Tree-ring-width chronologies from moisture stressed sites fail to capture volcanic eruption associated extreme low temperature events

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Tree-rings have been extensively used to develop temperature reconstructions using conifer species growing in different parts of the Himalaya. The reconstructions are based on the existence of both positive and negative relationship between the tree-ring chronologies and instrumental temperature records. However, the reconstructions based on positive relationship between tree-ring and temperature series are few. Regional temperature reconstructions developed using tree-ring series have revealed a significant correlation with the regional data which degraded gradually with distance from the tree-ring sampling sites indicating dominant orographic control on climate. On critical assessment of the available tree-ring-based temperature reconstructions, glaring anomalies were reported especially in case of the extreme years coinciding with the volcanic eruption associated cooling. Tree-ring-based reconstructions from Kashmir and Nepal, where temperature has direct forcing on tree-ring widths, indicated unusually cold temperatures in 1816, coinciding with the Tambora volcanic eruption in April 1815 in Indonesia. However, in the case of the chronologies having negative relationship with temperature, usually warmer conditions are reconstructed against the narrow rings usually observed in 1816. The narrow rings in 1816 could have been caused due to volcanic eruption induced cooling as well as reduced solar radiation restricting the photosynthesis. Thus changes in the limiting factor led to the break in relationship between tree-ring indices and climate parameters. In view of this, it is suggested that the environmental variables having direct relationship with tree growth should be reconstructed from tree-ring chronologies as there exists a fair possibility that the growth limiting factor such as temperature remains stable over time.

Keywords: Himalaya, Tambora, temperature reconstruction, tree-ring-width, volcanic eruption, wood density.

Introduction

TREE-RING series are widely used in palaeoclimatic studies due to high precision in dating of growth rings and calibration with observational meteorological records[1,2]. The environmental variable most limiting the growth of trees in a region (Liebig's law of the minimum) could be reconstructed from tree ring series. In dendroclimatological studies the sites are selected with the focus to identify sites where a single common growth factor has dominant control on growth[3]. The annual variations in limiting factors determining the growth are reflected in physical and chemical properties of annual wood increments. However, the most basic principle of tree-ring-based reconstruction lies in temporal stability of relationship between tree-ring and weather parameter being reconstructed. Ring-widths[4–15] and density series[4,5,10] have been commonly used in India and neighbouring Himalayan countries to develop long-term temperature records. Most of the temperature reconstructions thus far developed from the Himalayan region in India and Nepal are based on the existence of negative relationship between temperature and tree-ring-width series except that of Hughes[4,5] from the valley of Kashmir; Cook *et al.*[9] and Sano *et al.*[10] from Nepal where temperature series were found to be directly correlated with the tree-ring-width and density series.

Temperature reconstructions thus far developed from the Himalayan region (India and Nepal) have revealed sound verification statistics and inter-proxy cross validations, irrespective of the type of correlation, whether positive or negative, that existed between tree-ring and temperature series. The temperature reconstructions based on the existence of negative correlation between tree-ring series and temperature usually do not reflect cool years following the year of volcanic eruption. However, in contrary, warm years were reconstructed against the narrow rings except in one reconstruction of July–September temperature from Sikkim, northeast India[14]. The most glaring anomaly in temperature reconstructions thus far available is from the western Himalayan region[6–8,11] and western Nepal[13]. We present here the critical evaluation of available temperature reconstructions especially from India and Nepal part of the Himalaya to understand the possible causes of such failures in capturing extreme cold years and recommend future strategies to develop reliable temperature reconstructions from ring-width series.

