Would tree ring data of *Betula utilis* be potential for the analysis of Himalayan glacial fluctuations?

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Tree rings of Birch (Betula utilis) growing along moraines around Bhojbasa, close to the snout of Gangotri glacier, Garhwal Himalaya have been analysed to assess relationships among tree growth/climate vis-à-vis glacial fluctuations. It has been noted that the growth of this tree has negative relationship with temperature of January, March and April, and direct relationship with precipitation of March, April and June, and temperature of February. Moreover, increased tree growth in recent years has also been recorded coinciding with the rapid retreat of Gangotri glacier. It could be hypothesized that the fast retreat of this glacier might be the cumulative effect of several climatic parameters which enhance tree growth, i.e. increased precipitation of March, April and June associated with increased winter temperature and low snowfall.

Keywords: *Betula utilis*, Gangotri glacier, glacial fluctuations, tree rings.

TREE line in the Himalayan region varies from site to site depending on the position of the snow line. Its location in the western part of the Himalayas is at about 3600 m. It descends as low as 2550 m in Gilgit or is as high as 5000 m at Thalle La in the Karokoram range[1]. Trees confined at the upper tree line ecotone are found to be much sensitive to both climatic changes and glacier fluctuations. Hence tree ring data of these trees seem to be potential archives to analyse temporal variations of climate as well as glacial advance and retreat. Most of the tree studies from this region are confined to conifers[2–8] and from sites located far away from the present-day glacier snout. No attempt had been made earlier to analyse tree ring data of broad-leaved taxa growing close to the glacier snout from the Himalayan region.

Birch (*Betula utilis*) is a medium sized deciduous tree that often forms an open forest at the upper tree line[9] close to the snout of many glaciers extending over the entire Himalayan region. Due to its close proximity to the glaciers, temporal growth behaviour of this tree might be linked with the glacial dynamics of the Himalayan region. Here tree ring analysis of birch, a broad-leaved taxa growing at 3900 masl about 3 km south of the snout of the Gangotri glacier, has been discussed in terms of its dendroclimatic perspective and its probable linkage with the climatic changes of the region and fluctuations of the Gangotri glacier.

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Location of study site and material collection

Tree-ring samples were collected from birch trees growing along moraines at Bhojbasa, about 2.5–3 km downstream from the present position of the snout of the Gangotri glacier (Figure 1). This site is characterized by sub-alpine open forest with a few birch trees along with *Salix* forming the upper tree line zone (Figure 2). Conifers (*Pinus wallichiana*) grow at a distance of 6 km towards down stream at an altitude of ca. 3700 masl.

Generally, two increment cores, one each at the opposite direction per tree at breast height were collected. In a few cases only one core was collected as the other side was not suitable for collecting samples. From this site 53 cores were collected from 26 trees attaining 10 to 15 m height and 1–2.5 m in girth (Figure 3), growing on moderately steep slopes. Most of the birch trees have been cut down for the purpose of fuel wood. However a few are left, as the area is now designated as protected forest. The vegetation just above this zone, in the vicinity of the glacier, is characterized by alpine steppe-type.

Climate and glacial history

The Gangotri glacier situated in the Uttarkashi district, Uttaranchal, western Himalaya, is one of the largest valley glaciers of India[10]. The glacier is around 30 km long, 0.5–2.5 km wide and covers an area of around 143.58 km^2 (ref. 10). It originates from the Chaukhamba group of peaks (7001 masl) and flows in the northwesterly direction forming the source of Bhagirathi River at Gaumukh

