Late Pleistocene–Holocene vegetation and climate change from the Western and Eastern Himalaya (India): palynological perspective

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A palynological assay of the studies carried out from the Western and the Eastern Himalaya (India) during the Late Pleistocene and Holocene is presented here. The Western Himalaya is affected by both the Indian Summer Monsoon (ISM) and Western Disturbances, whereas the Eastern Himalaya receives precipitation only from the ISM. During the Late Pleistocene (~77 ka), a cold and arid climate supported steppe vegetation in the Western Himalaya. In the Eastern Himalaya, around 66 ka, a cool and dry climate supported the savannah vegetation with few scattered trees of *Pinus* and *Tsuga*. A number of warm-moist fluctuations are also perceptible during the Late Pleistocene. The impacts of Last Glacial Maximum, Holocene Climatic Optimum, Medieval Warm Period and Little Ice Age are well discernible in the vegetation in both the regions. Within a broad similarity, the climate change and associated vegetation succession varied from region to region; as the palynological records are characterized by the evidences of prolonged humid phases in the eastern sector, whereas the arid events are better marked in the western part. The similarities and incompatibilities in the climate and vegetation between the Western and Eastern Himalaya during the Late Pleistocene and Holocene are discussed in the present paper.

Keywords: Climate change, Himalaya, India, palaeopalynology, vegetation dynamics.

Introduction

THE Quaternary Period (~2.6 Ma) has shown dramatic changes in global climate with fluctuations between the glacials and interglacials[1,2]. The late Quaternary climate has been suggested variously to be stable[3,4], unstable with periodic fluctuations[5,6] or subject to rapid changes[7–9]. Within the late Quaternary, the Holocene (last ~11,700 year to present) climate has been found to be even more variable[10] and these variations have been larger and more frequent than commonly recognized. Comparison of palaeoclimate records with climate forcing time series suggests that changes in insolation, related both to the Earth's orbital variations and to solar variability, played a central role in the global scale changes in the climate of the last 11,700 years[10]. Thus, the Holocene climate has not been stable, but rather it has been dynamic at scales significant to humans and ecosystems which have been manifested in both the terrestrial and marine records[10,11]. The Pleistocene (2.58 Ma–11.7 BP), on the other hand, is characterized by repeated glaciations and is known as the Ice Age. The Last Glacial Period (115,000–11,700 year BP) is regarded as the end of the Pleistocene and the beginning of the Holocene. There are four major glacial (cold) events, such as Günz, Mindel, Riss and Würm and three interglacials (warm), such as Günz-Mindel, Mindel-Riss and Riss-Würm during the Pleistocene in the Alps, which is followed in the Indian context as well.

In the Indian context, the Quaternary palaeoclimatic studies are important for understanding the Indian Summer Monsoon (ISM) variability and the effect of Western Disturbances (WDs) (winter precipitation), which have a great impact on the agrarian economy. 'Monsoon', in South Asia, is almost a synonym to climate[11]. The ISM or South Asian Summer Monsoon (SASM), one of the subsystems of the Asian Summer monsoon (ASM)[12], plays a critical role in the global climate, as well as in the hydrological and energy cycles[13]. It also plays a key role in transporting heat and moisture from the warmest parts of the tropical oceans to the mid-latitudes. The potential impacts of ISM variations include droughts and floods over India and other parts of South Asia, directly affecting agricultural productivity, economic development and societal well-being in one of the most densely populated regions of the world[14–18]. ISM provides ~80% of the annual precipitation over India during June–September[17], influencing the agriculture and socio-economic development of the country. Therefore, understanding of the ISM variability is important, both to understand the present climatic conditions and also for future climatic predictions[19]. The WDs, which are actually cyclonic storms associated with the mid-latitude Subtropical Westerly Jet (SWJ), on the other hand, produce short but extreme precipitation over northern India. The WDs are more intense over the Himalayas due to orographic land–atmosphere

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interactions. During December, January and February, snowfall due to WDs is the dominant precipitation in the Higher Himalaya that sustains the regional snowpack and replenishes the regional water resources[20]. Topographic heterogeneity, land use variability and varying snow cover extent are the important climate controls for the ISM[21].

Monsoonal dynamics in the Indian context is manifested primarily by precipitation (mostly rainfall); hence, expressed as hydroclimatic variability. The prime reason for selecting the Western and Eastern Himalayan regions for the present appraisal is that the Western Himalaya is under the influence of both the ISM as well as the WDs, whereas only the ISM affects the Eastern Himalayan region. Besides, the other fundamental reasoning for taking up the present study is due to the fact that: (i) the diversity of vegetation is more in the Eastern Himalaya; (ii) the tree-line/snowline is higher in the Eastern Himalaya compared to that in the Western Himalaya, and (iii) the Eastern Himalaya is warmer and more humid and has less temperature range.

Importance of palynology in climatic reconstructions

Palynology[22], the study of organic-walled microfossils of plant origin, especially the pollen grains and spores, provides important information to reconstruct the past vegetation and concurrent climatic changes. As the vegetation is strongly affected by climate, characteristic changes in the pollen assemblages reflect the climatic fluctuations at a specific time or area[23].

An overview of the pollen-based vegetation dynamics during the Late Pleistocene–Holocene will provide insights into the vegetational and climatic changes in the Western and Eastern Himalaya (India), influenced by the variations in the ISM and WDs. In the Indian subcontinent, the pollen-based Quaternary palaeoclimatic research commenced in the early part of the 20th century, when sediments from Pangong Lake (Ladakh), situated at an altitude of 4250 m amsl, were pollen analysed[24]. Based on pollen evidence, it was inferred that the lake sediments were of an interglacial period. Such studies were resumed by studying the Upper and Lower Karewa deposits of Kashmir, which highlighted the depositional environment that was essentially equivalent to what is prevalent today[25]. Subsequently, the pollen spectra from the Pangong Lake in Ladakh were described and the climatic conditions were inferred to the second interglacial period[26]. Later, in the late fifties, systematic palaeoclimatic studies were initiated from the various parts of the country, with more emphasis on the Himalayan regions, mainly through the pollen analytical studies of lacustrine deposits. An appraisal of such studies (Figure 1; Table 1), conducted from the Western and Eastern Himalaya (India) is presented here. Based on the existing palynological data (Figure 2), a comparison between the two regions of the Himalaya has been summarized, wherein the similarities and incongruities between the Late Pleistocene–Holocene climate and vegetation are discussed in their temporal and spatial aspects.

Vegetation

The vegetation of the Western and Eastern Himalaya is characterized by the presence of nine different types of forests, namely sub-tropical broad-leaved hill forests, sub-tropical pine forests, sub-tropical dry evergreen forests, montane wet temperate forests, Himalayan wet/moist temperate forests, Himalayan dry temperate forests, sub-alpine forests, moist alpine forests and dry alpine forests[27,28]. *Sub-tropical broad-leaved hill forests* predominate in the Western Himalaya (Lesser and Greater/Higher Himalaya) and comprises *Quercus*, *Betula*, *Alnus*, *Juglans*, *Carpinus*, *Corylus* and *Ulmus* as the chief elements. *Sub-tropical pine forests* are found in the Western Himalayas and the chief forest elements are *Pinus roxburghii* and *Pinus kesiya*. *Sub-tropical dry evergreen forests* are also found predominantly in the northwestern Himalaya (mostly the Lesser Himalaya) and consist both of conifers and broad-leaved elements. *Montane wet temperate forests* are found between 1800 m and 3000 m elevations and are the characteristic features of the Eastern Himalaya, wherein *Pinus wallichiana*, *Picea spinulosa* and *Abies densa* are dominant. In the Western Himalaya also, they occupy altitudes between 1500 m to 3000 m, except in the areas where the rainfall is below 1000 mm. *Himalayan wet/moist temperate forests* are luxuriant with dense undergrowth and are found between 1500 m and 3000 m elevations in the Eastern Himalaya. *Himalayan dry temperate forests* consist of both coniferous forest elements, such as *Pinus*, *Abies*, *Picea*, *Juniperus*, *Salix* and *Podocarpus* and broad-leaved species, such as *Quercus*, *Betula*, *Alnus*, *Juglans*, *Carpinus*, *Corylus* and *Ulmus* and are distributed in the Lesser Himalaya in both the regions. *Sub-alpine forests* occur throughout the Himalaya above 3000 m elevation up to the tree-line limit. *Rhododendron*, *Quercus*, *Juniperus*, *Cedrus*, *Pinus* and *Betula* are the main constituents. *Moist alpine forests* occur above the tree-line (3500 m in the Western Himalaya and 4000 m in the Eastern Himalaya) in areas of good rainfall (over 2500 mm) on the windward side of the Greater Himalayan range. It represents a lush alpine meadow with diverse herbaceous ground flora. *Dry alpine forests* occur in the leeward side of the Himalayan range, where the rainfall is much lesser (rain shadow zone). It is distributed in the Trans-Himalayan region in northwest India. The alpine meadows are dry with ephemeral herbaceous elements. A general account of the vegetation, based on altitudinal variations, in both the Western and Eastern Himalaya has been shown in Table 2.