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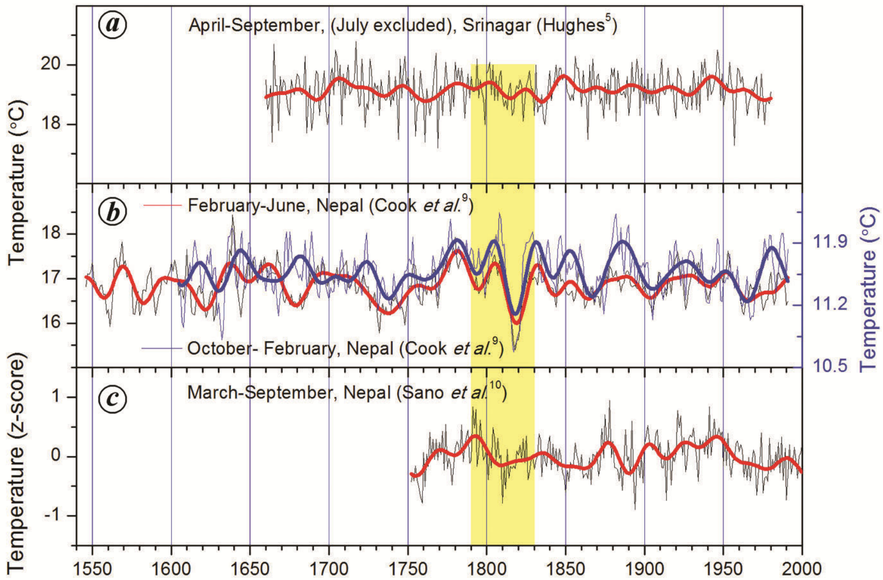

Figure 1. Temperature reconstructions from the Himalayan region with direct relationship between tree-ring chronologies and temperature records. ***a***, April–September (July excluded) for the valley of Kashmir[5]; ***b***, February–June and October–February temperature reconstruction for Kathmandu, Nepal[9]; ***c***, March–September temperature reconstruction for western Nepal[10]. Yellow bar represents the period of Dalton minimum when solar activity was very low and the period was also featured by volcanic eruptions of global and hemispheric scale climatic significance.

Temperature reconstructions based on existence of direct relationship between tree-ring-width and temperature series

There are only few tree-ring chronologies developed from the Himalayan region which showed a direct relationship with the growing season temperature[4,5,9,10]. Using tree-ring-width and maximum wood density data of *Abies pindrow*, Hughes[4] first developed April–May temperature reconstruction from the valley of Kashmir, which he later revised and extended back to AD 1660 for longer season (April–September (July excluded)) (Figure 1 *a*)[5]. Hughes[5] used well-replicated chronologies of *Abies pindrow* developed from a network of eight mountainous sites distributed at elevations between 2620 and 3400 m amsl in the valley of Kashmir. The reconstruction revealed cooling in 1816 and 1817 subsequent to the year of Tambora volcanic eruption in 1815 (Figure 2 *a*). Tambora that erupted in Indonesia in April 1815 is the largest historically documented eruption of the modern (instrumental) era[16,17]. This is one of the only four Holocene eruptions to have been assigned a Volcanic Explosivity Index (VEI) of 7 (ref. 18). Instrumental, historical and various tree-ring evidences all show widespread cold conditions, especially in eastern North America, Western Europe in 1816 (ref. 16). Various ice core data[19] also invariably show a strong acidity signal associated with the year of Tambora eruption. This volcanic activity has been shown to be an important cause of cooling, however, the relative contribution of it varied from region to region. Reduced solar radiation in subsequent years after the eruption could have led to reduced photosynthetic assimilation resulting in the formation of extremely narrow rings in subsequent 2–3 years. It has been demonstrated earlier that the volcanic eruption-induced cooling seriously affects the size of growth rings at temperature stressed sites[20,21]. Maximum latewood density chronologies of circum-boreal tree-ring network, sensitive to summer temperature, have shown precise correspondence with the timing of explosive volcanic eruptions[20]. Ring densities show synchronous evidence of volcanically induced cooling reflected in the reconstructions that were made using temperature (April–September) sensitive chronologies where it is primarily assumed that the limiting factors remain the same and do not change over time[20].

Tree-ring-width chronology network of six indigenous species (*Abies spectabilis*, *Tsuga dumosa*, *Pinus wallichiana*, *Juniperus recurva*, *Picea smithiana* and *Ulmus wallichiana*) from 32 sites in Nepal were used by Cook *et al.*[9] to develop temperature reconstruction (February–June, AD 1546–1991; October–February, AD 1605–1991) for Kathmandu (Figure 1 *b*). The tree ring materials used to derive temperature reconstructions usually came from closed-canopy forests with various levels of natural and anthropogenic disturbances. The temperature reconstructions of the above two seasons showed conspicuous cooling in 1815–16 after the eruption of Tambora in April 1815 (February–June temperature; Figure 2 *a*), with the temperature depression from the long-term mean on the order of 1.5°C for February–June and 0.8°C for

