	0.84 (0.0001)	0.27 (0.2001)
1700–1749		0.78 (0.0001)	0.59 (0.0001)	0.66 (0.0001)	0.28 (0.047)
1750–1799		0.84 (0.0001)	0.68 (0.0001)	0.67 (0.0001)	0.37 (0.008)
1800–1849		0.88 (0.0001)	0.58 (0.0001)	0.79 (0.0001)	0.24 (0.097)
1850–1899		0.87 (0.0001)	0.63 (0.0001)	0.80 (0.0001)	0.45 (0.0011)
1900–1949		0.85 (0.0001)	0.44 (0.0012)	0.67 (0.0001)	0.25 (0.0786)
1950–1996		0.78 (0.0001)	0.50 (0.0003)	0.70 (0.0001)	0.26 (0.0709)
1675–1996	Bhagirathi	1.00 (0.0)	0.63 (0.0001)	0.84 (0.0001)	0.44 (0.0001)
1675–1699			0.63 (0.0007)	0.84 (0.0001)	0.27 (0.1864)
1700–1749			0.71 (0.0001)	0.85 (0.0001)	0.45 (0.0011)
1750–1799			0.64 (0.0001)	0.82 (0.0001)	0.53 (0.0001)
1800–1849			0.65 (0.0001)	0.92 (0.0001)	0.34 (0.0158)
1850–1899			0.65 (0.0001)	0.87 (0.0001)	0.55 (0.0001)
1900–1949			0.47 (0.0006)	0.80 (0.0001)	0.343 (0.0146)
1950–1996			0.64 (0.0001)	0.90 (0.0001)	0.48 (0.0006)
1675–1996	Tons		1.00 (0.0)	0.57 (0.0001)	0.22 (0.0001)
1675–1699				0.45 (0.0232)	0.033 (0.8746)
1700–1749				0.68 (0.0001)	0.34 (0.0168)
1750–1799				0.59 (0.0001)	0.25 (0.0773)
1800–1849				0.61 (0.0001)	0.08 (0.5788)
1850–1899				0.67 (0.0001)	0.34 (0.0154)
1900–1949				0.40 (0.0035)	0.015 (0.919)
1950–1996				0.58 (0.0001)	0.23 (0.1257)
1675–1996	Satluj			1.00 (0.0)	0.50 (0.0001)
1675–1699					0.25 (0.2307)
1700–1749					0.43 (0.0017)
1750–1799					0.59 (0.0001)
1800–1849					0.32 (0.0218)
1850–1899					0.58 (0.0001)
1900–1949					0.56 (0.0001)
1950–1996					0.53 (0.0001)

the Tambora eruption, but the cause for it is not yet well ascertained. On the basis of the established tree-growth and climate (temperature and precipitation) calibrations using tree-ring-width chronologies developed from various moisture-stressed sites in western Himalaya<sup>6–9,15</sup>, extremely low growth in Himalayan cedar trees during 1816 could be assumed to be caused by warm and dry climate. However, contrary to this, tree-ring reconstructions from Nepal (Central) Himalaya<sup>19</sup> showed cool conditions during 1816. Considering the large-scale climatic effect of the Tambora eruption as reported from elsewhere<sup>20,21</sup>, it is assumed that similar climatic conditions over the two regions of the Himalaya could have prevailed during 1816. However, records of contrasting temperature anomalies in the western and central parts of the Himalaya in 1816 inferred from tree rings could only be possible if the limiting factor affecting the growth of trees changed in either of the two regions. Ash deposits recognized in sediment cores of Karachi in northeastern Arabian Sea related to the Tambora eruption<sup>22</sup>, indicate heavy aerosol load in the atmosphere over the Indian subcontinent. The thick aerosol cloud over the region could have hindered the solar radiation from reaching the ground. The reduced solar radiation caused by the Tambora eruption affecting photo-

synthesis might have led to poor growth of Himalayan cedar at moisture-stressed sites in the western Himalaya. However, this needs to be tested using other high-resolution climate proxies. Studies have shown that the concentration of  $\delta^{13}\text{C}$  in tree rings could be related to changes in light level<sup>23,24</sup>. The decreasing solar irradiance leads to low photosynthetic activity and increased inter-cellular  $\text{CO}_2$  concentration, resulting in a relative depletion in  $\delta^{13}\text{C}$ . Therefore, the concentration of  $\delta^{13}\text{C}$  in tree rings of Himalayan cedar from the western Himalaya, where tree growth is limited by moisture stress accentuated by higher temperature, could provide valuable information to verify extreme climatic events such as that of 1816. Such records gleaned from multi-proxies should provide valuable clues to understand the relative sensitivity of the region to climate forcing, such as volcanic eruption.

It has been noted that contrasting climatic extremes often occurred in different basins and more frequently in Tons and Chandra-Bhaga during the early part of the 20th century (Figure 3). Contrary to the pattern noted in the Tons basin, the number of extreme cool and wet years increased in the Satluj and Chandra-Bhaga basins during the latter part of the 20th century compared to the early part of the century. Percentile distribution of scores in principal component

series from different basins showed that Satluj and Chandra-Bhaga are relatively prone to extreme hot and dry climatic events relative to other basins. The five percentile data distribution limits showed that the magnitude of hot and dry climate extremes gradually increased in the Satluj basin contrary to the relative decrease in Alaknanda, Bhagirathi and Tons basins over around the past three centuries. However, no such shift was noticeable in the magnitude of cool and wet extremities in the basins, except Satluj where it increased during the latter part of the 20th century. Such changing pattern in climatic conditions, as inferred from tree rings is bound to have significant impact on biodiversity and agriculture practices over the specific regions.

Tree-ring-width chronologies of Himalayan cedar prepared from moisture-stressed sites in Alaknanda, Bhagirathi, Tons, Satluj and Chandra-Bhaga river basins were analysed to understand basin specificity in climate change during the past 325 years. The study revealed cool and wet climatic extremes to be more basin-specific compared to hot and dry ones, largely due to strong orographic control on precipitation. The cool and wet extremes do not show any pattern, except in Tons and Bhagirathi basins where the magnitude gradually decreased towards the latter part of the 20th century. Alaknanda, Satluj and Chandra-Bhaga basins experienced higher magnitude cool and wet extremes during the latter part of the 20th century. Such a divergent pattern of climate extremes in different basins due to anthropogenic impact or subtle change in climate will have significant impact on biodiversity and socio-economy of the region.

Extreme hot and dry climate during 1816 in the western Himalaya as inferred from tree rings when large-scale cooling coinciding with the Tambora eruption was reported from other regions, needs to be verified using additional proxies like  $\delta^{13}\text{C}$ . Such multiproxy cross-validations would help in arriving at valid conclusions required for understanding the relative importance of volcanic forcing on climate.

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