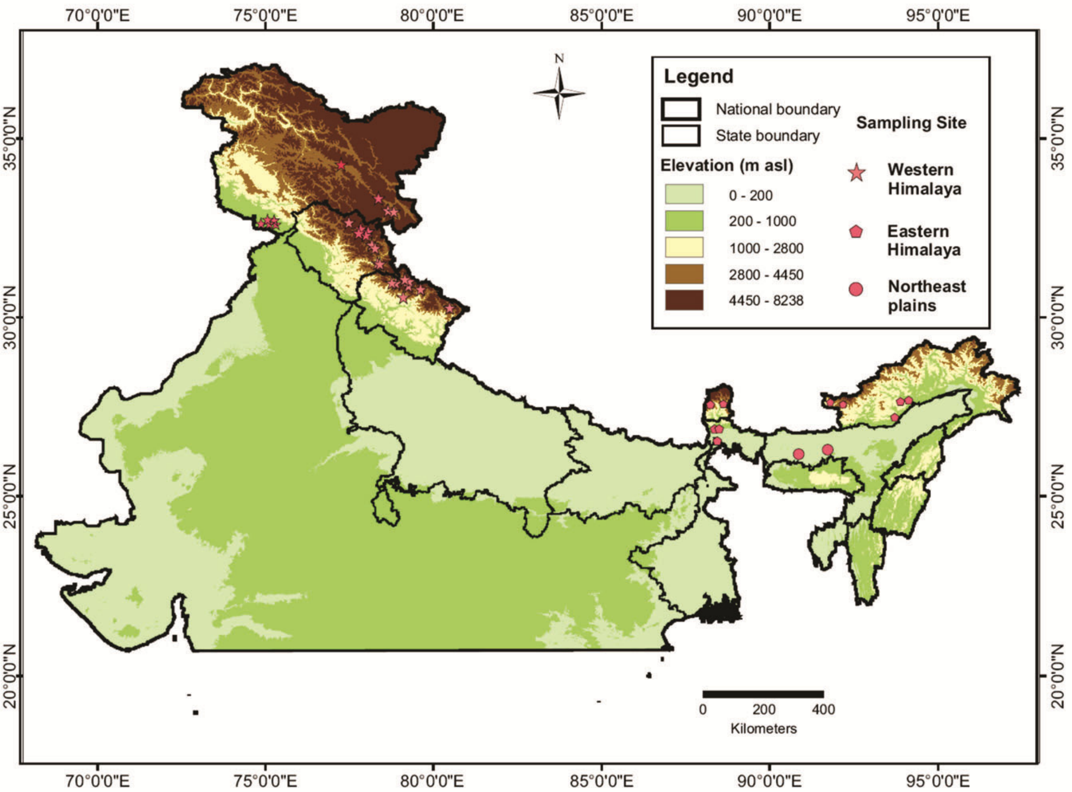

Figure 1. Shuttle radar topographic mission digital elevation map of India showing the locations of palaeoclimatic studies (shown with the 'star' for Western Himalaya, 'polygon' sign for Eastern Himalaya and 'circle' for northeastern plains). The details of the studies, their salient features and other relevant information are given in Table 1. The figure is created using ArcGIS 10.3.

Climate

The Western and Eastern Himalaya experience three different types of climate; cold, humid winter type climate (Dfc), Tundra type climate (Et) and polar type climate (E), which is based upon annual and monthly means of temperature and precipitation[28,29]. Cold, humid winter type climate (Dfc) is found in the Siwalik Hills and Lesser Himalaya (also in northeast India) and is characterized by a humid summer and cold humid winter. The winter temperatures are around 10°C and the summer temperature is <18°C. Tundra type climate (Et) occupies the higher altitudes of Western and Eastern Himalaya. The average temperature of the warmest month varies between 0°C and 10°C, which falls with a rise in altitude. A yearly variation of rainfall takes place in these areas. Polar type climate (E) is found in the higher mountainous areas of the Himalaya. The temperature of the warmest month of these areas is <10°C. Precipitation mostly occurs in the form of snow, and these areas remain under snow during the greater part of the year.

Nearest Climate Research Unit Time Series (CRU TS) 4.01, 0.5×0.5 gridded climate data points, 1901–2016, showing mean monthly precipitation and temperature around the Western and Eastern Himalaya (India)[30] has been represented in Figure 3. In the Western Himalaya, the mean annual temperature (MAT) is 13.92°C and the mean annual precipitation (MAP) is 717.6 mm, whereas the MAT and MAP of the Eastern Himalaya are 23.27°C and 2471.61 mm respectively. Most of the precipitation (~75–80%) occurs through the ISM during June to September; whereas, some winter precipitation also takes place in the Western Himalaya during the winter months (December, January, and February) due to WDs.

Modern pollen–vegetation relationship from the Himalaya

Pollen dispersal studies, undertaken from the palynological analysis of surface sediments, give an idea about the pollen–vegetation relationship, that is, how well the surrounding vegetation is represented in the palynological records. The relationship between the surrounding vegetation and its representation in the pollen records is not always linear or directly proportional due to differences amongst the various taxa in pollen production, dispersal and preservation. More importantly, the pollen–vegetation relationship is a pre-requisite for the Quaternary vegetation reconstructions, as these are required to

