Sub-alpine trees testify late 20th century rapid retreat of Gangotri glacier, Central Himalaya

Article *in* Quaternary International · November 2020

DOI: 10.1016/j.quaint.2020.08.052

Jayendra Singh
Wadia Institute of Himalayan Geology

Ram Yadav
Birbal Sahni Institute of Palaeobotany

P.s. Negi
Wadia Institute of Himalayan Geology

Quaternary International 565 (2020) 31–40

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Sub-alpine trees testify late 20th century rapid retreat of Gangotri glacier, Central Himalaya

Jayendra Singh [*], Ram R. Yadav, Pyar S. Negi, Tanupriya Rastogi

Wadia Institute of Himalayan Geology, Dehradun, 248001, India

ARTICLE INFO

Keywords:
Tree ring
Gangotri glacier
Temperature
Central Himalaya
India

ABSTRACT

Our understanding on glacier-climate link in the Himalayan region is constrained due to lack of long-term observational and high-resolution proxy records. Hostile weather conditions and difficult approaches to access glaciers due to rough terrains largely limit observational studies on glaciers in the Himalaya. Sub-alpine trees and shrubs close to glaciers, growth of which is very sensitive to fluctuations in temperature, provide precise continuous record on climate and glacier behaviour to supplement the observational records back to several centuries. To unfold the Gangotri glacier dynamics in the past, we developed tree-ring chronologies and studied the colonization pattern of the trees in the region. Tree-ring chronologies of Himalayan birch and Himalayan pine developed from their respective upper tree line ecotone in the Gangotri glacier forefields showed impact of temperature on the growth variations. A comparison of Himalayan pine chronology with temperature proxies revealed regional and hemispheric scale temperature signal. Using tree-ring chronologies we show expansion (retreat) of the Gangotri glacier during cool (warm) phases that are also in agreement with the glacier fluctuation records from Central Asia and Southern Tibet. Moreover, using tree colonization pattern in the glacier forefields we established for the first time that the Gangotri glacier terminus receded ~1.853 km since the late 16th century (1571 C.E.), major part of which (1.79 km) receded since 1935 C.E. The glacier retreat, associated with the onset of 20th century warming got accelerated since 1957 C.E. (1.567 km). In view of our findings, the Gangotri glacier might further face accelerated recession in the 21st century under the projected warming.

1. Introduction

Glaciers, the natural reserve of fresh water, have receded in recent decades all over the globe indicating their sensitivity to global warming (Barry, 2006). Similarly glaciers in the Himalaya, the highest in number outside the Polar Regions, have also lost mass in recent decades (Immerzeel et al., 2010; Scherler et al., 2011; Bolch et al., 2012; Kääb et al., 2012; IPCC, 2014) and it has been speculated that the Himalayan glaciers are retreating even faster than the glaciers in other regions of the world (Cruz et al., 2007). However, in exception to this some glaciers in Karakoram are either stable or even have advanced in recent decades (Hewitt, 2009). In view of this, owing to large geographical extent of the Himalayan Mountains and regional differences in climate due to dominant orographic forcing, a generalization on the state of glaciers over the whole Himalaya-Karakoram system is difficult (Immerzeel et al., 2010; Bolch et al., 2012; Shea et al., 2015; Ragettli et al., 2016). Our understanding on glacier response to climate change is limited largely due to the lack of long-term data on glacier behaviour across the Himalaya. For instance, of the 10,000 glaciers in the Indian Himalaya, only 11 have been studied in detail for mass balance and little more than 100 glaciers are being monitored for terminus fluctuation since last few decades (Bolch et al., 2012; Dobhal et al., 2008; Bhambri et al., 2012).

The Gangotri glacier (30° 43′ 22″-30° 55′ 49″ N and 79° 04′ 41″-79° 16′ 34″ E), source of the Bhagirathi River, is one of the largest glaciers in the Himalaya. Although it is one of the most well documented glaciers in the Himalaya in terms of terminus measurement (Srivastava, 2012), its precise dynamics in the past few centuries is not well constrained. The presence of lateral, recessional moraines and supra-glacial lakes indicate that the Gangotri glacier has retreated in the past in response to climate change (Bolch et al., 2012; Bhambri et al., 2012; Auden, 1937; Mayewaski and Jeschke, 1979; Naithani et al., 2001; Srivastava, 2004; Vohra, 2010; Negi et al., 2012; Bhattacharya et al., 2016; Singh et al., 2017). On a centennial scale, the youngest expansion of the Gangotri glacier (Bhujbas Stage) coincident with the Little Ice Age (LIA) is stated to have

* Corresponding author.
E-mail addresses: jayendrasingh@wihg.res.in (J. Singh), rryadav2000@gmail.com (R.R. Yadav), negi_psingh@wihg.res (P.S. Negi), tanu.rrastogi@gmail.com (T. Rastogi).

https://doi.org/10.1016/j.quaint.2020.08.052
Received 10 May 2019; Received in revised form 7 July 2020; Accepted 31 August 2020
Available online 7 September 2020

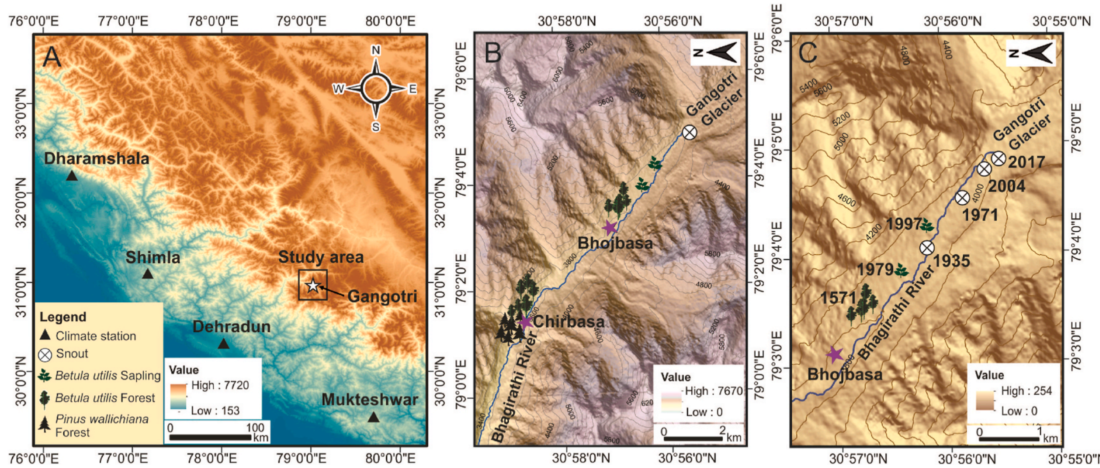

Fig. 1. Location map of the study area. A-Tree-ring sampling sites in the Bhagirathi River basin and meteorological stations, B- Location of forest stands of Himalayan birch and Himalayan pine in Bhojbasa and Chirbasa, C- Himalayan birch trees and sapling positions with their respective establishment years. Maps were generated using ArcGIS 10.4.1 and CorelDRAW X6 software. Fig. 1A was generated using freely available SRTM GL1, Global 30m data (http://opentopo.sdsc.edu/rasterOutput?jobId=rt1521441167154&metadata=1; DOI: 10.5069/G9445JDF; Farr et al., 2007) through Open Topography Portal (https://opentopography.org). Fig. 1B and C were generated using 12.5m Open Access Alos Palsar data (Dataset: ASF DAAC, 2015, ALOS PALSAR_Radiometric_Terrain_Corrected_high_res; Includes Material © JAXA/METI, 2007. Accessed through ASF DAAC, 04 June 2018. DOI: 10.5067/Z97HFCNKR6VA).

taken place ~440-210 yrs BP (1510–1740 C.E.) when it advanced ~3.7 km (with respect to the observations made in 1992; Sharma and Owen, 1996). The Gangotri glacier terminus is stated to have terminated/remained stationary at Bhojbasa for at least 200 years before it began to retreat in the late 19th century (Sharma and Owen, 1996; Srivastava, 2012) and since then continuously lost mass (Owen et al., 2009). Later, the cosmogenic radio-nuclide (CRN) dates indicated younger age for the Bhujbas Stage of the Gangotri glacier expansion, i.e., ~200–300 yrs BP (1750-1650 C.E.) (Barnard et al., 2004). However, the existence of Himalayan birch (*Betula utilis* D. Don) forest with a constituent tree dating back to 1571 C.E. in Bhojbasa (Bhattacharyya et al., 2006), ~3.26 km down to current (July, 2017) position of the Gangotri glacier terminus (Lat. 30.924840° N, Long. 79.080974 E; based on Google Earth imagery dated 10.07.2017) endorsed that there existed a forest as early as 1571 C.E. or even before if the oldest tree in the forest stand was missed or had possibly died before sampling. Himalayan birch, a medium sized deciduous tree, is shade intolerant and prefers to grow in open areas (Troup, 1921). Such an old age of Himalayan birch trees clearly indicates that Bhojbasa was snow/ice free much before 1571 C.E., as build up of organic matter in freshly exposed moraines could have taken several years prior to the arrival of first colonizing Himalayan birch trees. Retreat of 3.7 km of the Gangotri glacier terminus up to 1992 C.E. (Sharma and Owen, 1996) since the LIA is also in contrast with the other glaciers in the Central Himalaya where debris covered glaciers lose most mass by surface lowering rather than the terminus recession as a result of which many Himalayan glaciers remain close to their LIA extents (Benn et al., 2012; Rowan, 2017).