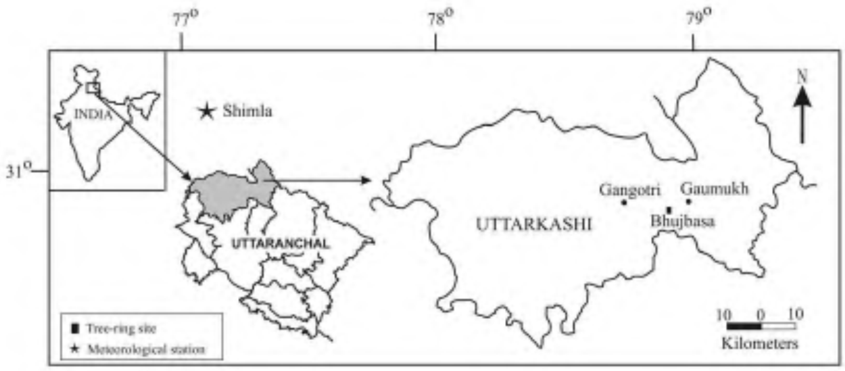

Figure 1. Location of tree-ring sampling site and meteorological station used in the study.

Figure 2. Out wash plain and a patch of birch (*Betula utilis*) forest on moraine deposits around Bhojbasa. Tl, Tree line; Tm, Terminal moraines; G, Gangotri glacier and Tr-SS, Tree-ring sampling site.

Figure 3. Collection of samples (tree-cores) from birch trees through increment borer.

(4000 masl). Long climatic records around Gangotri glacier are not available, since regular meteorological monitoring was started only a few years back by the Department of SASE, Chandigarh and NIH, Roorkee. The area receives rainfall during monsoon months from June to September. Snow falls during winter and spring. Based on the available meteorological data (for the period 2000–03 and for months for May–October), it has been noted that rainfall is highly variable (131.4–368.8 mm) from year to year, with the average seasonal rainfall being about 260 mm. Average daily maximum and minimum temperature is 14.7 and 4.1°C respectively, whereas average mean temperature is 9.4°C. July has been recorded as the warmest month[11].

In the Himalayan region in general, the meteorological stations are few and situated mostly at lower elevations. This makes it difficult to use climatic data to build climate/ tree growth/glacial fluctuation relationships at the upper tree line. Similarly, glacier mass balance data also are not available for longer duration for any particular Himalayan glaciers. Systematic glacier monitoring has only been started since the last few decades through contributions mainly from the GSI. Annual data for a particular glacier for a long and continuous period are not available till date. It has been recorded that negative mass balance is a common feature of most of these glaciers[10,12], except positive glacial mass balance recorded in two glaciers, e.g. Gara glacier during 1974–75, 1975–76 (ref. 13) and during 1982–83 (ref. 14) and in Gor Garang during 1981–82 (ref. 15); both these glaciers are located in Kinnaur, Himachal Pradesh. Among all the glacier surveys in our country, the Gangotri glacier has been given special attention, and in recent years besides GSI, other organizations have also made contributions. The rapid retreat of this glacier during the last several decades has also been a common feature like other Himalayan glaciers. Recently[16], the recession pattern of Gangotri glacier has been compiled since AD 1935. It shows that during 1935–56, annual snout retreat was low (10.16 m), while it was maximum during 1975–76 (38.00 m). During 1977–96, the retreat was about 28.20 m. Another study[17] showed that the recession is about 850 m since 1971–95 (i.e. at the rate of 34 m/yr). The study also estimated about 2 km of retreat over the last 200 years and that the retreat was slower prior to 1971. Recession during 1996–99 was again recorded[18] slower, i.e. at the rate of 19 m/yr.