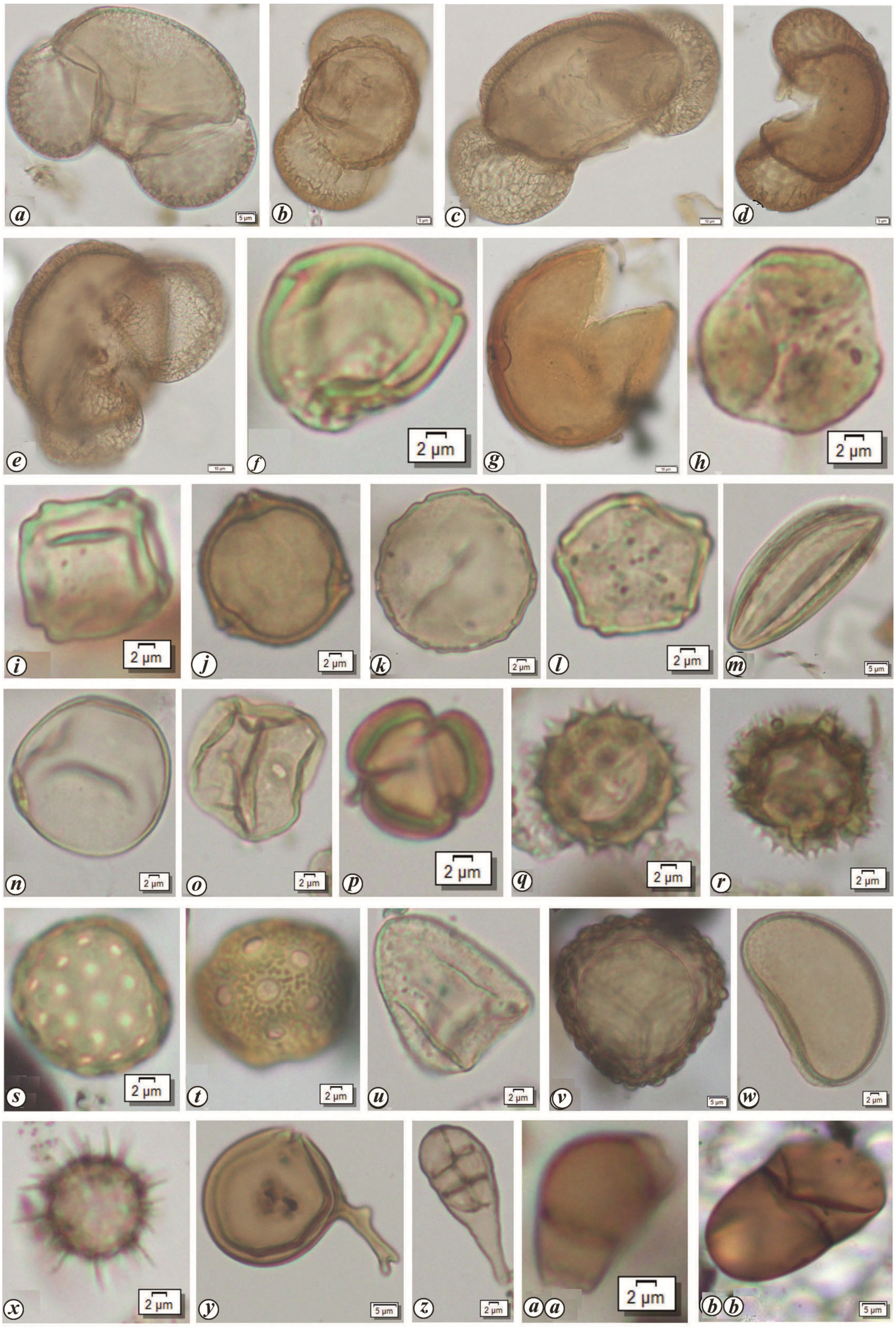

Figure 2. Important arboreal (trees and shrubs; ***a–m***) and non-arboreal pollen (herbs; ***n–x*** and non-pollen palynomorphs; ***y–ab***). ***a***, *Pinus*; ***b***, *Cedrus*; ***c***, *Abies*; ***d***, *Picea*; ***e***, *Podocarpus*; ***f***, *Corylus*; ***g***, *Juniperus*; ***h***, *Quercus*; ***i***, *Alnus*; ***j***, *Carpinus*; ***k***, *Juglans*; ***l***, *Ulmus*; ***m***, *Ephedra*; ***n***, Poaceae; ***o***, Cerealia; ***p***, *Artemisia*; ***q***, Tubuliflorae (Asteroideae: Asteraceae); ***r***, Liguliflorae (Cichorioideae: Asteraceae); ***s***, Amaranthaceae; ***t***, Caryophyllaceae; ***u***, Cyperaceae; ***v***, Trilete fern spore; ***w***, Monolete fern spore; ***x***, *Lemna*; ***y***, *Glomus*; ***z***, *Alternaria*; ***aa***, *Curvularia*; ***ab***, *Diplodia*.

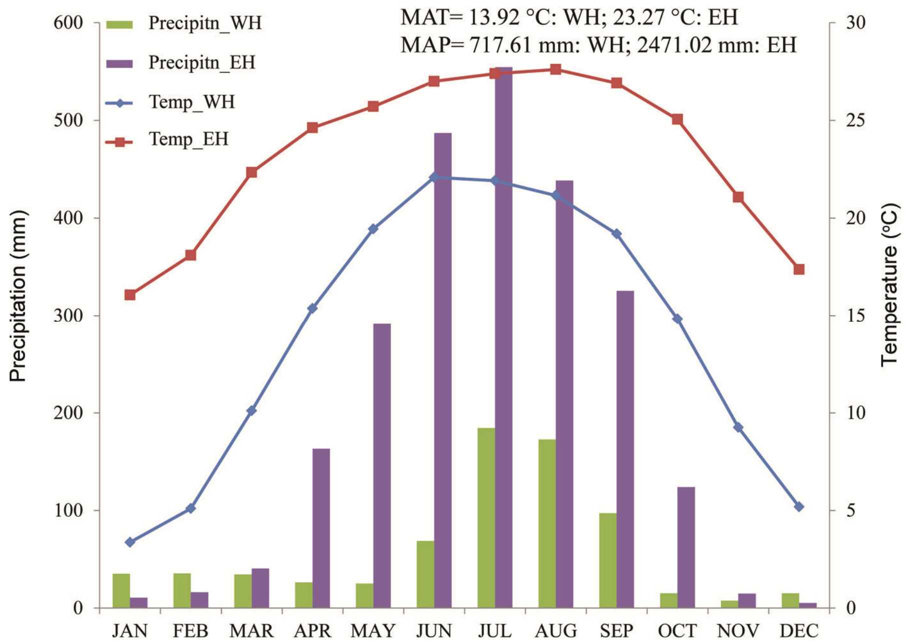

Figure 3. Nearest Climate Research Unit Time Series (CRUTS) 4.01, 0.5×0.5 gridded climate data point, 1901–2016, showing mean monthly precipitation and temperature around the Western and Eastern Himalaya (India). These data are 116-year climate averages for the period 1901–2016; MAT, Mean annual temperature; MAP, Mean annual precipitation; WH, Western Himalaya; EH, Eastern Himalaya.

develop the modern analogues for better interpretation of fossil pollen assemblages. The studies carried out on the pollen–vegetation relationship aspect from the various forest types in the Himalaya, irrespective of altitude, in general, demonstrate the absolute dominance of *Pinus* spp. over other pollen taxa. *Pinus* is a high pollen producer and also disperses exceptionally well by upwelling air currents, which enable its pollen to over-represent the pollen assemblages[28,31–42]. Other conifers, such as *Cedrus*, *Podocarpus*, *Abies*, *Picea*, *Juniperus* and *Tsuga*, as well as the broad-leaved taxa, such as *Alnus*, *Betula*, *Ulmus*, *Quercus*, *Carpinus*, *Corylus*, *Juglans*, *Ilex*, *Mallotus*, *Elaeocarpus* and *Aesculus*, are infrequent and/or under-represented. This could be due to their low pollen production, poor pollen dispersal efficiency and/or poor preservation in the substrate, compared to *Pinus*. *Cedrus* is well represented within the *Cedrus* belt (2000 m) but its percentage declines drastically towards higher and lower elevations in the Greater and Trans Himalayas. In addition, *Salix*, *Fraxinus*, Rosaceae, Moraceae, Sapotaceae, *Emblica officinalis*, *Myrica*, *Rhododendron*, *Celtis*, *Populus*, *Bauhinia*, *Acacia*, *Shorea*, *Cinnamomum*, *Acer*, Liliaceae, Saxifragaceae, Fabaceae and Primulaceae are also represented meagerly, absent and/or under-represented in the pollen spectra. Other coniferous taxa, such as *Podocarpus*, *Juniperus* and *Tsuga*, have their representation in the modern pollen spectra in the Siwaliks and Lesser Himalaya and are transported from long distances through wind. The broad-leaved taxa, such as *Betula*, *Ulmus*, *Carpinus*, *Corylus*, *Ilex* and *Elaeocarpus*, are also transported from the higher altitudes. Poaceae, Cerealia, Asteraceae (Tubuliflorae and Liguliflorae), Amaranthaceae and Malvaceae are the other prominent taxa in the pollen spectra, revealing their actual composition in the ground flora. The record of Cerealia and other cultural plant pollen taxa, such as Amaranthaceae, Caryophyllaceae, Brassicaceae and *Artemisia* is indicative of the agricultural activities around some of the sampling sites. Tubuliflorae and Liguliflorae (Asteraceae), in good values, could be indicating the pastoral activities around the areas of study as these plants are avoided by sheep, goat and cattle due to their unpalatable nature. Cyperaceae, *Polygonum*, *Hygrophila* and Apiaceae point to local wet conditions due to melt water streams. The aquatic taxa, such as *Typha*, *Lemna*, *Utricularia* and *Potamogeton*, as well as algal spores, such as zygospores of *Spirogyra* and *Zygnema*, *Pseudoschizaea* and *Botryococcus* indicate water bodies around the sampling sites. Ferns (monolete and trilete (types I and II) fern spores) reflect the damp and shady environments around the respective areas of study.

A perusal of the studies conducted on pollen dispersal aspects from the different regions of the Himalaya reveals that the pollen–vegetation relationship is generally not directly proportional due to the over-representation of extra-local elements compared to the local taxa. These studies reflect an absolute dominance of *Pinus* pollen across the Himalaya, which overwhelms the other pollen taxa. In some instances, the ground vegetation of herbaceous elements is also not properly represented. Extreme care is, therefore, required while developing the modern analogues as over-/under-representation of certain taxa may not give the true vegetation scenario of a particular region.