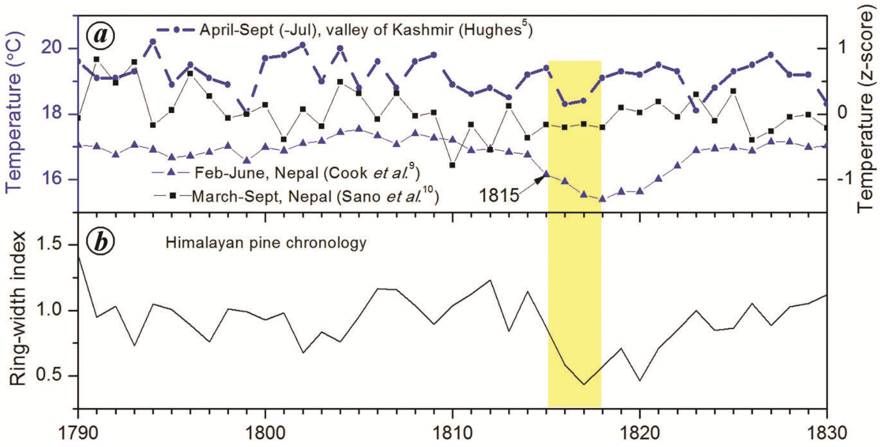

Figure 2. Temperature and ring-width variation in sub-alpine Himalayan pine in the western Himalaya, India during Dalton period (AD 1790–1830). ***a***, Temperature reconstructions revealed significant drop in temperature for 2–3 years subsequent to the eruption of Tambora volcano (yellow bar)[5,9,10]. ***b***, Reduced radial growth in Himalayan pine growing in sub-alpine tree-line in the western Himalaya (Singh *et al.*, unpublished data).

October–February[9]. Both the reconstructions also revealed below-average temperature broadly contemporaneous with the Little Ice Age; however, there existed clear seasonal differences. The cool temperatures are mainly restricted to 1670–1770 in the February–June temperature reconstruction; however October–February record generally indicated below-average temperatures from 1605 to 1770 and a long-term warming trend up to 1880. The two reconstructions also revealed generally good agreement at inter-decadal time scales from 1720 to 1950, with interesting differences before 1720 and after 1950. October–February temperature reconstruction showed 20th century warming, whereas February–June temperature, consistent with the observational records cooled since the 1960s (ref. 9).

Sano *et al.*[10] analysed ring-width and tree-ring density parameters of *A. spectabilis* growing near timberline of 3850 m amsl on the northeast-facing slope in western Nepal. March–September mean temperature reconstruction extending back to AD 1752 was developed using ring-width, minimum, maximum and mean density chronologies (Figure 1 *c*). This reconstruction revealed common feature appearing in February–June temperature reconstruction of Kathmandu, Nepal[9]. Both the reconstructions of February–June[9] and March–September[10] showed sharp cold period in 1810s, which is attributable to the eruption of Tambora in 1815 and another unknown eruption in 1809–1810 (Figure 2 *a*)[22].

Recently, Singh *et al.* (unpublished data) prepared a ring-width chronology of Himalayan pine (*P. wallichiana*) (AD 1643–2016) from upper tree-line in the sub-alpine western Himalaya. This chronology showed direct and relatively strong relationship with mean temperature of October, November and December prior to growth year, indicating that warm winters favour the growth of Himalayan pine at upper tree-line zones in the western Himalaya. Winter temperature directly affecting the radial growth of the Himalayan pine was possible as many of the conifers are known to perform a 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. Himalayan pine chronology revealed the lowest three-year mean growth indices during 1816–1818 (0.57), almost three standard deviations below the long-term mean (AD 1643–2016), indicating that cooling associated with the Tambora eruption could have caused severe growth reduction in high-elevation sub-alpine Himalayan pine trees in the western Himalaya (Figure 2 *b*).