Tree-ring chronology preparation

Samples were mounted and processed using standard procedures of tree-ring analysis[19–21]. Boundaries of tree-ring in birch are faint, delineated by a light line of terminal parenchyma (Figure 4). Thus counting of rings under stereo zoom microscope requires careful examination. Moreover, there are missing rings in many of these cores. Out of 8920 rings counted, 91 (1.0202%) are found missing. Each ring of these cores was dated to the calendar year of its formation using the cross-dating technique[22]. Ring widths of each dated core were measured using an increment-measuring stage with 0.001 mm precision coupled with a microcomputer. Later, these measurements and dates were checked using the computer program COFECHA[23,24]. Cores having errors were re-examined to evaluate the source of errors and corrections were made. Ring-width data were standardized using the program ARSTAN[25,26], which removes growth trends related to age and stand dynamics while retaining the maximum common signal to form tree-ring indices. In the present study, we applied double-detrending methods with a negative exponential or linear regression equation in the first step and a 30-yr smoothing spline in the second step. Finally, 432 years long tree-ring chronology of this species has been established, which extends from AD 1571 to 2002 (Figure 5).

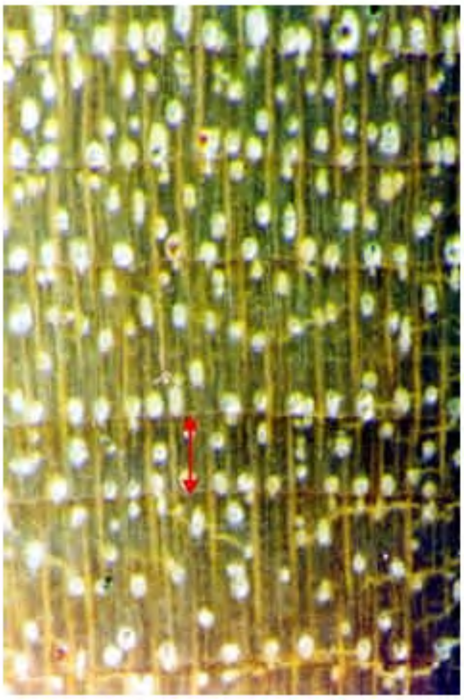

Figure 4. Tree-ring feature of birch (arrow indicates one annual ring).

Several descriptive statistics were calculated to describe the site chronologies (Table 1). Mean sensitivity (MS), a measure of the mean percentage change from each measured yearly ring value to the next, ranges from 0 where there is no difference to 2 where zero value (an absent or missing ring) occurs next to 1, with high mean sensitivity measurements interpreted as an indication that the ring-width series may have dendroclimatological utility[19]. The MS value in this site chronology has been found to be (0.24). Autocorrelation is the association between ring width for the year ($t - 1$) and the subsequently formed ring t, $t + 1$, to $t + k$. In this chronology the value is moderate (0.41), which indicates that some persistence trend exists. Expressed population signal (EPS) is a measure of the correlation between the mean chronology derived from the core samples and the population from which they were drawn. A value of 0.85 has been put forward as a reasonable threshold[27] and is exceeded here (0.928). Strength of signal between trees (common variance) has been estimated by calculating the signal-to-noise ratio[27,28] which is 12.96.

Tree growth and climate relationship

Climatic variables, which seem to be significant in limiting the growth of birch in this region, were determined through orthogonal bootstrap regression[29]. A large number of regressions (called response functions) are tested between standardized tree-ring series and various climatic variables. Out of these, temperature during January–April, and pre-

Table 1. Selected statistics of tree-ring chronology of *Betula utilis* at Bhojbasa Gangotri

Chronology time span	AD 1571–2002
Number of trees (radii)	26 (53)
Mean sensitivity	0.2424
Standard deviation	0.2884
Autocorrelation order 1	0.4129
Common interval time span	AD 1891–1952
Number of trees (radii)	23 (40)
Mean correlations among all radii	0.370
Mean correlations between trees	0.360
Mean correlations within trees	0.643
Signal-to-noise ratio	12.962
Expressed population signal	0.928
Variance explained	40.54%