Vegetation dynamics and inferred climate change from the Western Himalaya

Vegetation-based palaeoclimatic reconstruction is one of the most potent and reliable tools, as vegetation is one of the main climatic reservoirs of the Earth; the other four climatic reservoirs being the atmosphere, ocean, land surfaces and cryosphere. The global distribution and composition of vegetation is largely controlled by the climate. Vegetation plays a critical role in the Earth's biotic and abiotic systems through its effects on surface albedo[43], atmospheric aerosol[44], greenhouse gas composition and global carbon cycling[45]. Consequently, vegetation and ecosystems are sensitive to even minor fluctuations in the climate. As palynological studies from the Western Himalaya are quite widespread, therefore, for ease of presentation, and for clarity, we are presenting the works from the different parts of the Western Himalaya on the basis of geological sub-divisions of the Himalaya.

Lesser Himalaya

Chirpine–oak forests occupied the area in the vicinity of Dewar Tal (1727 m amsl), sub-tropical belt of Garhwal Himalaya, between ~2500 and 2300 year BP under a cool and dry climate. Between ~2300 and 2000 year BP, the forests expanded under a warm-moist climate. Between ~2000 and 1400 year BP, decline of chirpines and oaks and increase of grasses along with other herbs, is suggestive of a cool–dry climate. Subsequently, the climate turned favourable between ~1400 and 400 year BP and maximum development of oak forests took place. Since the last 400 years, the decline of oaks at the expense of chirpines indicates a cool and dry climate[46].

Mixed chirpine–oak forests, dominated by *Pinus* cf. *roxburghii* (chirpine) existed around the Mansar Lake of the Jammu province in the Lesser Himalaya between 9000 and 8000 year BP under a cool and dry climate[47]. Between 8000 and 7000 year BP, with the expansion of oak (*Quercus* cf. *incana*) and other broad-leaved taxa, the existing forests were transformed into mixed oak–chirpine forests in response to the initiation of a warm and humid climate. Between 7000 and 3000 year BP, reduction of broad-leaved taxa and a simultaneous improvement of the conifers, especially *Pinus* cf. *roxburghii*, indicate a cool and dry climate, prevailing in the region. Subsequently, between 3000 and 750 year BP, the expansion of oak and most of the broad-leaved taxa suggests the prevalence of a warmer and more humid climate. Since 750 year BP to Present, the mixed chirpine–oak forests came into prominence and replaced the existing mixed oak–chirpine forests, indicating a deterioration of climate of the region. In another study from Surinsar Lake (Jammu), alteration of both mixed oak (*Quercus*)-broad-leaved/chirpine (*Pinus* sp.) forests and mixed chirpine/oak-broad-leaved forests since the last 9500 years to the Present was suggested[48].

Mixed conifer/broad-leaved forests occurred around the Gharana wetland of RS Pura sector in the Jammu District between 8536 and 5296 year BP under a cool and dry climate, probably indicating decreased monsoon precipitation[49]. Subsequently, mixed broad-leaved/conifer forests came into existence by succeeding the mixed conifer/broad-leaved forests between 5296 and 2776 year BP under a warm and humid climate with increased monsoon precipitation, partly corresponding to the Holocene Climatic Optimum (HCO). Between 2776 and 1376 year BP, with further expansion of broad-leaved forest elements, the dense mixed broad-leaved/conifer forests came into prominence in response to a further increase in monsoon precipitation. From 1376 year BP to the Present, the climate deteriorated, as manifested by the replacement of dense mixed broad-leaved/conifer forests by increased conifer forests in the region. Another study from the Samba district of the Jammu and Kashmir, observed that between 3984 and 2784 year BP, due to insufficient pollen assemblage, no definite inferences on palaeovegetation could be made[49]. A pluvial environment could, hence, be inferred. Subsequently, between 2784 and 1584 year BP, the mixed broad-leaved/conifer forests with the dominance of broad-leaved taxa and comparatively lesser conifers appeared in the region under a warm and humid climate, probably indicating increased monsoon precipitation. Between 1584 and 320 year BP, the climate turned cool and dry with the replacement of mixed broad-leaved/conifer forests by conifer-dominated forests under a cool and dry climate, attributable to decreased monsoon precipitation. Since 320 year BP to Present, the mixed conifer/broad-leaved forests were succeeded by the mixed broad-leaved/conifer forests under the prevailing warm and humid climate, indicating an increased monsoon precipitation.

Mixed broad-leaved/conifer forests occurred around the Bajalta Lake area of the Jammu district between 3205 and 2485 year BP under a warm and humid climate[50]. Between 2485 and 1585 year BP, the conifers increased comparatively, and show dominance over the existing broad-leaved taxa, under a cool and dry climate with reduced monsoon precipitation. Subsequently, between 1585 and 865 year BP, the climate further deteriorated, attributed to further reduction in monsoon precipitation. Since 865 year BP to Present, the broad-leaved taxa expanded and dominated over the conifers, indicating a warm and humid climate in the region with increased monsoon precipitation, partly corresponding with the Medieval Warm Period (MWP).

Greater Himalaya

Alpine scrub vegetation chiefly comprising *Alnus*, *Betula*, *Rhododendron* and *Quercus* (broad-leaved taxa) together with *Pinus*, *Abies* and *Picea* (conifers) suggested to occur prior to 720 year BP under a warm and moist climate around Tipra Bank Glacier of Garhwal Himalaya[51]. Subsequently at ~620 year BP, *Juniperus*-scrubs replaced the alpine scrub, and broad-leaved elements also declined under a cold and dry climate. The climate again changed to warm and moist ~460 year BP (AD (CE hereafter) 1401–1887) as reflected by the decline of junipers, as well as increase of ferns, and good values of *Pinus*, *Picea*, *Abies* and *Cedrus*. However, the last phase of this study is not compatible with the cold–dry period of the Little Ice Age (LIA) in other works.

Mixed temperate conifer/broad-leaved forests, chiefly comprising *Pinus*, *Cedrus*, *Betula* and *Quercus* associated with *Abies*, *Alnus*, *Salix* and *Carpinus* were suggested between ~2800 and 1900 year BP around the Chharaka Tal (Sat Tal) area (altitude; ~3500 m) under cool and moist climatic conditions[52]. Subsequently, as a result of the decline of *Pinus*, *Betula*, *Alnus*, *Quercus* and sedges, a deterioration in the climate (less cool and moist) was suggested between ~1900 and 1200 year BP. Subsequent to this period (~1200 year BP to the Present), the expansion of *Pinus*, *Cedrus* and *Abies*, together with sedges, grasses, *Artemisia* and Ranunculaceae (non-arboreals) indicates further deterioration of climate (cold and dry).

A cold–wet climate with increased monsoon during 7800 year BP around Dokriani Bamak Glacier, Uttarakhand was suggested based on the distribution of *Quercus semicarpifolia* and *Pinus wallichiana*[53]. Between 7200 and 5000 year BP, further amelioration of the climate was suggested with highest monsoon intensity at around 5000 year BP. Between 4500 and 3500 year BP, a progressive cooling took place; however, around 3500 year BP, minimum monsoon activity was observed. Between 3500 and 1000 year BP, an increase in the monsoon intensity was suggested with minor cold–dry events at 3000 and 2000 year BP. Between 1000 and 800 year BP, a decrease in the monsoon was indicated, followed by a strengthening towards the present times.

Betula, *Salix*, *Pinus* and *Cedrus* dominated vegetation flourished in the vicinity of Bhujbas, near Gangotri Glacier, Uttarakhand ~9000 year BP under warm–moist conditions[54]. Between ~8300 and 7600 year BP, a decline in the above elements occurred in the region under a comparatively cooler climate. Between 7000 and 6000 year BP, a comparative increase in *Betula*, *Salix*, *Pinus* and *Cedrus* dominated vegetation suggests that the climate again turned towards warm-moist, which represents the HCO. Subsequently, after 6000 year BP onwards, a decline of *Betula*, *Salix*, *Alnus*, conifers, ferns and aquatics and an increase in *Ephedra* and Chenopodiaceae/Amarathaceae (now Amaranthaceae) suggest a comparatively drier climate. Around 1000 year BP, a comparatively colder phase was noticed when *Betula*, *Salix* and conifers declined and *Ephedra* and Amarathaceae increased.