Temperature reconstructions based on existence of negative relationship between tree-ring-width and temperature series

Borgaonkar *et al.*[15] using ring-width chronologies of Himalayan cedar (*Cedrus deodara*) from sites in Manali, Shimla and Kanasar in the western Himalaya developed premonsoon (March–April–May) temperature extending back to AD 1775. The reconstruction revealed slightly cool conditions during AD 1780–1840 and warm conditions during AD 1841–1890. No evidence of Tambora volcanic eruption associated cooling was recorded by the authors. Subsequent to the temperature reconstruction by Borgaonkar *et al.*[15], various temperature reconstructions for the pre-monsoon (March–April–May) and summer (May–June–July–August (MJJA)) season for the western Himalayan region were reported by several authors where multi-site ring-width chronology network of Himalayan fir (*Abies pindrow*), Himalayan cedar[6–8,23] and Himalayan pencil juniper (*Juniperus polycarpos* C. Koch)[11] were used. The millennium-long mean summer MJJA temperature

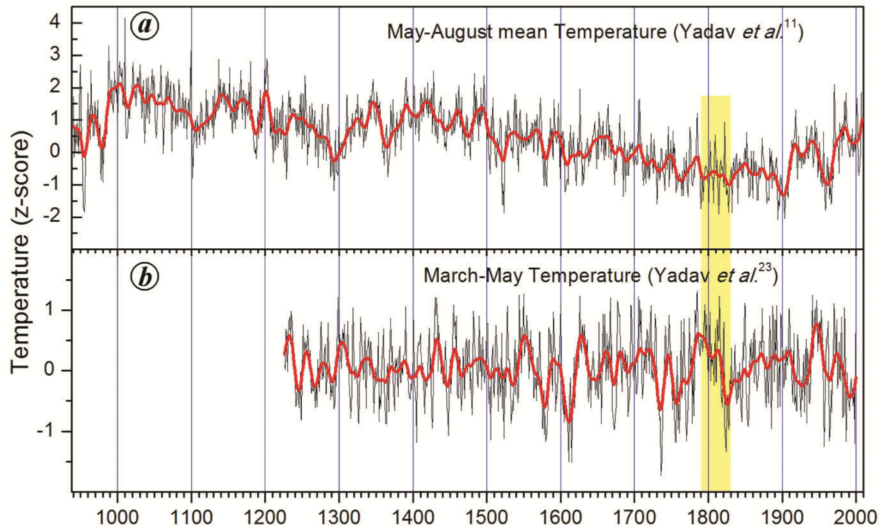

Figure 3. Temperature reconstructions from the Himalayan region with indirect relationship between tree-ring and temperature series. ***a***, May–June–July–August mean temperature for the Lahaul region, Himachal Pradesh, western Himalaya[11]; ***b***, March–April–May temperature reconstruction for the western Himalaya, India[23]. Yellow bar represents the period of Dalton minimum when solar activity was very low and the period was also featured by volcanic eruptions of global and hemispheric scale climatic significance.

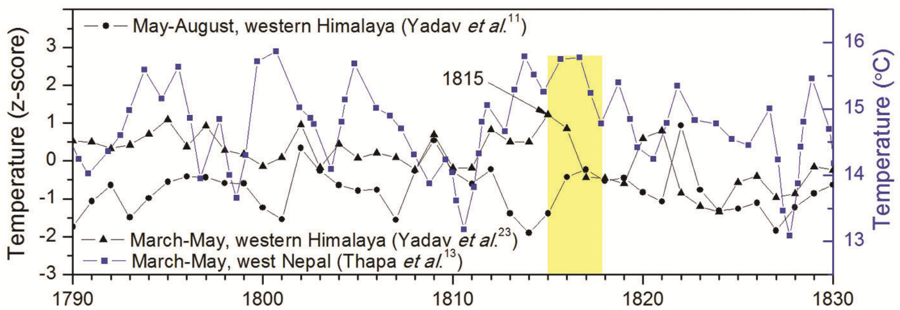

Figure 4. Temperature variation in the western Himalaya, India[11,23] and western Nepal[13] during the Dalton period (AD 1790–1830). The reconstructions were developed using tree-ring chronologies showing negative relationship with regional temperature. Note that the years subsequent to Tambora eruption (yellow bar) were usually warm contrary to that observed in temperature records developed when direct relationship existed between tree-ring and temperature series.