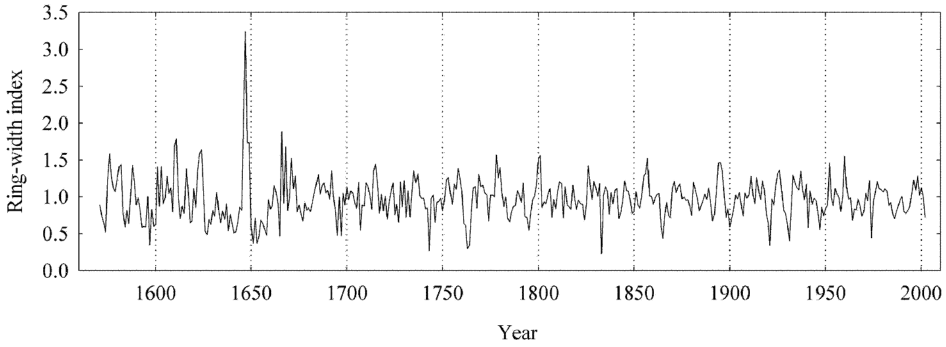

Figure 5. Tree-ring chronology of birch extending from AD 1571 to 2002 at Bhojbasa.

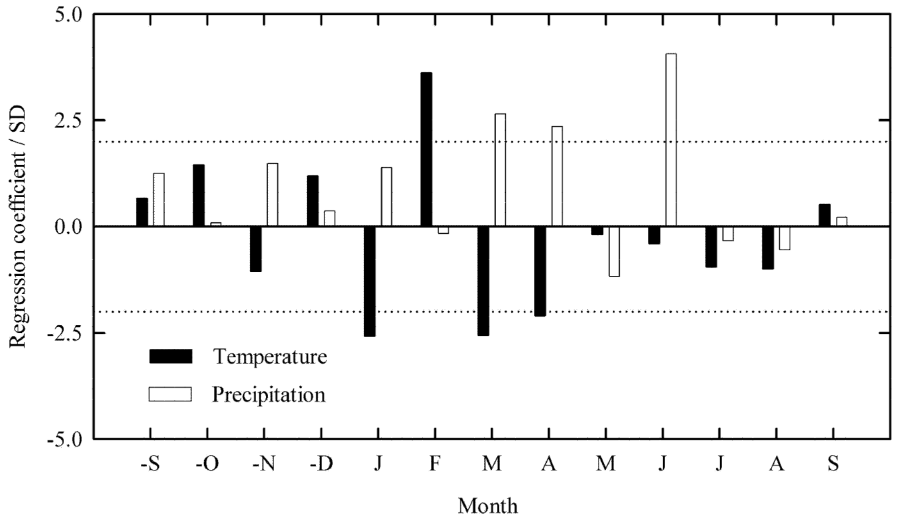

Figure 6. Response function plot of birch showing tree growth/climate (with mean temperature and total precipitation of Shimla) relationships (dotted horizontal line indicates significance level ($P < 0.05$) above and below).

cipitation during March, April and June are found to be significant (Figure 6). Due to non-availability of long climatic records close to the sampling site, an attempt was made to find out growth response in relation to available long climatic records of Shimla station. The climatic records (mean temperature and total precipitation) cover a time span of AD 1876–1988 and AD 1963–88 respectively, with some missing values. All missing values in these climatic records were estimated using the computer program MET of the Dendrochronology Program Library (developed by the Laboratory of Tree Ring Research, Tucson, Arizona, USA). In the analysis of tree growth and climate relationship, climatic data from AD 1877 to 1988 (mean monthly temperature and monthly precipitation) and corresponding length of tree ring width data over an interval starting from September of the prior growth year to the September of the current growth year were considered. This study reveals that warmer condition and low precipitation during March and April are not favourable for growth. Higher temperature and less rainfall during these months lead to reduced ring width due to higher evapo-transpiration. Several other studies from the western Himalayan region also reveal that most of conifers exhibit negative response to pre-monsoon temperature[4–8]. Thus it appears that the pre-monsoon temperature has a vital role in the growth of both broad-leaved as well as conifers of this region. Persistent low temperature during winter at higher elevations for a longer period declines the rate of both photosynthesis and respiration, but sudden increase in temperature for a short period favours respiration over photosynthesis. As a result, there is loss of stored food[30]. This may be the reason for a negative relationship with the January temperature. Physiological studies on sub-alpine conifers growing in the Alps have shown that at low temperature, water movements into the trees decreases sharply, resulting in stomatal closure and decreased carbon assimilation[30]. But the positive relationship with increased winter temperature (during February) and tree growth recorded here might be due to the fact that the temperature during this period could not reach a lower value to favour respiration over photosynthesis. Generally, the minimum temperature for net photosynthesis lies between –2 and –5°C, while respiration has been measured at –12°C (ref. 31).