An open *Juniperus–Betula* forest was suggested to have occupied the area vacated by the glacier around the outwash plain of the Gangotri Glacier, probably indicating a comparatively cooler and moist climate than the one prevailing at present between 2000 and 1700 year BP (ref. 55). A relative abundance of local arboreals (*Juniperus*, *Betula*, *Salix*) and extra-local elements (mainly *Pinus*) between 1700 and 850 year BP (CE 250–1100) indicate a further amelioration of the climate with an increase in both precipitation and temperature, partly correlating with the MWP; CE 750–1200). Subsequently around 850 year BP, a shift in the vegetation pattern, with a sharp increase in *Ephedra*; *Artemisia* and members of Asteraceae (steppe elements), as well as a decrease in ferns and *Potamogeton* indicate a trend towards drier climatic conditions (correlatable with the LIA; CE 1550–1850).

The tree-line taxa, such as *Betula* and *Juniperus* occurred around the site of study (3100 m amsl) in Rukti Valley, Kinnaur, Himachal Pradesh, between 11,786 and 4857 year BP (Early to Middle Holocene)[56]. During the Late Holocene (~1640 year BP), a decrease in the values of the above said taxa was noticed. This variation in the distribution of these taxa suggests that till Middle Holocene, the tree-line was close to the study site (3100 m amsl), that is at a lower altitude than its present day distribution between 3800 and 3900 m amsl. Accordingly, the glacier snout might also be at lower elevations (~3500 m amsl) than its present day location at 4300 m amsl altitude.

The pollen data from Dokriani valley, Garhwal Himalaya, suggests that between 12,406 and 10,633 year BP, sparse vegetation was recorded under cool–dry climatic conditions around the study area; and the glacier snout might have been located at lower elevations in comparison to its present position[57]. Subsequently, an increase in the growth of diversified taxa close to the site indicated Early Holocene climatic amelioration, when the glacier might have retreated at a faster rate around 10,633 year BP. Further, between 9670 and 9000 year BP and 7100 year BP, some intermittent cool–dry episodes were recorded when glaciers showed a reduction in retreat rate or came to stagnation.

Mixed conifer/broad-leaved forests were suggested since ~6.6 ka, with intermittent phases of expansions of broad-leaved tree taxa, especially Oaks (*Quercus*), or invasion of conifers, especially pine (*Pinus*), with an increase (moist) or decrease (dry) in the ISM respectively, around Sangla Valley of Kinnaur, Himachal Pradesh[58]. They further indicated that the climate was warm and moist during 16.6 ka, which turned into cool at around 13.3 ka. However, an increase in ISM since 11.5 ka was noticed. Subsequent warm conditions could be generalized by the advancement of Birch (*Betula*) line to higher altitudes following the resultant retreat of the glacier.

A cold and dry climate during the last 7 k year was suggested around the Pindari Valley, Kumaun Himalaya[59]. Between 7 and 4.9 k year BP, with high conifers associated with broad-leaved and herbaceous taxa, a warming in the climate was suggested. Subsequently, between 4.9 and 1.7 k year BP, the climate again turned into cold and dry, which is evidenced by an increase in alpine herbaceous taxa with a gradual decline of conifers and broad-leaved taxa. Between 1.75 and 0.9 k year BP, the presence of both conifers and broad-leaved taxa along with fair amount of *Rhododendron* indicates a relatively warm and moist climate (MWP). Between 0.9 and 0.2 k year BP, a comparative decline in conifers and broad-leaved taxa (except *Quercus* and *Rhododendron*) indicates a drastic climatic change towards aridity (LIA). Around 300 year BP onwards, the conifers and broad-leaved taxa along with herbaceous elements indicate a prevailing warm and moist climate.

Trans Himalaya

The Trans Himalayan regions of India include the high-altitude deserts of Ladakh (Jammu and Kashmir) and Lahaul-Spiti (Himachal Pradesh). Pollen data from North-West Himalaya comprising the Tso Kar Lake (~5000 m amsl), Ladakh, suggests that during 77–10 ka, the area was dominated by Chenopodiaceae–*Artemisia* steppe, indicating a continuation of the existing cold–arid conditions. However, expansion of *Juniperus*, *Betula*, *Hippophae*, *Lonicera* and other scrub taxa within the steppe was also recorded under a comparatively warm–moist climate. Five warm–moist fluctuations have been recognized during 77–34 ka and four during 30–10 ka from the study area[60].

A comprehensive study from Tso Kar inferred that an alpine desert vegetation occurred in the region between 15.2 and 14 k year BP, possibly indicating dry and cold climatic conditions[61]. The high influx of long-distance transported *Pinus sylvestris*-type pollen suggests prevailing air flow from the west and northwest. The spread of alpine meadow communities and local aquatic vegetation indicate climatic amelioration, although weak, after 14 k year BP. Influx of *Pinus roxburghii*-type and *Quercus* suggests the strengthening of the summer monsoon and reduced effect of westerly winds. Between 12.9 and 12.5 k year BP, further spread of *Artemisia* and species-rich meadows occurred in response to the improved moisture conditions. The vegetation subsequently changed towards drier desert-steppe under the influence of more frequent WDs and associated snowfalls. The frequent WDs and associated precipitation favoured the persistence of alpine meadows on edaphically moist sites. Between 12.2 and 11.8 k year BP (Younger Dryas (YD) interstadial), the spread of Chenopodiaceae-dominated vegetation indicates an extremely weak monsoon. After the late glacial/early Holocene transition, the *Artemisia*-dominated steppe and wet alpine meadows with Gentianaceae indicate a major increase in humidity in response to the increased summer monsoon. Between 10.9 and 9.2 k year BP, the activity of monsoonal influence reached its maximum around the Tso Kar region. Between 9.2 and 4.8 k year BP, with the subsequent proliferation of the alpine meadow, steppe and desert-steppe vegetation, a moderate reduction in the moisture supply is indicated in response to the weaker summer monsoon and the accompanying enhancement of the winter westerly flow. However, around 8 k year BP, the highest water levels of Tso Kar probably reflects the combined effect of both monsoonal and westerly influence in the region. After 4.8 k year BP, an expansion of Chenopodiaceae-dominated desert-steppe indicates an abrupt shift towards aridity in the Tso Kar region. Between 2.8 and 1.3 k year BP, scarce vegetation cover and unfavourable growing conditions, possibly indicate a further weakening of the ISM.

Chenopodiaceae-*Ephedra-Artemisia* steppe-type vegetation was suggested around Lamayuru (Ladakh), Trans-Himalayan region prior to 35 ka, which indicates the prevailing semi-arid climate of this region[62]. Subsequently, around 35 k year BP, with the migration of *Betula* into the steppe, a comparatively less arid climate, than before, was inferred. Around 22 k year BP, the further increase in *Ephedra–Arlemisia*–Chenopodiaceae assemblage suggests comparatively favourable climatic conditions. Finally, the climate turned cooler and drier with the expansion of steppe taxa.

Changes in the mean annual precipitation (MAP) were reconstructed during the last 12,000 years from Tso-Moriri, a northwestern Himalayan lake, in Ladakh[63]. The study revealed that between 11 and 9.6 ka, a gradual decline in MAP was reconstructed. Further, it was postulated that between around 5.2 and 3 ka, changes in the climatic conditions affected the ancient Harappan Civilization. Between 4.5 and 4.3 ka, increased dryness between ~4 to 3.6 ka and ~ 3.2 ka, increased aridity associated with North Atlantic cooling was inferred. Subsequently, between 3.5 and 3 ka, collapse of the Harappan Civilization was inferred.

From the other Trans Himalayan region of Lahaul-Spiti, palynological studies from Kunjum La, Batal, suggested that around or before 2–1.8 ka, dry alpine steppe elements existed under a cold and dry climate. Between 1.8 and 1.37 ka, *Juniperus* expanded within the steppe under warm–moist climatic conditions. Further, the subsequent expansion of dry steppe elements till 800 year BP indicates a change of climate from warm–moist to cold–dry. Between 800 and 496 year BP, further expansion of *Juniperus* indicates a warm–moist climate. Since 496 year BP to the Present, the steppe taxa expanded under drier climatic conditions[64].