The Gangotri glacier for its huge ice mass has great potential to modify the hydrology of the Ganga River, the largest river system in India covering ~2525 km length, the major basin area (80%) of which lies in India and rest in Bangladesh. Variation in the river water supply as a function of glacier melt significantly affects the socio-economy of these countries as the Ganga basin, home to ~450 million people, is one of the most populous regions on the Earth with ~550 individuals/km^2, which rises up to ~900 individuals/km^2 in the delta region. The dynamics of the Gangotri glacier, despite being so relevant to the human society, remains confounding antecedent to the observational records. In view of this we took up the present study with the aim to address the following questions: 1) Can the colonization pattern of trees be taken as the calendar chronology of glacier terminus fluctuation? 2) Is there distinct climate signal in ring-width chronologies from upper tree line zones? 3) Is there any relationship in ring-width chronologies and glacier fluctuation? and 4) What are the important forcings on glacier fluctuations?

2. Data and methods

2.1. Geology and geomorphology of the study area

The Gangotri glacier, situated north of the Main Central Thrust (MCT) and flowing in northwest direction towards Gaumukh, is one of the longest valley-type glacier in the Garhwal Himalaya, Uttarakhand (Naithani et al., 2001). It originates from Chaukhamba group of peaks (6957 m asl) and is bordered by Satopanth and Bhagirathi Kharak glacier (in east), Chorabari glacier (in west), and Mandani Parbat (in south) (Singh et al., 2019). The glacier is ~30.2 km long, width varies from 0.5 to 2.5 km, and elevation ranging from 4120 to 7000 m asl (Naithani et al., 2001). Considering average thickness of the glacier ice to be 200m, the estimated volume of ice is 28.716 km^3 (Srivastava, 2012). The glacier region lies in the Central Crystalline zone and rock types mainly found in this region are quartzite, phyllite, tourmaline granite, mica schist, sericite schist and fine grained limestone (Bhatt, 1963). Along the glaciated area, the Gangotri granite, a fine grained variety, which is one of the largest bodies of the Higher Himalayan Leucogranite belt in the Garhwal Himalaya (Heim and Gansser, 1939; Gansser, 1964; Le Fort, 1975; Yin, 2006) is exposed (Jain et al., 2002). Glacio-geomorphological landforms of depositional as well as erosional origin are found in the glacier valley (Naithani et al., 2001). Two morphological zones (glacial and glacio-fluvial) related to the pattern of retreat and Equilibrium Line Altitude (ELA) have been distinguished. The glacial zone is characterized by the presence of landforms like supraglacial moraines, supraglacial lakes, lateral moraines, recessional moraines and hummocky moraines, whereas the glacio-fluvial zone stretching from the front of the glacier to the upstream of Bhojbasa is dominated mainly by outwash plains. The sediments in the glacial zone are unstratified, poorly sorted and primary in origin as compared to those in the glacio-fluvial zone which demonstrate a secondary provenance and are stratified with moderate sorting. The sediment size decreases, whereas roundness and percentage of matrix increases from the glacial to the glacio-fluvial zone (Singh et al., 2017).

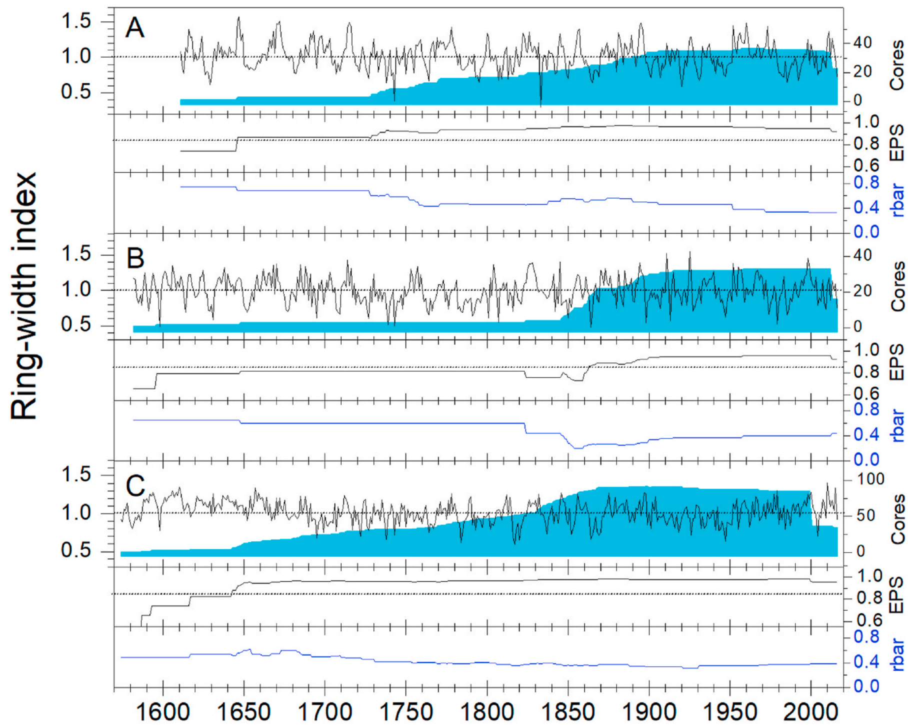

Fig. 2. Himalayan birch ring-width chronology plotted together with number of tree cores used over time, and respective running EPS and rbar from Bhojbasa (A), Chirbasa (B) and Himalayan pine chronology from Chirbasa, Bhagirathi basin (C).

Table 1
Statistics of Himalayan birch and Himalayan pine ring-width chronologies produced from different sites in Bhagirathi basin, Uttarakhand.

Site	Species	Chronology length (C.E.)	Trees/cores	EPS level ≥0.85	Mean sensitivity	Std Dev	AR1	SNR	Common Variance %
Bhojbasa	*Betula utilis*	1611–2016	20/37	1646–2016	0.16	0.21	0.52	8.685	39.07
Chirbasa	*Betula utilis*	1582–2016	20/33	1863–2016	0.16	0.17	0.31	9.083	38.58
Chirbasa	*Pinus wallichiana*	1574–2016	51/90	1643–2016	0.19	0.19	0.34	15.753	29.12

Note: EPS - Expressed Population Signal, Std Dev. - Standard deviation, AR1 - First order autocorrelation, SNR-Signal-to-noise ratio.

2.2. Tree-ring data

Tree-ring materials of Himalayan birch (*Betula utilis* D. Don) and Himalayan pine (*Pinus wallichiana* A. B. Jacks.) in the form of increment cores collected in 2012 and 2016 C.E. from upper tree line ecotone in the Gangotri glacier forefield (Fig. 1), Uttarkashi, Uttarakhand, Central Himalaya constituted the target materials in present study. Tree ring materials were usually sampled at breast height (1.37 m above the ground) to estimate climatic signals in the ring widths. To develop the chronology of glacier fluctuations younger trees and saplings growing towards the terminus in glacier forefield were cored at the root collar zone to precisely estimate dates (years) when the tree started growing at particular location. Attempts were made to sample undisturbed trees with circular boles, however, in the case of very old Himalayan birch, trees with asymmetric boles were also sampled to get the maximum possible age. Growth ring sequences in increment cores were crossdated and ring-widths measured using established dendrochronological procedures (Stokes and Smiley, 1968; Fritts, 1976). Precisely dated ring-width measurement series of Himalayan birch and Himalayan pine were processed using signal-free standardization method (Melvin and Briffa, 2008) to prepare the mean chronologies of the respective species. The signal-free detrending method mitigates the effect of the segment lengths (Cook et al., 1995) and also helps in preservation of low frequency variability in excess of the individual tree-ring series used in mean chronology development. The ring-width measurements of Himalayan birch were detrended using a cubic smoothing spline (Cook and Peters, 1981) that preserved 50% of the amplitude over a wavelength of 50 years. However, in the case of Himalayan pine smoothing spline of 67% of the series length was used. The detrended individual ring-width measurement series were then combined to mean chronologies by calculating biweight robust means (Cook, 1985). The statistical details of each chronology such as chronology span, number of samples used and signal strength indicators such as Expressed Population Signal (EPS) (Wigley et al., 1984) and the average correlation between series (rbar) are indicated in Fig. 2A–C and Table 1.