Temporal tree growth/climate/glacier relationship

It is expected that cold winds blowing from the glacier have a significant role in reducing the growth of trees in the vicinity. This impact could be more in the years of an advancing glacier and might have caused lower tree growth for a considerable period by reducing the growing period. It has been recorded that birch trees have exhibited declined growth during years of either glacial advancement or having positive mass balance in the western Himalayan region. Tree growth has been recorded low during AD 1860–69 and AD 1890–1909, when more than 50% glaciers of the Trans Himalayan region had shown advancements[32]. Similarly, low tree growth has been recorded during years having positive glacial mass balance noted in some glaciers, viz. during 1974–75, 1975–76 (ref. 13) and 1982–83 (ref. 14) in Gara glacier, and 1981–82 in Gor Garang[15]. Earlier, in an exploratory analysis, growth of *P. wallichiana* growing in Kinnaur, Himachal Pradesh has also been found low during the years having positive glacial mass balance[33]. Thus suppressed growth extending for five or more years in the present birch chronology are more likely to be linked with years of positive glacial mass balance or slower rate of glacial retreat. Periods of suppressed growth are recorded during 1571–74, 1583–86, 1590–1600 1626–45, 1650–70, 1674–82, 1739–51, 1761–65, 1793–97, 1815–17, 1819–25, 1860–69, 1898–1902, 1928–32, 1943–51, 1962–70 and 1981–89 in the 432-year tree-ring chronology (Figure 7). According to the relationship of tree growth and climate as discussed earlier, lower tree growth during these years might be due to increased pre-monsoon temperature and/or decreased precipitation during both pre-monsoon and in June. Several studies[34,35] revealed that a year with higher snowfall or increased pre-monsoon temperature has negative and positive correlations respectively, with the following monsoon rainfall. Further on analysing empirical relationship between climate versus glacier dynamics, it has been shown that the gradual onset of wet season preceded by drier climate has a role in enhancing the ablation rate[36], forming a condition suitable for retreat of the glaciers. The growth surges of birch trees with minor fluctuations in recent years might have resulted in the gradual onset of rainfall in March–April or June after preceding drier conditions during winter or spring respectively, which in turn has a negative role in glacial accumulation. The monitoring of snout position to determine glacial fluctuations discussed earlier, showed that the rate of recession since AD 1956 was rapid (approx 27.33–38 m/yr)[16]. The high retreat of glaciers is believed to be linked with increased winter temperature[37]. Climatic data from Tibetan plateau also reveal an increasing winter trend of 0.32°C and the greatest rate of warming 0.35°C per decade occurred at the highest elevation sites[38]. Even in the climatic records of Shimla plotted as anomaly of winter (DJF) temperature versus precipitation (Figure 8), there are more periods of positive anomalies of temperature from 1950 onwards, whereas around AD 1897–1907 there is high anomaly in negative temperature and positive precipitation. Similarly, in comparison to winter precipitation versus June precipitation (Figure 9), it has been noted that there are more positive anomalies in June precipitation in recent years, when rate of retreat of glacier is also high. As discussed earlier, higher growth of *B. utilis* in this region is related with the increasing trend of February temperature, and March–April and June precipitation. These climatic parameters also exhibit good correlation with ensuing low winter precipitation and increased winter temperature. Based on this relationship, it could be hypothesized that the rapid retreat of Gangotri glacier might be due to cumulative effect of increased March, April and June precipitation associated with increased winter temperature and low snowfall. Interestingly, tree-ring data of birch also respond well to regional episodes of cooling of the northern hemisphere. It has been recorded that growth in most of these trees analysed is low in April 1815, the year of eruption of Tambora, Indonesia. This cooling might have caused decreased precipitation during June. Tree growth has also been recorded low during the period 1790–96, when 600,000 people died of starvation in northern India as a direct result of limited monsoon rainfall and low soil moisture[39]. Similarly, lower tree growth corresponds to glacier advancements recorded during 1900, 1920 and 1970 in many low-latitude glaciers[40,41]. Moreover, long-term cooling indicating the Little Ice Age (LIA) that is believed to cover the time span from the sixteenth to the nineteenth century[42], is not a persistent cool phase in the western Himalaya, but it seems to be interrupted by shorter, warm phases. This is evident in tree-ring data also by the presence of several short phases of both growth surges and suppressed zones. In the eastern part of the Himalayas also, there is evidence of a reduction in late-summer temperature variability from the late 1700s to 1900, but it does not show any significant negative anomaly over longer duration[43]. Earlier dendroclimatic analyses from the western Himalaya[4,5,7] also suggest that there is no clear evidence of a LIA in the Himalayas. But in subsequent detailed analyses its impact has been noticed from this region, which is indicated by several episodes of negative anomaly in temperature interrupted by a brief period of positive anomaly[8]. Interestingly, the impact of such a cold period for longer duration has been reported from the adjacent Tibetan Plateau, Trans-Himalayan region[44,45]. Several growth-suppressed periods recorded in the present birch chronology are also found to coincide with the cooling recorded from the Tibetan Plateau[44,45]. Such common periods are noted during the early sixteenth century, mid-seventeenth century, mid-eighteenth century,