Grasses and sedges dominated over shrubby elements under a cold and dry climate ~2 ka BP around the Takche Lake, Lahaul-Spiti region of Himachal Pradesh[65]. This cold–dry condition continued till around 1 ka. Subsequently, with the decline of grasses and sedges, the climatic conditions became warm and moist. From 400 year BP to the present, an increase of steppe taxa indicates the change of climate from warm–moist to cold and dry.

The glaciers advanced towards the lower elevations between 2300 and 1500 year BP under the prevailing cold and dry climate in the upper Spiti region (Sitikher bog near Kunzum Pass), Himachal Pradesh[66]. Between 1500 and 900 year BP, the retreat of glaciers and a shift of tree-line towards higher elevations was suggested under a warm and moist climate. From 900 year BP onwards, cold and arid climatic conditions have been observed, resulting in the descent of tree-line taxa.

The pollen data from Naychhudwari bog, Himachal Pradesh, revealed that between ~1300 and 750 year BP, the glaciers receded and tree-line ascended to higher elevations, around the alpine belt of this region, under a warm and moist climate. Subsequently, between 750 and 450 year BP, intermittent deterioration and amelioration of climate was witnessed. Since 450 year BP onwards, the glaciers advanced and the tree-line descended under the impact of a prevailing cold and dry climate in the region[67].

Alpine desert-steppe, meadows and shrubs had developed in the Lahaul Valley, based on the records of non-arboreal pollen, during the Holocene, wherein arboreal pollen (extra-local) indicated moisture carrying monsoonal air flow from the south[68]. The increased $\delta^{13}C$ and low TOC values between ~12,880 and 11,640 year BP suggest the weakening of SW monsoon and low organic carbon production, corresponding to the YD cold event. Between ~11,640 and 8810 year BP, enhanced precipitation in the Chandra Valley in response to an increased SW monsoon strength is indicated by the gradual depletion in carbon isotope ratio. A short spell of cold and dry climate with a gradual decrease in SW monsoon intensity between ~10,398 and 9778 year BP is closely linked with the Bond Event-7. The other prominent cold–dry events recorded in the study are (i) 8810 to 8117 year BP, that roughly corresponds to the global 8.2 ka cold event, (ii) 4808 to 4327 year BP, closely preceding the global 4.2 ka cold–arid period, and (iii) 1303 to 1609 year AD, corresponding to the LIA. The expansion of broad-leaved taxa and the effective growth of meadow vegetation between 6732 and 3337 year BP marked the warm and wet HCO period. The warm and moist climate from 1158–647 year BP corresponds with the MWP. A notable decrease in local (meadow) and regional (alpine steppe) vegetation, indicating a major climatic shift towards cold and dry conditions (YD cold event), which intensified progressively till 11,640 year BP was suggested from the same site[69]. Prior to 12,880 year BP (preceding the YD), a significant wet and warm phase was recorded, depicting the Ållerød interstadial (warm phase). The gradual re-appearance of local and regional flora, indicating the initiation of relatively wet and warm conditions, also indicates the culmination of the YD.

Broad-leaved birch (*Betula*) forests and coniferous forests occupied the Triloknath glacier valley region of Lahaul, Himachal Pradesh between 6300 and 5379 year BP under a warm and moderately humid climate[70]. Between 5379 and 3167 year BP, the broad-leaved birch forest declined, reflecting the deterioration of climate (less-humid). Between 3167 and 2228 year BP, the further diminishing of broad-leaved forests continued as a consequence of the severity of climate (dry climate). Subsequently, between 2228 and 962 year BP, the maximum expansion of broad-leaved forests implies that the region witnessed a warm and humid climate. Between 962 and 300 year BP, further increase in broad-leaved forests indicates that the climate became warm and more humid, the early part of this phase coinciding with the MWP. A pulsatory cool climatic phase towards the termination of this phase around 350 years ago (CE 1650) is also evidenced by a sharp decline in the broad-leaved forests, more likely reflecting the impact of the LIA event.

Vegetation dynamics and inferred climate change from the Eastern Himalaya

As compared to its western counterpart, studies from the Eastern Himalaya are few and far between. Nonetheless, some studies with good chronology, resolution and quantification of palynological data have been able to throw light on late Quaternary vegetational changes and concurrent climatic fluctuations from the eastern region.

Open grasslands was suggested, based on the palynological study, around the Mirik Lake (Darjeeling Himalaya), ~20,000 year BP (ref. 71). Grasses and sedges, as well as herbaceous Ranunculaceae and Caryophyllaceae, along with sporadic arboreals, such as *Quercus*, *Alnus*, *Pinus*, *Cupressus* and *Tsuga* were the chief constituents of the existing open grassland vegetation. The overall vegetation composition indicates a cold and dry climate during the Last Glacial Maximum (LGM). Subsequently between 18,000 and 11,000 year BP, with the gradual increase in *Quercus*, *Alnus*, *Betula* and *Carpinus*, mixed broad-leaved forests replaced the open grassland under a warm and moist climate. However, a short-term deterioration of climate was recorded between ~12,000 and 11,000 year BP during which an abrupt decline in oak (*Quercus*) frequency was seen under a cool and dry climate. Between 10,000 and 4000 year BP, with the marked expansion of oak, as well as the debut, though sparsely, of some thermophilous broad-leaved temperate elements, such as *Juglans*, *Rhododendron* and *Ulmus*, a period of optimal climate is suggested. Oak forests continued to

Table 1. Vegetation dynamics and inferred climatic change in the different areas of the Western and Eastern Himalayan and in the northeastern plains (India). The ages have been taken as given by the respective workers, without any alternations. The table has been arranged according to the year-wise studies undertaken

Area/locality with reference	Period (year BP/cal year BP; unless otherwise stated)	Vegetation dynamics	Inferred climate change
Western Himalaya			
Kunzum La (32°33′N : 77°42′E), Batal, Himachal Pradesh; Bhattacharyya, 1988	Around or before 2–1.8 ka BP	Dry alpine steppe elements	Cold and dry
	~1.8 and 1.37 ka BP	Expansion of *Juniperus* within the steppe	Warm and moist
	Till 800 year BP	Expansion of dry steppe elements	Cold and dry
	~800 and 496 year BP	Expansion of *Juniperus*	Warm and moist
	From 496 year BP to Present	Expansion of dry steppe elements	Drier
North-west Himalaya including Tso-Kar Lake (33°10′N : 78°00′E), Ladakh; Bhattacharyya, 1983	77–10 ka BP	Chenopodiaceae-*Artemisia* steppe	Cold and arid
	30–28, 21–18.375, 16 and 10 ka	Episodes of expansion of *Juniperus*, *Betula*, *Hippophae*, *Lonicera* and other scrub taxa within the steppe	Warm-moist fluctuations
Takche Lake (32°27′N : 77°38′E), Lahaul-Spiti, Himachal Pradesh; Mazari *et al*., 1995	~2 ka	Dominance of grasses and sedges over shrubby elements	Cold and dry
	Till ~1 ka	Continuation of the dominance of grasses and sedges over shrubs	Cold and dry
	1 ka–400 year BP	Decline of grasses and sedges	Warm and moist
	From 400 year BP to Present	Increase of steppe taxa	Cold and dry
Tipra Bank Glacier (30°–31°N : 79°–80°E), Uttarakhand; Bhattacharyya and Chauhan, 1997	Prior to 720 year BP	Alpine scrub vegetation	Warm and moist
	~620 year	Debut of *Juniperus*-scrubs and decline of broad-leaved elements	Cold and dry
	~460 year BP (AD (CE hereafter) 1401–1887)	Decline of junipers, as well as increase of ferns, and good values of *Pinus*, *Picea*, *Abies* and *Cedru*	Warm and moist
Chharaka Tal (Sat Tal) (31°10′N : 78°E), Garhwal Himalaya; Chauhan *et al.*, 1997	~2800–1900 year BP	Mixed temperate conifer/broad-leaved forests	Cool and moist
	~1900–1200 year BP	Decline of *Pinus*, *Betula*, *Alnus*, *Quercus* and sedges	Deterioration in the climate (less cool and moist)
	~1200 year BP to Present	Expansion of *Pinus*, *Cedrus* and *Abies*, together with sedges, grasses, *Artemisia* and Ranunculaceae (non-arboreals)	Further deterioration of climate (cold and dry)
Sitikher bog (32°30′N : 77°40′E), Kunzum Pass, Himachal Pradesh; Chauhan *et al.*, 2000	2300–1500 year BP	Glaciers advanced towards the lower elevations	Cold and dry
	1500–900 year BP	Retreat of glaciers and shift of tree-line towards the higher elevations	Warm and moist
	900 year BP to Present	Glaciers/tree-line descended	Cold climate which continues till present time
Dewar Tal (30°N : 79°E), Garhwal Himalaya, Uttarakhand; Chauhan and Sharma, 2000	2500–2300 year BP	Chirpine-oak forest	Cool and drier
	2300–2000 year BP	Expansion of forests	Warm and moist
	2000–1400 year BP	Decline of chirpine and oak and increase of grasses	Cool and dry
	1400–400 year BP	Development of oak forests	Favourable climatic (warm and moist)
	400 year BP to Present	Decline of oak in expense of chirpine	Cool and dry