Many of the high-elevation species in the western Himalaya, consistent with the observations in other high latitude and altitude regions, are known to be expanding to the higher elevations in response to warming (Dubey et al., 2003; Rawat, 2012; Singh et al., 2012; Yadava et al., 2017). The colonization pattern of the Himalayan birch, constituting the upper most treeline species in the western Himalaya, in response to recent warming has not been studied so far. To understand the temporal colonization pattern of Himalayan birch in the Gangotri glacier forefield we surveyed young trees and saplings growing along the altitudinal gradients from Bhojbasa towards the glacier terminus. Only right bank of the Bhagirathi River could be surveyed as left bank was not approachable. Young Himalayan birch trees were found growing in clumps at places in the Gangotri glacier forefield. We collected increment cores from the Himalayan birch saplings growing at several places but only the oldest ones from each site was considered to estimate the establishment of seedling. Best efforts were made to core the trees from the root collar zone to retrieve maximum number of growth rings. Establishment year of the Himalayan birch saplings at specific location and distance from the terminus was taken into account to estimate the position of terminus in the past years.

2.3. Climate data

Long-term weather records from high-elevations close to the tree-ring sampling sites in the Himalaya are not available. Automatic weather station data from Bhojbasa (2000–2013 C.E.) show temperature and precipitation patterns closely similar to Mukteshwar as well as CRU TS 3.24 gridded data (Harris et al., 2014) (Fig. 3). We used gridded temperature and precipitation data (30.5–31.5 °N 78.5–79.5 °E (CRU TS 3.24; Harris et al., 2014); close to Bhojbasa (30.5–31°N 78.5–79 °E) to evaluate relationship with the tree-ring chronologies. However, Mukteshwar as well as gridded temperature and precipitation data revealed a poor relationship with tree-ring width chronologies. In view of this we applied regional mean temperature series developed by merging homogeneous temperature records of Dehradun, Dharamshala, Mukteshwar and Shimla (Fig. 1A) for tree growth climate relationship study. The monthly temperature data of each station was standardized relative to the 1961–1990 C.E. mean and standard deviation before averaging. However, in case of precipitation we applied data of Mukteshwar only as we observed large scale inconsistency in monthly precipitation data of different stations. Climatology of Bhojbasa (3900 m asl) shows annual precipitation ~260 mm (Mean 2000–2013 C.E.), of which 79% falls in June–September (Gusain et al., 2015). The summers are usually cloudy in Bhojbasa and average sunshine from May to October (2000–2003 C. E.) has been recorded to be ~5.6 h (Singh et al., 2005) indicating that vegetation growth could be highly constrained owing to low sunshine hours.

3. Results and discussion

3.1. Ring-width chronologies

Ring-width chronologies of Himalayan birch prepared from Bhojbasa (1611–2016 C.E.) and Chirbasa (1582–2016 C.E.) are presented in Fig. 2A and B and Table 1. The chronology statistics are very similar to that reported earlier by Bhattacharyya et al. (2006). The age of the oldest Himalayan birch tree sampled from Bhojbasa by us extends back to 1611 C.E. However, still older trees of Himalayan birch from Bhojbasa extending back to 1571 C.E. were recorded by Bhattacharyya et al. (2006). The age of this tree could be still longer as pith was not retrieved in core sample (Bhattacharyya et al., 2006). The Himalayan birch chronology from Chirbasa extended from 1582 to 2016 C.E., however, sufficient sample replication extended back to 1863 C.E. only. Himalayan birch chronologies from Bhojbasa and Chirbasa revealed strong coherence on year-to-year and inter-decadal scale with significant Pearson correlation ($r = 0.59$, 1863–2016 C.E.). To understand the common variability in growth of Himalayan birch at two sites Principal Component Analysis was performed using ring-width chronologies for the common period 1863–2016 C.E.

Himalayan pine ring-width chronology (Fig. 2C; Table 1) extended back to 1574 C.E. However, the chronology length used in the analysis with sufficient replication of samples extended back to only 1643 C.E.. The chronology statistics are similar to that reported earlier by Singh and Yadav (2000) and Shekhar et al. (2017).

3.2. Climate signal in ring-width chronologies

To investigate the climate forcing on radial growth, ring-width chronologies of Himalayan birch, their first principal component (PC#1) with eigen value > 1 and Himalayan pine were used in bootstrapped correlation analyses using program DENDROCLIM2002 (Biondi and Waikul, 2004). Monthly climate data (regional temperature series, 1951–1998 C.E., and precipitation data of Mukteshwar) for a climate window from October of the previous growth year to October of current year were used in correlation analyses (Fig. 4). The climate data of months prior to the growth year were included in correlation analyses as photosynthetic assimilates of the dormant season could also significantly contribute to the radial growth of trees. Mean temperature of January, February, May, June, July and September showed direct relationship with PC#1 of Himalayan birch, however, it was significant for February, June and September only (Fig. 4A). Precipitation of December prior to the growing season showed significant negative relationship with PC#1 of Himalayan birch chronologies (Fig. 4A). Similar to our findings Bhattacharyya et al. (2006) had also reported weak climate signal in Himalayan birch ring-width chronology from Bhojbasa, showing positive relationship with February temperature only.

Himalayan pine chronology from Chirbasa showed direct relationship with mean temperature of October, November, December of the year prior to the growing season and January, February, and April of the growth year, which was significant for December only (Fig. 4B). Precipitation usually showed weak negative correlation except for the months of January, May, July and August (Fig. 4B). The response function results of the two species revealed that warm February and summers favour the growth of Himalayan birch and warm winters favour the growth of Himalayan pine over the study sites. Winter temperature directly affecting the radial growth of the Himalayan pine could be possible as many of the conifers are known to perform considerable amount of photosynthesis at such high-altitude locations. The photosynthetic reserves of the preceding winter could be utilized for growth in the ensuing growing season. Similar to our findings various studies have shown that certain species can perform photosynthesis at very low temperatures (Kramer and Kozlowoski, 1979). There are also reports that some conifers in Northwest Pacific fix around 30–65% of their total annual carbon budget during the dormant winter season (Emmingham and Waring, 1977; Waring and Franklin, 1979). Similar to our findings, ring-width chronologies of different conifers viz.,

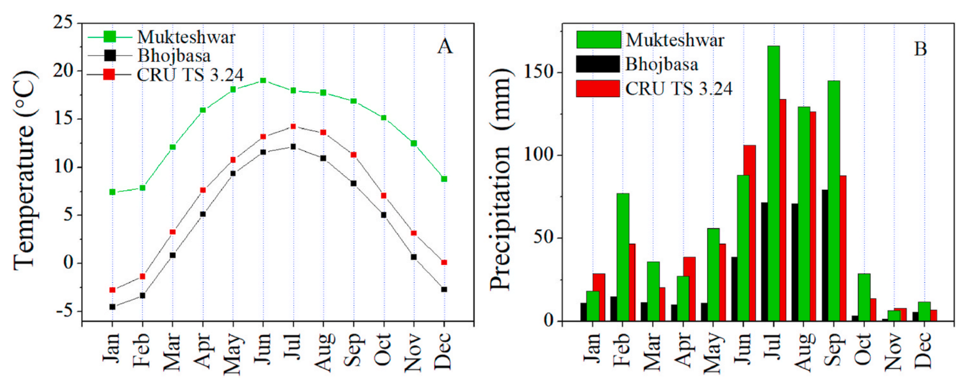

Fig. 3. Climate diagram (A-monthly temperature, and B- precipitation) of Mukteshwar, Bhojbasa, and CRU TS3.24 gridded data (Harris et al., 2014).

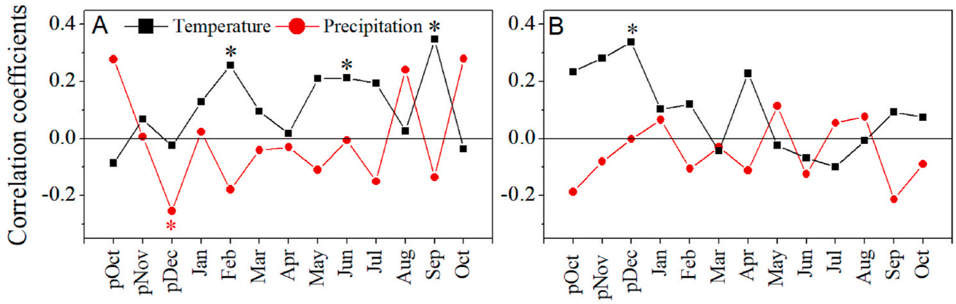

Fig. 4. Bootstrap correlation analyses between PC#1 of Himalayan birch chronologies from Bhojbasa and Chirbasa (A) and Himalayan pine ring-width chronology prepared from Chirbasa (B) with regional temperature and precipitation of Mukteshwar. Correlations significant at $p < 0.05$ are marked by an asterisk. Correlations were calculated for the common period 1951–1998 C.E. when temperature data of all the four meteorological stations used in preparing the regional data were available.