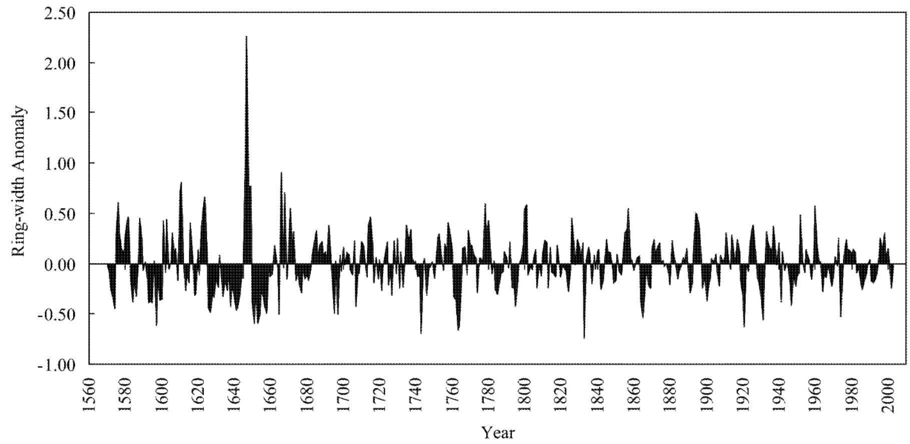

Figure 7. A 432-year (AD 1571–2002) tree-ring chronology of *B. utilis* from Bhojbasa showing periods of suppressed and released growth in relation to long-term mean of tree-ring indices.