reconstruction developed using tree-ring-width data network of Himalayan pencil juniper (*Juniperus polycarpos* C. Koch) from the monsoon-shadow zone in the western Himalaya, India[11] revealed centennial-scale variations with the periods of protracted warmth encompassing the 11–15th centuries (Figure 3 *a*). A decreasing trend in mean summer temperature occurred since the 15th century with the 18–19th centuries being the coldest interval of the last millennium, coinciding with the expansion of glaciers in the western Himalaya. The MJJA temperature reconstruction revealed 1810–1909 being the coolest hundred years of the last millennium (Figure 3 *a*). The MJJA temperature subsequent to the Tambora eruption in 1816 and 1817 was reconstructed to be warmer relative to that of the previous year (Figure 4). The temperature reconstruction further revealed onset of the warming trend in the MJJA temperature reconstruction since the early 20th century. Decadal scale variations in premonsoon (March–April–May) mean temperature (Figure 3 *b*)[23] showed cold conditions during 1573–1622, 1731–1780 and 1817–1846 in the western Himalaya. Though 1810s–1830s were reported to be relatively cool, signatures of cooling associated with the Tambora eruption, especially in 1816 are not marked in March–April–May temperature reconstruction (Figure 4).

Ring-width chronology of *Picea smithiana* from western Nepal showing indirect relationship with March–April–May temperature was used to develop temperature reconstruction (AD 1640–2012)[13]. The reconstruction failed to show cool episodes in the 1810s (Figure 4) associated with the eruption of Tambora in Indonesia as noted in earlier temperature reconstructions from Kashmir[4,5] and Nepal[9]. The reconstruction of March–April–May temperature revealed 1816 to be warmer than the previous year[13].

Abies densa ring-width chronologies from north Sikkim based on the existence of a significant inverse relationship with temperature were used by Bhattacharyya and Chaudhary[24] to develop July–August–September temperature reconstruction back to AD 1757. The reconstruction revealed second warmest 10-year mean for 1813–1822 after the 1978–1987 mean, opposite to the cooling reported in other regions of the Himalaya where chronologies showing direct relationship with temperature were used[4,5,9,10]. Yadava *et al.*[25] developed ring width chronology of larch (*Larix griffithiana*) from high-elevation north Sikkim, which extended back to AD 1760. However, due to the lack of sufficient sample replication, the reconstruction of mean late summer (July–August–September (JAS)) temperature extending back to only AD 1852 was developed[25]. The 10-year running mean of the temperature reconstruction revealed 1996–2005 as the warmest period (mean anomaly 0.56°C) in past ~150 years. The warming trend revealed in JAS temperature reconstruction is consistent with the upward shift in ecological range of alpine plant species and retreat of glaciers in Sikkim. From north Sikkim, Borgaonkar *et al.*[14] using ring width chronology of Himalayan hemlock (*Tsuga dumosa)* developed JAS mean temperature reconstruction extending back to AD 1705. The temperature reconstruction of JAS by Borgaonkar *et al.*[14] is the only temperature reconstruction based on the existence of negative relationship between ring width chronology and temperature that revealed extremely cold 1816 and 1817 indicating post-Tambora eruption cooling.

Conclusion

Precisely dated tree-ring-width, and density chronologies of various conifer species from the Himalayan region in India and Nepal have been extensively used to develop temperature reconstructions of different seasons. The temperature reconstructions based either on the existence of positive or negative relationship between the tree-ring chronologies and instrumental temperature records from geographically adjacent regions have largely demonstrated consistency on decadal and inter-decadal scales. However, there existed glaring anomalies especially in case of the extreme years coinciding with the volcanic eruption associated cooling. The tree-ring-based reconstructions from Kashmir and Nepal, where temperature has direct relationship with tree-ring chronologies indicated cold temperature in 1816, coinciding with the Tambora volcanic eruption in April 1815 in Indonesia. However, contrary to this, chronologies showing negative relationship with temperature revealed usually warmer conditions against the narrow rings observed in 1816. The radial growth reduction in trees, where temperature showed a negative relationship with the tree-ring chronologies, could have been caused due to Tambora eruption associated reduction in solar radiation required for photosynthesis. Such changes in the limiting factor could have led to the break in relationship between tree-ring indices and climate parameters subsequent to Tambora eruption. In view of such disruptions in relationship between tree-ring and climate parameters, it is suggested that the tree-ring chronologies showing a direct relationship with temperature should be used in temperature reconstructions as in such cases the temperature remains the major growth limiting factor.

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