Himalayan cedar (*Cedrus deodara*) and Himalayan spruce (*Picea smithiana*) from high elevation sites in the western Himalaya have also shown direct relationship with winter temperature (Borgaonkar et al., 2011).

3.3. Glacier terminus estimation from tree establishment

Himalayan birch constitutes the upper most forest limit in the Gangotri glacier forefield with sign of gradual expansion to upper elevations. The number of growth rings in increment cores extracted from the root collar zone of Himalayan birch saplings/young trees provided reliable estimate of the establishment age. Location and number of growth rings in young trees and GPS position of glacier terminus (Table 2; Srivastava, 2012) in different years were used to estimate distance between glacier terminus and Himalayan birch establishment year. We have taken the distance between the glacier terminus and tree establishment position constant over times for all practical purposes, with the caveat especially for the extreme climatic conditions. The distance of colonizing trees from the glacier terminus in LIA is expected to be higher due to the cooling effect of thicker and larger snow/ice cover compared to the 20th century.

Moraine deposits, marking the extent of glacier, are nutrient deficient that can hardly support vegetation. The pioneer tree species colonize the moraines several years after exposure when sufficient organic matter gets accumulated in the soil after successive colonization by mosses, lichens, alpine scrubs and bushes. Himalayan birch is important primary colonizing tree species in the Gangotri glacier forefield, the ecesis period of which could take several years to decades. However, ecesis period of plant species, which requires successive observations for several years, is not yet studied in case of any species in the Himalayan region. In view of this, we have considered the tree-ring determined age of Himalayan birch on moraines as its minimum age. We observed young saplings of Himalayan birch spreading sporadically towards the upper elevations closer to glacier terminus. Young bushy Himalayan birch sapling on highest elevation on right bank of the Bhagirathi River was spotted 1.54 km down to the Gangotri glacier terminus (3915 m asl) (Fig. 1C, Table 3). The increment core collected from root collar zone of the thickest stem extending up to the pith showed an age of 20-years (1997–2016 C.E.). Though there were number of patches of young Himalayan birch saplings on moraines along the river, young Himalayan birch trees older than the first one were noticed only 2.36 km down to the terminus (3881 m asl) that revealed 38-years age (1979–2016 C.E., Fig. 1C). As the first GPS reading of glacier terminus is available only for 1971 close to the year of sapling establishment, retreat rate of the glacier terminus was calculated based on current (July, 2017) and 1971 GPS derived terminus position (Table 2; Srivastava, 2012). Based on above two points the glacier terminus retreat rate from 1971 to 2017 C.E. is estimated to be 18.1 m/yr. Considering the retreat rate of 18.1 m/yr Himalayan birch sapling establishment in 1997 and 1979 C.E. at two respective points are estimated to be 1.16 km and 1.654 km away from the terminus respectively (Table 3). Mean distance of the Himalayan birch sapling establishment from the Gangotri glacier terminus, estimated from the above two points could be taken as 1.407 km. Taking this into account the distance of the oldest Himalayan birch in Bhojbasa (1571–2002 C.E.) from the glacier terminus at its establishment time could be taken as ~1.407 km (Table 3). Taking this distance into account the glacier terminus, which is 3.26 km in 2017 from Bhojbasa, is estimated to be (3.26–1.407 km) ~1.853 km down from its current (July, 2017) position in 1571 C.E. We expect that the age of Himalayan birch trees which colonized the Bhagirathi River valley in Bhojbasa could be even older than 1571 C.E. as the oldest tree in the Himalayan birch forest stand could have been missed/died before sampling. Bhattacharyya et al. (2006) also mentioned that old trees in the forest stand have been cut in Bhojbasa for fuel wood; therefore, there is possibility that some Himalayan birch trees in Bhojbasa could have been even older than the recorded date of 1571 C.E. We also opine that the oldest sampled tree dating back to 1571 C.E. could even be older than the recorded age as retrieval of the pith is not mentioned in the sample (Bhattacharyya et al., 2006). Even if the core sample reached close to the pith, which is not mentioned in the original publication of Bhattacharyya et al. (2006), the actual age of this tree could be still older by few years to decade(s) depending on the time required by the tree to gain the coring height (breast height 1.37 m). As growth rate of sub-alpine Himalayan birch is not known in the Bhagirathi River valley we take here 1571 C.E. as its establishment age after which the Gangotri glacier terminus retreated ~1.853 km. Taking the Gangotri glacier terminus position in 1935 (Srivastava, 2012) and 2017 C.E. into account, the glacier retreated 1.79 km alone since 1935 C.E., however, its net retreat was only ~63 m during 1571–1934 C.E. The glacier terminus retreat has accelerated since 1957 (1.567 km), which is consistent with the observed regional warming (Bhutiyani et al., 2007; Borgaonkar et al., 2011).

Table 2
GPS derived terminus position of the Gangotri glacier (after Srivastava, 2012) relative to the July, 2017 position.

S. No.	Year	Lat (°N)	Long (°E)	Altitude (m)	Distance from glacier terminus (km)
1	2017	30.924840	79.080974	4073	0
2	2004	30.92708794	79.07945284	3922	0.29
3	1971	30.93059182	79.07517186	3899	0.85
4	1935	30.93627975	79.06769543	3867	1.79

3.4. Climate signal in ring-width chronologies and relationship with glacier fluctuation

PC#1 of Himalayan birch ring-width chronologies with eigen value > 1 indicated statistically significant correlation with the ring-width chronology of Himalayan pine (Pearson correlation 0.30, $p = 0.00017$, 1863–2016 C.E.). The inter-decadal variations in above two series also revealed very good consistency (Fig. 5) indicating common climate forcing on tree growth. In view of the presence of low-frequency variations and longer series length we used Himalayan pine chronology to understand linkage with glacier fluctuation. The Himalayan pine

Table 3
The Gangotri glacier retreat since 1571 C.E. The rates are estimated based on the recruitment dates of Himalayan birch trees near the glacier terminus and terminus position taken with GPS in 1971 and 2004 (Srivastava, 2012), and 2017 (this study). Terminus retreat rate is estimated to be 18.1 m during 1971–2017.

S. No.	Glacier terminus/tree site and elevation (m asl)	Lat. (°N)	Long. (°E)	Distance from the glacier terminus in July 2017 (km)	Chronology span (length/age), establishment year**	Distance from terminus in establishment year with respect to the terminus position in July, 2017***
1	Terminus position July, 2017, 4073	30.924840	79.080974	0 km		
2	Himalayan birch, 3915	30.93546	79.07062	1.54 km	1997–2016 C.E. (20yrs), 1997	1.16 km
3	Himalayan birch, 3881	30.94012	79.06385	2.36 km	1979–2016 C.E. (38yrs), 1979	1.654 km
4*	Himalayan birch (open forest, Bhojbasa), 3864			3.26 km	1571–2002 C.E. (432 yrs)	~1.407 km (average of 2 and 3)
5	Himalayan birch (open forest, Bhojbasa), 3864	30.94663	79.05816	3.26 km	1611–2016 C.E. (406 yrs)	

Note:
* Himalayan birch chronology from Bhojbasa prepared by Bhattacharyya et al. (2006).
** Earliest date of the chronology is the year when the tree got established at the location.
***Distances were calculated using retreat rate of 18.1 m/yr in 1971–2017.

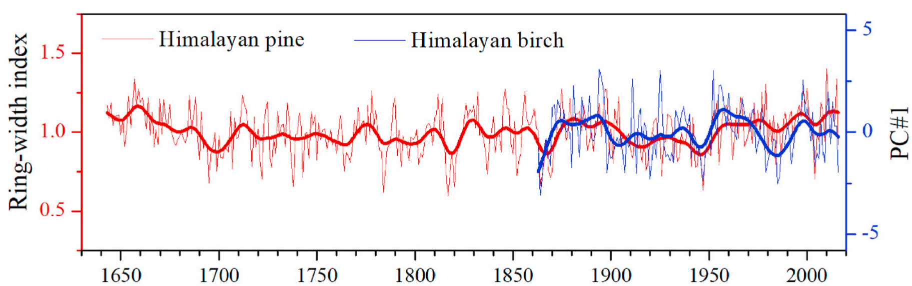

Fig. 5. Ring-width chronology of Himalayan pine (1643–2016 C.E.) from Chirbasa plotted together with PC#1 of Himalayan birch chronologies from Bhojbasa and Chirbasa in Bhagirathi basin, the Gangotri glacier. Thick lines are 20-year low pass spline filter.

chronology showed significant Pearson correlation with October-November-December mean temperature ($r = 0.34$, $p = 0.019$, 1952–1998 C.E.) and close similarity in low frequency variations as well (Fig. 6A). In view of such a close relationship observed between tree-ring chronology and temperature, Himalayan pine chronology could be taken as an indicator of temperature changes in the region. Low/high growth indices in the chronology reflect cool/warm conditions (Fig. 6B).