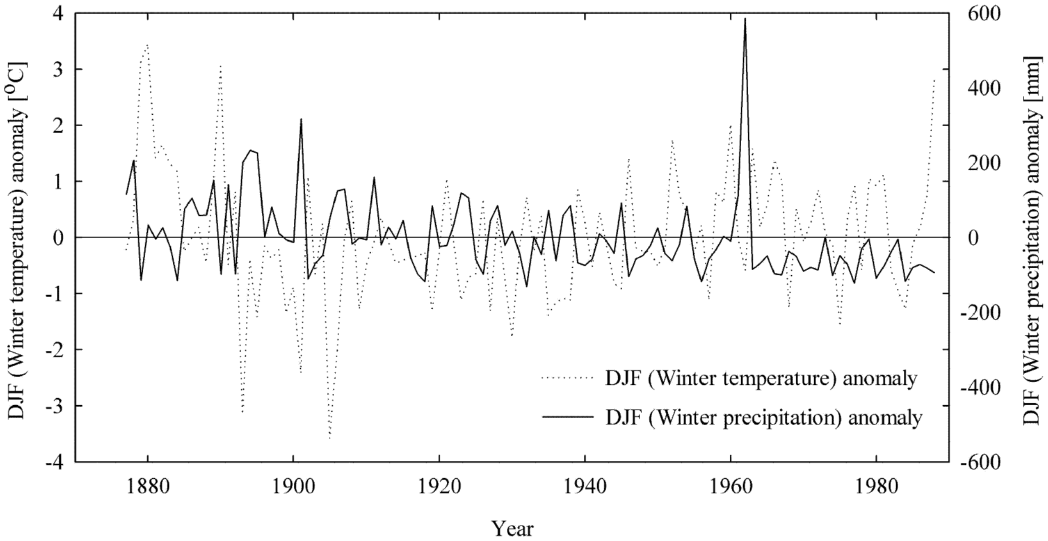

Figure 8. Climatic data (December–February) of Shimla shown as anomaly of both temperature and precipitation relative to their respective means.

and 1920s and 1960s. Tree-ring dates reveal that these birch trees colonized at this morainic deposit at Bhojbasa at least a little before AD 1590, the approximate age of older trees in the present study. Absence of older trees prior to that date might be because the climatic conditions that prevailed at that time were unsuitable for the settlement of birch trees. This is also evident in the tree-ring data, which exhibit more periods of suppressed growth in the early part of the tree-ring chronology. This is also supported by evidence of coolest period during 15th and 16th centuries of China in the last 1000 years[45]. Other possibilities may be that either older trees were already logged or they faced senile death, as many such trees having huge girth are found rotten inside. Dates of these trees also suggest that moraines on which these trees are growing are definitely older than AD 1590, the age of establishment of the oldest birch tree on this deposit. It also provides support to the fact that the present tree-ring site was either ice-free or it was not close to the snout, since the dates of these trees growing on this deposit. It is difficult to imagine that during LIA trees could survive if the snout was closer to this moraine on which these trees thrived, with the advancement of the glaciers. This also indicates that the impact of LIA was not severe in this part of the Himalayas, when birch trees used to grow there. We do not have information regarding threshold limit of lower temperature, which limits the growth of trees in this region. Thus trees over 500 years have been found growing between Gangotri and Bhojbasa, which also suggests that temperature during the LIA at Gangotri does not cross the threshold limit of minimum temperature, which could kill the trees of this region. In a recent study based on analyses of varied proxy data from the northern hemisphere, it is inferred that the twentieth century was the warmest during the past 1000 years, with AD 1989–98 and 1998 being the warmest decade and year respectively[46]. The present