(*Contd*)

Table 1. (*Contd*)

Area/locality with reference	Period (year BP/cal year BP; unless otherwise stated)	Vegetation dynamics	Inferred climate change
Dokriani Glacier (30°50′–30°52′ N : 78°47′–78°51′E), Uttarakhand; Phadtare, 2000	~7800 year BP	Conifers decrease at the expense of oaks (*Quercus semicarpifolia*)	Cold-wet with strengthening of monsoon
	7200–5000 year BP	Oaks increased comparatively with the simultaneous reduction of conifers	Further amelioration of climate
	4500–3500 year BP	Conifers increased and oaks started decreasing	Progressive cooling
	~3500 year BP	Profileration of conifers and further decrease of oaks	Minimum monsoon activity
	3500–1000 year BP	Oaks increased and comparative decrease of conifers	Increased monsoon
	3000–2000 year BP	Increase of conifers	Minor cold dry events; monsoon again decreased
	~1000 to 800 year BP	Further increase of conifers	Decreased monsoon
	~800 year BP to Present	Oaks increased and conifers decreased	Strengthening of monsoon
Bhujbas (30°N : 79.35°E), Gangotri Glacier, Uttarakhand; Ranhotra *et al.*, 2001	~9000 year BP	*Betula*, *Salix*, *Pinus*, *Cedrus* and other conifers used to grow	Warm and moist
	8300–7600 year BP	Decline of the above elements	Cooler
	7000–6000 year BP	Appearance of *Betula*, *Salix*, etc.	Warm and moist
	6000 year BP to Present	Decline in pollen/spore percentage of *Betula*, *Salix*, *Alnus*, conifers, ferns and aquatics and increase in *Ephedra* and Cheno/Ams	Comparatively drier climate
	~1000 year BP	*Betula*, *Salix*, conifers decline with the increase in *Ephedra* and Cheno/Ams	Comparatively colder phase
Bhujbas (30–31°N: 79.5°E), Gangotri Glacier, Uttarkashi District Uttarakhand; Kar *et al.*, 2002	2000–1700 year BP	Open *Juniperus*–*Betula* forests	Comparatively cooler and moist
	1700–850 year BP	Increase in local arboreals (*Juniperus*, *Betula*, *Salix*) and extra local elements (mainly *Pinus*)	Further amelioration of climate with increase of both precipitation and temperature (MWP)
	~ 850 year BP	A shift in the vegetational pattern with sharp increase in *Ephedra* and other steppe elements notably *Artemisia* and members of Asteraceae	Drier climatic conditions (LIA)
Naychhudwari bog (32°30′N : 77°43′E), Himachal Pradesh; Chauhan, 2006	1300–750 year BP	Alpine vegetation	Warm and moist
	750–450 year BP	Glaciers receded and tree-line ascended to higher elevation	Intermittent deterioration and amelioration of climate
	450 year BP to Present	Glaciers advanced and tree line descended	Cold and dry
Lamayuru palaeolake (34°N : 76°E), Ladakh, Trans-Himalaya; Ranhotra *et al.*, 2007	Prior to 35 k year BP	Chenopodiaceae–*Ephedra*–*Artemisia*	Semi-arid
	~35 k year BP	Migration of *Betula* into steppe	Comparatively less arid than before
	~22 k year BP	*Ephedra*–*Artemisia*–Chenopodiaceae	Comparatively favourable climatic
	Subsequent phase	Expansion of steppe taxa	Cooler and drier

(*Contd*)

Table 1. (*Contd*)

Area/locality with reference	Period (year BP/cal year BP; unless otherwise stated)	Vegetation dynamics	Inferred climate change
Mansar Lake (32°41′28″N : 75°8′52″E), Jammu, Jammu and Kashmir; Trivedi and Chauhan, 2008	9000–8000 year BP	Mixed chirpine (*Pinus* cf. *roxburghii*) – oak (*Quercus*) forests	Cool and dry
	8000–7000 year BP	Mixed oak–chirpine forests	Warm and humid
	7000–3000 year BP	Reduction in broad-leaved taxa	Cool and dry
	5500–4250 year BP	Presence of sandy deposits	Brief spell of pluvial activity
		Expansion of oak and most of the broad-leaved taxa	Warm and more humid
	3000–750 year BP	Mixed chirpine–oak forests	Deterioration of climate
	750 year BP to Present		
Surinsar Lake (32°45′N : 75°2′E), Jammu, Jammu and Kashmir; Trivedi and Chauhan, 2009	9500–7700 year BP	Mixed oak–broad-leaved/chirpine Forests	Warm and humid
	7700–6125 year BP	Mixed chirpine/oak–broad-leaved forests	Cool and dry
	6125–4330 year BP	Expansion of oak and its broad-leaved associates	Moderately warm and humid
	4330–4000 year BP	Presence of sandy layer	A brief spell of pluvial environment
	4000–2100 year BP	Decline in oak and other broad-leaved taxa and a concurrent increase in chirpine	Cool and dry
	2100–800 year BP	Presence of sandy deposit	Pluvial episode
	800 year BP to Present	Slight advance in the oaks	Amelioration of climate
Tso-Kar Lake (33°10′N : 78°00′E), Ladakh; Demske *et al.*, 2009	~ 15.2 to 14 kyr BP	Alpine desert vegetation	Dry and cold
	After ~ 14 kyr BP	Spread of alpine meadow communities and local aquatic vegetation	Weak sign of climate amelioration
	~ 12.9 and 12.5 kyr BP	Further spread of *Artemisia* and species-rich meadows	Improved moisture conditions
	~12.2–11.8 kyr BP (YD Interstadial)	Chenopodiaceae-dominated vegetation	Extremely weak monsoon
	Late Glacial/Early Holocene transition	*Artemisia*-dominated steppe and wet alpine meadows	Strengthening of summer monsoon
	~10.9 and 9.2 kyr BP		Maximum monsoon
	~ 9.2 to 4.8 kyr BP	Development of the alpine meadow, steppe and desert-steppe vegetation	Weaker summer monsoon and enhancement of the winter westerly flow
	~ 8 kyr BP	Highest water levels of Tso Kar	Combined effect of both monsoonal and westerly influence
	After ~ 4.8 kyr BP	Expansion of Chenopodiaceae-dominated desert-steppe	An abrupt shift towards aridity
	2.8–1.3 kyr BP	Scarce vegetation cover	Weak monsoon
Rukti Valley (31°24′E : 78°18′E), Kinnaur, Himachal Pradesh; Ranhotra and Bhattacharyya, 2010	~11,786–4,857 cal year BP	Tree-line taxa, such as *Betula* and *Juniperus* were well characterized in the site of investigation	Variation in distribution of these taxa suggests that till Middle Holocene tree line was close to the study site (3100 m amsl), i.e. at lower altitude than its present day distribution between 3800 and 3900 m amsl
	~1640 cal year BP	Less representation of the above mentioned taxa	Accordingly, the glacier snout might also be at lower elevations (~3500 m amsl) than its present day location at altitude (~4300 m amsl)

(*Contd*)

Table 1. (*Contd*)