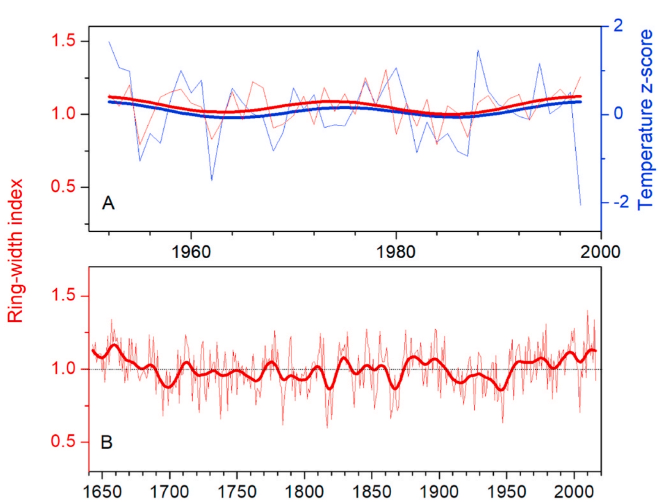

Fig. 6. Ring-width chronology of Himalayan pine (Red color) plotted together with October–December regional temperature (1952–1998 C.E., Blue color; A) and Ring-width chronology of Himalayan pine (1643–2016 C.E.; B). Thick lines are 20-year low pass filter. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Interestingly we noted that the low frequency variations in Himalayan pine chronology were also found to be consistent with temperature reconstructions for Asia (PAGES 2k Consortium, 2013) and the Northern Hemisphere (Wilson et al., 2016) (Fig. 7A–C). We observed that the radial growth in Himalayan pine was very low during the late 17th-early 18th, late 18th-early 19th, 1860s and early 20th century. The late 17th-early 18th and late 18th-early 19th century growth suppressions reflected in the Himalayan pine chronology are consistent with the Maunder Minimum (1645–1715 C.E.) and Dalton Minimum (1790–1830 C.E.) (Eddy, 1976) (Fig. 7A) respectively, when sun spot activity was much reduced. The Dalton Minimum period was also associated with strong explosive volcanic eruptions. The ejection of huge amount of volcanic ashes, sulphuric compounds, into the upper troposphere and lower stratosphere resulted in formation of aerosols, thus increasing the optical depth of the stratosphere. The short wave solar radiation is partly scattered by the aerosols back to space and partly absorbed. The absorbed energy is emitted as long wave radiation down towards the Earth's surface and back to space resulting in cooling of global near-surface temperatures (Robock and Mao, 1995). The explosive volcanism has been implicated to be the dominant forcing for the temperature drop in Dalton Minimum Period (Wagner and Zorita, 2005) in the early 19th century. The eruption of Tambora in Indonesia in 1815 C.E., the largest in last 500 years, is associated with very low summer temperature causing maximum drop in global surface temperatures by 0.7–0.8 K (Sachs and Graf, 2001). Himalayan pine chronology revealed the lowest three-year mean growth indices during 1816–1818 (0.57) almost three standard deviation below the long-term mean (1643–2016 C.E.), indicating that cooling associated with the Tambora eruption caused severe growth reduction in sub-alpine trees in the Central Himalaya. Tree-ring records from Nepal have also revealed cold episodes coinciding with the Tambora eruption (Cook et al., 2003).

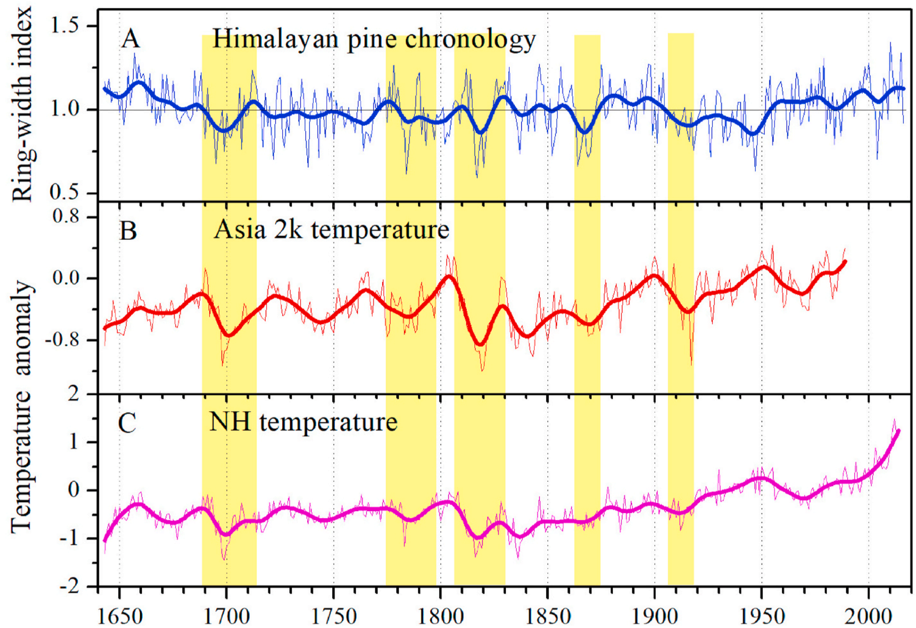

Fig. 7. A-Ring-width chronology of Himalayan pine (1643–2016 C.E.), B- Annual temperature reconstruction for Asia (PAGES 2k Consortium, 2013), C- Mean summer (May–August) temperature reconstruction for the Northern Hemisphere (Wilson et al., 2016). The respective series were filtered with 20-year spline to show low frequency variations in series.

Table 4
Rate of retreat of the Gangotri glacier terminus ([a]- after Singh et al., 2017 and [b]-after Bhambri et al., 2012).

Period (C.E.)	Annual terminus retreat (m)	Reference
1935–1976	23.95	Singh et al., 2017[a]
1976–1990	17.44	Singh et al., 2017[a]
1990–2001	12.55	Singh et al., 2017[a]
2001–2005	10.14	Singh et al., 2017[a]
2005–2012	11.48	Singh et al., 2017[a]
2001–2015	10.00	Singh et al., 2017[a]
1935–1956	10.16	Jangpangi, 1958[a]
1956–1971	27.33	Vohra, 1971[a]
1971–1974	27.34	Puri and Singh, 1974[a]
1974–1975	35.00	Puri, 1984A[a]
1975–1976	38.00	Puri, 1984B[a]
1976–1977	30.00	Puri, 1984C[a]
1977–1990	28.08	Puri, 1991[a]
1990–1996	28.33	Sangewar, 1997[a]
1935–1996	18.8	Ravi Shanker and Srivastava, 1999[a]
1962–1982	40	Tangri, 2002[a]
1990	37	Tangri, 2002[a]
1999	25	Tangri et al., 2004[a]
2004–2005	12.10	Kumar et al., 2008[a]
1965–2006	19.7 ± 0.6	Bhattacharya et al., 2016
2006–2015	9.0 ± 3.5	Bhattacharya et al., 2016
1935–1996	20	Srivastava, 2004[b]
1962–1999	34	Naithani et al., 2001[b]
1935–1997	40	Mukherjee and Sangewar, 2001[b]
1962–2000	42	Tangri et al., 2004[b]
1985–2001	23	Ahmad and Hasnain, 2004[b]
1962–2000	40	Bahuguna et al., 2007[b]
1962–2006	38	Bhambri and Chaujar, 2009[b]
1965–1968	5.9 ± 4.2	Bhambri et al., 2012[b]
1968–1980	26.9 ± 1.8	Bhambri et al., 2012[b]
1980–2001	21.0 ± 1.2	Bhambri et al., 2012[b]
2001–2006	7.4 ± 4.0	Bhambri et al., 2012[b]

Reduced radial growth in Himalayan pine in the late 17th-early 18th and early 19th century coinciding with the Maunder Minimum (1645–1715 C.E.) and Dalton Minimum (1790–1830 C.E.) (Eddy, 1976) are also consistent with the large-scale regional and hemispheric cooling (PAGES 2k Consortium, 2013; Wilson et al., 2016; Yadav et al., 2011; Krusic et al., 2015). Thirty one year running mean of the chronology indices showed lowest growth during 1692–1722 C.E. (mean 0.167 ± 0.03). Similarly, tree-ring records from Central Bhutan have also revealed 1690–1710 C.E. being the coolest in the last 600 years (Krusic et al., 2015) consistent with the lowest radial growth in Himalayan pine in the Central Himalaya (1690–1710 mean index 0.83 ± 0.03). Tree-ring based summer temperature records from Lahaul-Spiti in the western Himalaya have revealed the coolest period from 1700 to 1900 C.E. (Yadav et al., 2011) in the last millennium. The radial growth indices of Himalayan pine chronology were low from 1780s to 1810s, with very low growth especially during 1810s coinciding with the Dalton Minimum. This cool period is again consistent with the expansion of glaciers in southern Tibet (Bräuning, 2006) as well. Radial growth suppression in Himalayan pine in the 1860s–1870s and early 20th century consistent with the low rate of the Gangotri glacier terminus recession is in agreement with the increased glacier activity in trans Himalayan region (Mayewaski and Jeschke, 1979), southern Tibet (Bräuning, 2006) and Tien Shan (Kotlyakov et al., 1991; Solomina et al., 2016).