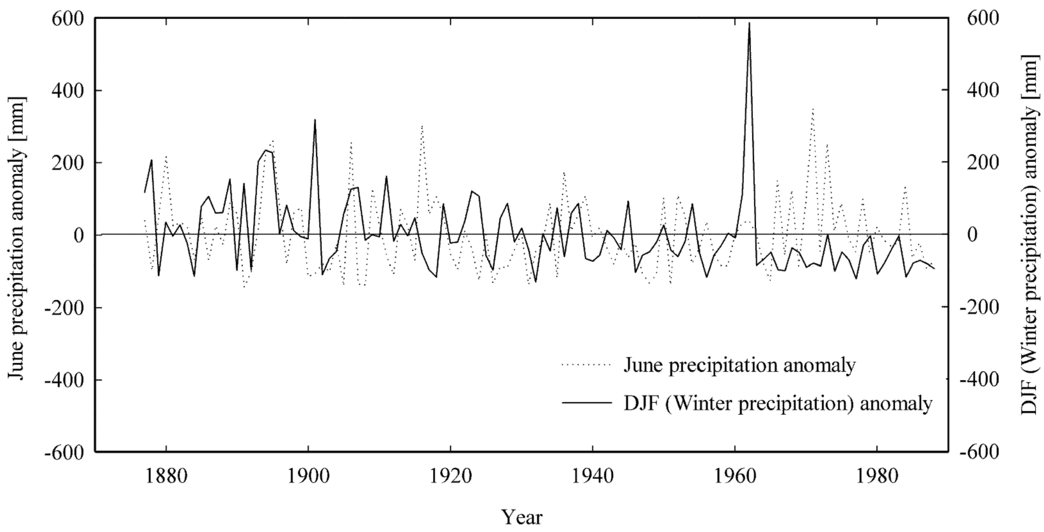

Figure 9. Climatic data (December–February precipitation and June precipitation) of Shimla shown as anomaly relative to their respective means.

chronology, which extends up to AD 2002, shows that there is a decline in tree growth during AD 1983–89 followed by increased tree growth from 1990 onwards, except 2002. Increased anthropogenic activities, mainly ruthlessly cutting of trees and woody scrubs, especially willow, juniper and birch all around the Gangotri region during the recent past, might also be important factors contributing towards the change of growth pattern in birch. Tree growth might have enhanced especially after deforestation due to realesd effect, resulting from the lack of competition, particularly around Bhujbas. Botanical explorations made earlier from this site indicated that the area was well forested by birch in not so distant past, which is characterized now by just a few trees. But growth surges have also been recorded in the same period even in tree-ring records of *P. wallichiana* analysed from the lower elevations at Chirbasa and Gangotri. Thus, simultaneously increased growth trend in two different species, pine and birch in two sites, Chirbasa and Bhojbasa respectively, suggests that it is not direct human influence but change of climate which is a common forcing factor operating at both sites, which has more likely played a significant role in limiting tree growth at both sites. Thus change in climate pattern is likely playing a major role in retreating the Gangotri glacier.

Conclusion

In a pioneer attempt in tree-ring analysis of birch (*B. utilis*), a broad-leaved tree from the Himalayan region growing adjacent to the snout of Gangotri glacier, the tree was found suitable for dendroclimatic analysis. It could be used for studies of the relationship between tree growth/ climate *vis-à-vis* glacial fluctuations. It has been noted that the growth of this tree has an inverse relationship with temperature of March and April, and direct relationship with precipitation of March, April and June. Moreover, increased tree growth in some years has been found to be well correlated with the rate of retreat of the Gangotri glacier. Thus rapid retreat of this glacier seems to be a cumulative effect of climatic changes, viz. increased March, April and June precipitation and increased winter temperature, which have a role in enhanced tree growth of birch. Several periods of suppressed growth in the tree-ring chronology covering a time span of AD 1571–2002, seem to correspond to years of either positive glacial mass balance or slow rate of retreat of the glaciers. These relationships which are out phases at some intervals might be result of limiting effect of other environmental factors which have not been dealt here. Though temperature and precipitation are the main governing factors for controlling glacial mass balance budget, others climatic and non-climatic factors also have a critical role. A detailed study will be taken up in the second phase of this work using multiple tree-ring chronologies of birch covering wider area of Himalayan sub-alpine region and using climatic data from a large number of meteorological stations, and taking into consideration the geomorphological and other evidences which would provide a better database to quantify tree growth/climate/glacial relationships in a longer timescale from the Himalayan region.

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