Table 5
Average area vacated near the Gangotri glacier terminus (after Bhambri et al., 2012).

Period (C.E.)	Average area vacated at terminus (10^3 m^2/year)
1965–1968	7.6 ± 2.0
1968–1980	13.7 ± 0.8
1980–2001	10.2 ± 0.5
2001–2006	3.2 ± 1.8
1965–2006	10.2 ± 0.9

The Gangotri glacier terminus fluctuation has been studied extensively since the early twentieth century and varying rate of retreat has been indicated by various researchers (Tables 4 and 5). In our present study we have used the Gangotri glacier terminus measurement data as given by Srivastava (2012). We observed that the Gangotri glacier terminus fluctuation is directly related to ring-width indices of Himalayan pine (Fig. 8) and mean October–December temperature. The Gangotri glacier terminus measurements since 1935 C.E. (Srivastava, 2012) show that the recession rate was slower in early 20th century when mean

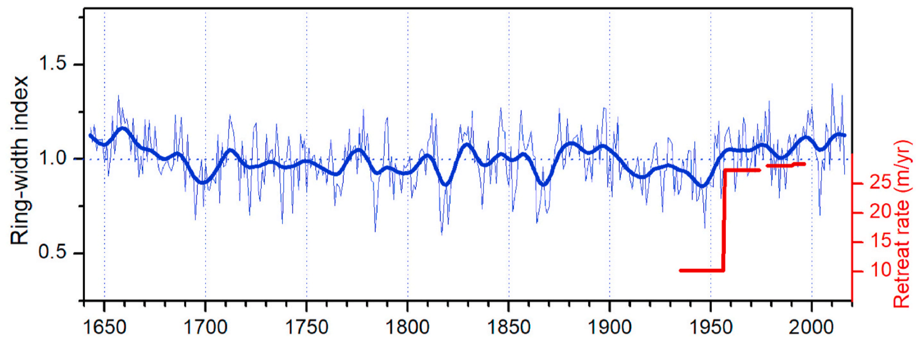

Fig. 8. Ring-width chronology of Himalayan pine plotted together with terminus retreat rate; after Srivastava (2012). Ring-width chronology was filtered with 20-year spline low pass filter.

winter temperatures were usually low across the western Himalaya (Borgaonkar et al., 2011). The slower rate of terminus retreat in the early 20th century, in general is consistent with the radial growth suppression of high-elevation Himalayan cedar in the western Himalaya as well (Borgaonkar et al., 2009), reflecting its regional nature when many of the glaciers in the Central Himalaya and southern Tibet advanced/remained stationary (Mayewaski and Jeschke, 1979; Kotlyakov et al., 1991; Bräuning, 2006). Tibetan Plateau ice core records of Dasuopu (Duan and Yao, 2003) also showed increased accumulation in the early 20th century. In view of the presence of such a strong regional and hemispheric temperature signal, Himalayan pine chronology could be taken as a sensitive and precise measure of the Gangotri glacier dynamics in context of the past 374 years (1643–2016 C.E.). Himalayan pine ring-width indices increased since the mid 20th century when retreat of the Gangotri glacier also gained pace (Fig. 8). Similar to our findings, Borgaonkar et al. (2011) also have noted late 20th century radial growth surge in other high elevation conifer species in the western Himalaya. Increase in growth indices in the late 20th century and faster retreat of glacier could be linked with warming in the western Himalayan region. The radial growth of trees has been found to be positively associated with temperature of autumn and winter seasons in case of evergreen needle leaf trees (Bhattacharyya and Yadav, 1996; Singh and Yadav, 2000; Borgaonkar et al., 2009, 2011). Weather records from the western Himalayan region clearly show warming trend consistent with the global trend (Borgaonkar et al., 2011) and the warming rate is higher since the late 20th century. However, winter warming in the western Himalayan region has been found to be relatively higher than in any other season (Bhutiyani et al., 2007; Borgaonkar et al., 2011). The warming in the Himalayan region has also been reported to be altitude sensitive, higher elevations showing higher rate of warming (Shrestha et al., 1999). Contrary to the increasing trend in temperature in the 20th century, observational precipitation data do not show any trend (Borgaonkar et al., 2011). In view of this, increasing temperature could be taken as a major factor responsible for the rapid retreat of the Gangotri glacier since the late 20th century. Rapid retreat rate of glaciers in the Himalayan region is a cause of concern to human society as glaciers are an important perennial hydrological resource feeding the major rivers in India which are life line of the country.

4. Conclusions

We developed ring-width chronologies of Himalayan birch from Bhojbasa (1611–2016 C.E.), Chirbasa (1582–2016 C.E.) and Himalayan pine from Chirbasa (1574–2016 C.E.) growing at their upper tree line ecotone in the Gangotri glacier forefield. The age of oldest Himalayan birch growing in Bhojbasa extended back to 1571 C.E. Using precisely dated ring-width chronologies of Himalayan birch and Himalayan pine as well as the colonization pattern of the former in the Gangotri glacier forefield we for the first time show the Gangotri glacier terminus fluctuations since 1571 C.E. Most interesting finding of the present study is the precise estimation of the location of the Gangotri glacier terminus ~1.853 km down from its current (July, 2017) position in the late 16th century (1571 C.E.). However, the earlier reports based on geochronological dates showed glacier terminus around 3.7 km from its position in 1992 that should have even crossed down the Bhojbasa ~200–300 yrs B. P. This is highly confounding as Himalayan birch forest dating back to 1571 C.E., located only 3.26 km away from the current (July, 2017) position of the glacier terminus, could not have existed over the glaciated areas. It could be possible that the geochronological dates could have got possibly erred by reworking of sediments by pedogenesis and resedimentation. The colonization pattern of Himalayan birch in the Gangotri glacier forefield has precisely revealed for the first time that the terminus receded ~1.853 km since the late 16th century (1571 C.E.), major part of which (1.79 km) receded since 1935, and the retreat got accelerated since 1957 C.E. (1.567 km) with the onset of rapid warming in the 20th century. Weather records from the western Himalayan region in general have revealed 1.6 °C warming in the 20th century with the higher rate of warming in winters. Relatively higher rate of warming reported at higher elevations as compared to lower elevations in the Himalaya also poses greater threat to glaciers. Over the 21st century under SRES A1B emission scenario the Hindu Kush-Himalaya region is projected to warm by 4–5.5 °C relative to 1971–2000 C.E. (Wiltshire, 2014), and winters are projected to warm even faster than the other seasons. Under such a projected warming in the 21st century (Wiltshire, 2014), the Gangotri glacier might face accelerated recession at an unprecedented rate as ever experienced in past 447 years posing serious concerns on water resource availability.

Authors' contributions

JS & RRY conceived, designed the research and generated tree-ring data. JS, RRY & TR performed data analyses. JS, RRY & PSN conducted field work. JS, RRY, PSN & TR wrote the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Authors express their sincere thanks to Director, Wadia Institute of Himalayan Geology, Dehradun for extending necessary facilities to carry out this work. Generous help offered by the Forest officials of Uttarakhand in collection of research materials is sincerely acknowledged. RRY sincerely acknowledges support of the Council of Scientific and Industrial Research (CSIR), New Delhi under Emeritus Scientist scheme (No. 21(1010)/15/EMR-II). Authors express their sincere thanks to the anonymous reviewers for their valuable suggestions which substantially

improved the manuscript.

References

Ahmad, S., Hasnain, S.I., 2004. Analysis of satellite imageries for characterization of glacio-morphological features of the Gangotri Glacier, Ganga headwater, Garhwal Himalayas. In Proceedings of Workshop on Gangotri Glacier, Lucknow, 26–28 March 2003 (eds Srivastava, D., Gupta, K. R. and Mukerji, S.), Geological Survey of India Special Publication 80, 61–67.

Auden, J.B., 1937. The snout of the Gangotri glacier, tehri garhwal. Record Geol. Surv. India 72, 135–140.

Bahuguna, I.M., Kulkarni, A.V., Nayak, S., Rathore, B.P., Negi, H.S., Mather, P., 2007. Himalayan glacier retreat using IRS 1C PAN stereo data. Int. J. Remote Sensing 28, 437–442.

Barnard, P.L., Owen, L.A., Finkel, R.C., 2004. Style and timing of glacial and paraglacial sedimentation in a monsoon-influenced high Himalayan environment, the upper Bhagirathi Valley, Garhwal Himalaya. Sediment. Geol. 165, 199–221.

Barry, R.G., 2006. The status of research on glaciers and global glacier recession: a review. Prog. Phys. Geogr. 30, 285–306.

Benn, D.I., Bolch, T., Hands, K., Gulley, J., Luckman, A., Nicholson, L.I., Quincey, D., Thompson, S., Toumi, R., Wiseman, S., 2012. Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards. Earth Sci. Rev. 114, 156–174.

Bhambri, R., Bolch, T., Chaujar, R.K., 2012. Frontal recession of Gangotri Glacier, Garhwal Himalayas, from 1965 to 2006, measured through high resolution remote sensing data. Curr. Sci. 102, 489–494.

Bhambri, R., Chaujar, R.K., 2009. Recession of Gangotri glacier (1962–2006) measured through remote sensing data. In Proceeding of National Seminar on Management Strategies for the Indian Himalaya: Development and Conservation, HNB Garhwal University, Srinagar 1, 254–264.

Bhatt, B.K., 1963. Preliminary study of the Bhagirathi basin between Uttarkashi and gomukh. In: Proceeding of National Symposium on Himalayan Geology, 15. Geol. Soc. India. Misc. Publ., Calcutta, pp. 1–8.

Bhattacharya, A., Bolch, T., Mukherjee, K., Pieczonka, T., Kropáček, J.A.N., Buchroithner, M.F., 2016. Overall recession and mass budget of Gangotri Glacier, Garhwal Himalayas, from 1965 to 2015 using remote sensing data. J. Glaciol. 62, 1115–1133.

Bhattacharyya, A., Yadav, R.R., 1996. Dendrochronological reconnaissance of *Pinus wallichiana* to study glacial behaviour in the western Himalaya. Curr. Sci. 70, 739–743.

Bhattacharyya, A., Shah, S.K., Chaudhary, V., 2006. Would tree ring data of *Betula utilis* be potential for the analysis of Himalayan glacial fluctuations? Curr. Sci. 91, 754–761.

Bhutiyani, M.R., Kale, V.S., Pawar, N.J., 2007. Long-term trends in maximum, minimum and mean annual air temperatures across the Northwestern Himalaya during the twentieth century. Climatic Change 85, 159–177.

Biondi, F., Waikul, K., 2004. DENDROCLIM2002: a C++ program for statistical calibration of climate signals in tree-ring chronologies. Comput. Geosci. 30, 303–311.

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J.G., Frey, H., Kargel, J.S., Fujita, K., Scheel, M., Bajracharya, S., Stoffel, M., 2012. The state and fate of Himalayan glaciers. Science 336, 310–314.

Borgaonkar, H.P., Somaru, R., Sikder, A.B., 2009. Assessment of tree-ring analysis of high-elevation *Cedrus deodara* D. Don from Western Himalaya (India) in relation to climate and glacier fluctuations. Dendrochronologia 27, 59–69.

Borgaonkar, H.P., Sikder, A.B., Ram, Somaru, 2011. High altitude forest sensitivity to the recent warming: a tree-ring analysis of conifers from Western Himalaya, India. Quat. Int. 236, 158–166.

Bräuning, A., 2006. Tree-ring evidence of 'little ice age' glacier advances in southern Tibet. Holocene 16, 369–380.

Cook, E.R., 1985. A Time-Series Analysis Approach to Tree-Ring Standardization. PhD dissertation. University of Arizona, Tucson, U.S.A.

Cook, E.R., Peters, K., 1981. The smoothing spline: a New approach to standardizing forest interior tree-ring width series for dendroclimatic studies. Tree-Ring Bull. 41, 45–53.

Cook, E., Briffa, K., Meko, D., Graybill, D., 1995. The 'segment length curse' in long tree-ring chronology development for paleoclimatic studies. Holocene 5, 229–237.

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

Cruz, R.V., Harasawa, H., Lal, M., Wu, S., Anokhin, Y., Punsalmaa, B., Honda, Y., Jafari, M., Li, C., Huu Ninh, N., 2007. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), IPCC Climate Change 2007: *Impacts, Adaptation And Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, pp. 469–506.

Dobhal, P.D., Gergan, J.T., Thayyen, R.J., 2008. Mass balance studies of the dokriani glacier, garhwal Himalaya, India. Bull. Glaciol. Res. 25, 9–17.

Duan, K., Yao, T., 2003. Monsoon variability in the Himalayas under the condition of global warming. J. Meteorol. Soc. Jpn. 81, 251–257.

Dubey, B., Yadav, R.R., Singh, J., Chaturvedi, R., 2003. Upward shift of himalayan pine in western Himalaya, India. Curr. Sci. 85, 1135–1136.

Eddy, J.A., 1976. Maunder minimum. Science 192, 1189–1202.

Emmingham, W.H., Waring, R.H., 1977. An index of photosynthesis for comparing forest sites in Western Oregon. Can. J. For. Res. 7, 165–174.

Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D., Alsdorf, D., 2007. The shuttle radar Topography mission. Rev. Geophys. 45, 1–33. https://doi.org/10.1029/2005RG000183. RG2004.

Fritts, H.C., 1976. Tree Rings and Climate. Academic Press Inc., New York, p. 567.

Gansser, A., 1964. Geology of the Himalayas. Interscience publishers, pp. 1–289.

Gusain, H.S., Kala, M., Ganju, A., Mishra, V.D., Snehmani, 2015. Observations of snow-meteorological parameters in Gangotri glacier region. Curr. Sci. 109, 2116–2120.

Harris, I., Jones, P.D., Osborn, T.J., Lister, D.H., 2014. Updated high-resolution grids of monthly climatic observations- the CRU TS3.10 Dataset. Int. J. Climatol. 34, 623–642.

Heim, A., Gansser, A., 1939. The central himalayas: geological observations of the Swiss expedition of 1936. In: Mem. Soc. Helv. Sci. Nat., 73, p. 245p.

Hewitt, K., 2009. The Karakoram Anomaly? Glacier Expansion and the 'Elevation Effect,' Karakoram Himalaya. Mt. Res.Dev. 25, 332–340. https://doi.org/10.1659/0276-4741(2005)025[0332:TKAGEA]2.0.CO;2.

Immerzeel, W.W., van Beek, L.P.H., Bierkens, M.F.P., 2010. Climate change will affect the Asian water towers. Science 328, 1382–1385.

IPCC, 2014. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E. S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A:Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1132.

Jain, A.K., Singh, S., Manickavasagam, R.M., 2002. Himalayan collision tectonics. In: Memoir Gondwana Research Group, 7, p. 114.

Jangpangi, B.S., 1958. Report on the survey and glaciological study of Gangotri glacier, TehriGarhwal district, Glacier No. III, Arwa valley, Satopanth and Bhagirathi Kharak glaciers, Garhwal district, U.P. Rep. Geol. Surv. India (Unpub.).

Kääb, A., Berthier, E., Nuth, K., Gardelle, J., Arnaud, Y., 2012. Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. Nature 488, 495–498.

Kotlyakov, V.M., Serebryanny, L.R., Solomina, O.N., 1991. Climate change and glacier fluctuation during the last 1,000 Years in the southern Mountains of the USSR. Mt. Res. Dev. 11, 1–12.

Kramer, P.J., Kozlowski, T.T., 1979. Physiology of Woody Plants. Academic Press, New York.

Krusic, P.J., Cook, E.R., Dukpa, D., Putnam, A.E., Rupper, S., Schaefer, J., 2015. Six hundred thirty eight years of summer temperature variability over the Bhutanese Himalaya. Geophys. Res. Lett. 42, 2988–2994. https://doi.org/10.1002/2015GL063566.

Kumar, K., Dumka, R.K., Miral, M.S., Satyal, G.S., Pant, M., 2008. Estimation of retreat rate of Gangotri Glacier using rapid static and kinematic GPS survey. Curr. Sci. 94, 258–262.

Le Fort, P., 1975. Himalayas: the collided range. Present knowledge of the continental arc. Am. J. Sci. 275, 1–44.

Mayewaski, P.A., Jeschke, P.A., 1979. Himalayan and Trans-Himalayan glacier fluctuations since AD 1812. Arctic Alpine Res. 11, 267–287.

Melvin, T.M., Briffa, K.R., 2008. A "signal-free'' approach to dendroclimatic standardization. Dendrochronologia 26, 71–86.

Mukherjee, B.P., Sangewar, C.V., 2001. Recession of Gangotri glacier through 20th century. Geol. Surv. India, Spl. Pub. 65, 1–3.

Naithani, A.K., Nainwal, H.C., Sati, K.K., Prasad, C., 2001. Geomorphological evidences of retreat of the Gangotri glacier and its characteristics. Curr. Sci. 80, 87–94.

Negi, H.S., Thakur, N.K., Ganju, A., Snehmani, 2012. Monitoring of Gangotri glacier using remote sensing and ground observations. J. Earth Syst. Sci. 121, 855–866.

Owen, L.A., Robinson, R., Benn, D.I., Finkel, R.C., Davis, N.K., Yi, C., Putkonen, J., Li, D., Murray, A.S., 2009. Quaternary glaciation of mount everest. Quat. Sci. Rev. 28, 1412–1433.

PAGES 2k Consortium, 2013. Continental-scale temperature variability during the past two millennia. Nat. Geosci. 6, 339–346.

Puri, V.M.K., 1984. Gangotri glacier - Report on the Interdepartmental Expedition - 1975. (Progress Report) Rep. Geol. Surv. India (Unpub.).

Puri, V.M.K., 1984. Gangotri glacier - Report on the Interdepartmental Expedition - 1976. (Progress Report) Rep. Geo. Surv. India (Unpub.).

Puri, V.M.K., 1984. Report on Gangotri Glacier Expedition, U.P. - 1977. (Progress Report) Rep. Geol. Surv. India (Unpub.).

Puri, V.M.K., 1991. Report on survey of selected (Gangotri) glacier by terrestrial photogrammetry, district Uttarkashi, U.P. (Progress Report) Rep. Geol. Surv. India (Unpub.).

Puri, V.M.K., Singh, S., 1974. Report on Gangotri glacier. (Progress Report) Rep. Geol. Surv. India (Unpub.).

Ragettli, S., Immerzeel, W.W., Pellicciotti, F., 2016. Contrasting climate change impact on river flows from high-altitude catchments in the Himalayan and Andes Mountains. Proc. Natl. Acad. Sci. U.S.A. 113, 9222–9227.

Ravi Shanker, Srivastava, D., 1999. Glaciated regime, environmental interaction and Himalayan ecosystem. Geol. Surv. India, Spl. Pub. 53, 17–21.

Rawat, D.S., 2012. Monitoring ecosystem boundaries in the Himalaya through an 'eye in the sky'. Curr. Sci. 102, 1352–1354.

Robock, A., Mao, J.P., 1995. The volcanic signal in surface-temperature observations. J. Clim. 8, 1086–1103.

Rowan, A.V., 2017. The 'Little Ice Age' in the Himalaya: a review of glacier advance driven by Northern Hemisphere temperature change. Holocene 27, 292–308.

Sachs, M., Graf, H.F., 2001. The volcanic impact on global atmosphere and climate. In: Lozán, L.L., Grasl, H., Hupfer, P. (Eds.), Climate of the 21st Century: Changes and Risks. Wissenschaftliche Auswertungen, pp. 34–37.
Sangewar, C.V., 1997. Report on glacier front fluctuation studies in parts of U .P. and H . P. Himalaya (Gangotri and Bhrigupanth, Bhagirathi basin). Rep. Geol. surv. India (Unpub.).
Scherler, D., Bookhagen, B., Strecker, M.R., 2011. Spatially variable response of Himalayan glaciers to climate change affected by debris cover. Nat. Geosci. 4, 156–159.
Sharma, M.C., Owen, L.A., 1996. Quaternary glacial history of the garhwal Himalaya, India. Quat. Sci. Rev. 15, 335–365.
Shea, J.M., Immerzeel, W.W., Wagnon, P., Vincent, C., Bajracharya, S., 2015. Modelling glacier change in the Everest region, Nepal Himalaya. Cryosphere 9, 1105–1128.
Shekhar, M., Bhardwaj, A., Singh, S., Ranhotra, P.S., Bhattacharyya, A., Pal, A.K., Roy, I., Martín-Torres, F.J., Zorzano, M.-P., 2017. Himalayan glaciers experienced significant mass loss during later phases of little ice age. Sci. Rep. 7, 10305.
Shrestha, A.B., Wake, C.P., Mayewski, P.A., Dibb, J.E., 1999. Maximum temperature trends in the Himalaya and its vicinity: analysis based on temperature records from Nepal for the period 1971-94. J. Clim. 12, 2775–2786.
Singh, P., Haritashya, U.K., Ramasastri, R., Kumar, N., 2005. Prevailing weather conditions during summer seasons around Gangotri Glacier. Curr. Sci. 88, 753–760.
Singh, C.P., Panigrahy, S., Thapliyal, A., Kimothi, M.M., Soni, P., Parihar, J.S., 2012. Monitoring the alpine treeline shift in parts of the Indian Himalayas using remote sensing. Curr. Sci. 102, 559–562.
Singh, D.S., Tangri, A.K., Kumar, D., Dubey, C.A., Bali, R., 2017. Pattern of retreat and related morphological zones of Gangotri glacier, garhwal Himalaya, India. Quat. Int. 444, 172–181.
Singh, D.S., Dubey, C.A., Kumar, D., Vishawakarma, B., Singh, A.K., TripathiA, Gautam, P.K., Bali, R., Agarwal, K.K., Sharma, R., 2019. Monsoon variability and major climatic events between 25 and 0.05 ka BP using sedimentary parameters in the Gangotri Glacier region, Garhwal Himalaya, India. Quat. Int. 507, 148–155.
Singh, J., Yadav, R.R., 2000. Tree-ring indications of recent glacier fluctuations in Gangotri, Western Himalaya, India. Curr. Sci. 79, 1598–1601.
Solomina, O.N., Bradley, R.S., Jomelli, V., Geirsdottir, A., Kaufman, D.S., Koch, J., McKay, N.P., Masiokas, M., Miller, G., Nesje, A., Nicolussi, K., Owen, L.A., Putnam, A.E., Wanner, H., Wiles, G., Yang, B., 2016. Glacier fluctuations during the past 2000 years. Quat. Sci. Rev. 149, 61–90.
Srivastava, D., 2004. Recession of Gangotri glacier. In: Srivastava, D., Gupta, K.R., Mukerji, S. (Eds.), Geological Survey of India, Spl. Pub., 80, pp. 21–31.
Srivastava, D., 2012. Status Report on Gangotri Glacier, Science and Engineering Research Board. Department of Science and Technology, New Delhi, p. 102. Himalayan Glaciology Technical Report No.3.
Stokes, M.A., Smiley, T.L., 1968. An Introduction to Tree-Ring Dating. The University of Chicago Press, Chicago.
Tangri, A.K., 2002. Shrinking glaciers of Uttaranchal; cause of concern and hope for the future. In: Pant, C.C., Sharma, A.K. (Eds.), Aspects of Geology and Environment of the Himalaya. GyanodayPrakashan, Nainital 359–367.
Tangri, A.K., Chandra, R., Yadav, S.K.S., 2004. Temporal monitoring of the snout, Equilibrium line and Ablation zone of Gangotri Glacier through remote sensing and GIS techniques- an attempt at deciphering the climatic variability. Geol. Surv. India, Spl. Pub. 80, 145–153.
Troup, R.S., 1921. The Silviculture of Indian Trees, vol. III. Clarendon press, Oxford.
Vohra, C.P., 1971. Report of the Training-Cum-Study Expedition to the Gangotri glacier. INCH, CSIR, New Delhi.
Vohra, C.P., 2010. Glaciers of asia-glaciers of India. In: Williams jr., R.S., Ferrigno, J.G. (Eds.), Satellite Image Atlas of Glaciers of the World. U.S. Geological Survey Professional, pp. 259–274. Paper 1386-f-5.
Wagner, S., Zorita, E., 2005. The influence of volcanic, solar and CO2 forcing on the temperatures in the Dalton Minimum (1790–1830): a model study. Clim. Dynam. 25, 205–218.
Waring, R.H., Franklin, J.F., 1979. Evergreen coniferous forests of the pacific northwest. Science 204, 180–186.
Wigley, T.M.L., Briffa, K.R., Jones, P.D., 1984. On the average value of correlated time series with applications in dendroclimatology and hydrometeorology. J. Clim. Appl. Meteorol. 23, 201–213.
Wilson, R., Anchukaitis, K., Briffa, K.R., Büntgen, U., Cook, E., D'Arrigo, R., Davi, N., Esper, J., Frank, D., Gunnarson, B., Hegerl, G., Helama, S., Klesse, S., Krusic, P.J., Linderholm, H.W., Myglan, V., Osborn, T.J., Rydval, M., Schneider, L., Schurer, A., Wiles, G., Zhang, P., Zorita, E., 2016. Last millennium northern hemisphere summer temperatures from tree rings: Part I: the long term context. Quat. Sci. Rev. 134, 1–18.
Wiltshire, A.J., 2014. Climate change implications for the glaciers of the Hindu kuah, Karakoram and himalayan region. Cryosphere 8, 941–958.
Yadav, R.R., Braeuning, A., Singh, J., 2011. Tree ring inferred summer temperature variations over the last millennium in western Himalaya, India. Clim. Dynam. 36, 1545–1554.
Yadava, A.K., Sharma, Y.K., Dubey, B., Singh, J., Singh, V., Bhutiyani, M.R., Yadav, R.R., Misra, K.G., 2017. Altitudinal treeline dynamics of Himalayan pine in western Himalaya, India. Quat. Int. 444, 44–52. https://doi.org/10.1016/j.quaint.2016.07.032.
Yin, A., 2006. Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation. Earth Sci. Rev. 76, 1–131.