Area/locality with reference	Period (year BP/cal year BP; unless otherwise stated)	Vegetation dynamics	Inferred climate change
Dokriani Valley region (30°48′–30°54′N : 78°40′–78°51′E), Uttarakhand; Bhattacharyya *et al.*, 2011	12,406–10,633 year BP	Sparse vegetation	Cool-dry; glacier snout might had been located at lower elevations in comparison to its present position
	~10,633 year BP	Increase in diversified taxa	Early Holocene climatic amelioration; glacier might have retreated at faster rate
	~9670–9000 year BP ~7100 year BP		Intermittent cool-dry episodes; glacier shows reduction in retreat rate or came to stagnation
Chandra peat (32.40°N : 77.20°E), Lahaul, Himachal Pradesh; Rawat *et al.*, 2012	Prior to 12,880 year BP	Alpine meadow vegetation	Wet and warm; Allerød interstadial preceding the YD
	Till 11,640 year BP	Notable decrease in local (meadow) and regional (desert steppe) vegetation	Cold and dry marking the onset of the YD
	YD terminates indicating initiation of the Holocene	Gradual reappearance of local and regional flora	Wet and warm conditions
Tso-Moriri Lake (32°54′N : 78°19′E), Ladakh; Leipe *et al.*, 2013	~11– 9.6 cal ka BP		Gradual decline in MAP
	~5.2–3 cal ka BP		Changes in climatic conditions affected the ancient Harappan Civilisation
	~4.5–4.3 cal ka BP		Increased dryness
	~4–3.6 cal ka BP		Increased aridity associated with North Atlantic cooling
	~3.2 cal ka BP		Increased aridity associated with North Atlantic cooling
	~3.5–3 cal ka BP		Collapse of the Harappan Civilisation
Chandra Valley (33°79′40.5″N : 78°34′27.4″E), Lahaul; Rawat *et al.*, 2015	~12,880–11,640 cal year BP	–	Weakening of ISM corresponding to the YD cold event
	~11,640–8810 cal year BP	–	Increased strength of ISM
	~10,398–9778 cal year BP	–	Cold and dry (decrease in SW monsoon) closely linked with bond event
	~8810–8117 cal year BP	–	Cold-dry corresponding to global 8.2 ka cold event
	~6732–3337 cal year BP	–	Warm and wet Holocene Climate Optimum (HCO) period
	~4808–4327 cal year BP	–	Cold-dry; 4.2 ka cold-arid period
	~1303–1609 cal year BP	–	Warm and moist climate corresponds with the Medieval Warm Period (MWP)
	~115–-647 cal year BP	Expansion of thermophillous broad leaved taxa and effective growth of meadow vegetation	Corresponding to Little Ice Age (LIA) event
Pindari Glacier area (30°15′36″N : 79°59′52″E); Uttarakhand; Bali *et al.*, 2015	~7 ka	Glacial sediments	Cold and dry
	7.0–4.9 ka	Conifers and broad-leaved taxa	Amelioration of climate
	4.9–1.7 ka	Acceleration of alpine herbaceous taxa; decline in conifers and broad-leaved taxa	Cold and dry
	1.7–0.9 ka	Increase in conifers and broad-leaved taxa	Warm and moist
	0.9–0.2 ka	Decline in conifers and broad-leaved taxa	Cold and dry (LIA)
	0.2 ka to Present	Conifers, broad-leaved and herbaceous taxa	Warm and moist

(*Contd*)

Table 1. (*Contd*)

Area/locality with reference	Period (year BP/cal year BP; unless otherwise stated)	Vegetation dynamics	Inferred climate change
Triloknath Glacier (32°39′25.51″–32°36′19.57″N: 76°39′32.71″–76°36′09.14″E), Lahaul Valley, Himachal Pradesh; Bali *et al.*, 2016	6300–5379 year BP	Broad-leaved birch (*Betula*) forests	Warm and moderately humid
	5379–3167 year BP	Decline of broad-leaved birch (*Betula*) forests	Warm and less humid
	3167–2228 year BP	Coniferous forest	Severe climate (cold and dry)
	2228–962 year BP	Expansion of broad-leaved birch (*Betula*) forests and improvement of coniferous forest	Warm and humid
	962–300 year BP	Further increase in broad-leaved taxa	Warm and more humid
	~300 year BP	Sharp decline in broad-leaved taxa	Cold and dry (LIA)
Rukti valley (31°10′–31°40′N : 78°05′–78°45′E), Kinnaur, Himachal Pradesh; Ranhotra *et al.*, 2017	~16.6 ka	–	Warm and moist
	~13.3 ka	–	Cool and dry
	Since ~11.5 ka	–	ISM increases
	~8.7 and ~7.8 ka	–	Distinct spike in the magnetic susceptibility values correspond to global 8.2 ka cool event
		–	Subsequent warm conditions could be generalized by the advancement of Birch (*Betula*) line to higher altitude following the resultant retreat of the glacier
Gharana Wetland (32°36′51.52″N : 74°38′58.15″E), Jammu; Jammu and Kashmir; Quamar, 2019a	~10,696–8,536 cal year BP	No inferences on palaeovegetation as no significant pollen was encountered except for a few stray pollen of *Pinus* sp. and members of the grass family (Poaceae)	Pluvial environment
	~8536–5296 cal year BP	Mixed conifer/broad-leaved forests	Cool and dry
	~5296–2776 cal year BP	Mixed broad-leaved/conifer forests	Warm and humid
	~2776–1376 cal year BP	Dense mixed broad-leaved/conifer forests	Further increase in monsoon precipitation
	~1376 cal year BP to Present	Mixed conifer/broad-leaved forests	Deterioration of climate
Nanga Wetland (32°33′15.44″N : 75°06′55.70″E), Samba; Jammu and Kashmir; Quamar, 2019a	~3984–2784 cal year BP	No definite inferences on palaeovegetation could be made as no significant pollen was encountered except for a few stray pollen of *Pinus* sp. and members of the grass family (Poaceae)	Pluvial environment
	~2784–1584 cal year BP	Mixed broad-leaved/conifer forests	Warm and humid with increased monsoon
	~1584–320 cal year BP	Mixed conifer/broad-leaved forests	Cool and dry
	~320 cal year BP to Present	Mixed broad-leaved/conifer forests	Warm and humid
Bajalta Lake (32° 45.621′N: 74°57.026′E), Jammu; Jammu and Kashmir; Quamar, 2019b	~3205–2485 cal year BP	Mixed broad-leaved/conifer forests	Warm and humid with increased monsoon precipitation
	~2485–1585 cal year BP	Mixed conifer/broad-leaved forests	Cool and dry with reduced monsoon precipitation
	~1585–865 cal year BP	Further increase in conifers	Deterioration of climate, reduced monsoon precipitation
	~865 cal year BP to Present (CE 1085 onwards)	Increase in broad-leaved taxa and simultaneous reduction of conifers	Warm and humid with increased monsoon precipitation (partly corresponding to the Medieval Warm Period (MWP) between AD 740 and 1150)

(*Contd*)

Table 1. (*Contd*)

Area/locality with reference	Period (year BP/cal year BP; unless otherwise stated)	Vegetation dynamics	Inferred climate change
Eastern Himalaya			
Mirik Lake (26°31′–21°18′N : 87°59′–98°53′E), Darjeeling; Sharma and Chauhan, 1994	~20,000 year BP	Open grassland	Cold and dry (LGM)
	18,000–11,000 year BP	Mixed broad-leaved forests	Warm and moist
	~12,000–11,000 year BP	Abrupt decline in oak (*Quercus*)	Cool and dry
	10,000–4,000 year BP	Marked expansion of oak (*Quercus*), as well as debut of *Juglans*, *Rhododendron* and *Ulmus*, though sparsely, alongwith decline of *Pinus* and *Tsuga*, as well as grasses and other ground flora	Period of optimal climate (HCO)
	2000–500 year BP	Pak (*Quercus*) forests continued to grow, however, sharp fluctuation in the values of *Quercus* and *Betula* and simultaneous improvement of *Pinus*	Gradual deterioration of climate
Jore-Pokhari (26°75′N : 88°25′E), Darjeeling; Chauhan and Sharma, 1996	~2500 year BP	Mixed broad-leaved oak (*Quercus*) forests	Warm temperate and humid
	1600–1000 year BP	Increase in the conifers and simultaneous reduction of broad-leaved tree taxa	Cooler climate
	1000–300 year BP	Increase of *Quercus*, *Betula*, *Alnus* and *Rhododendron* (broad-leaved taxa) and a simultaneous decrease of *Pinus* (a conifer/needle-leaved taxon)	Amelioration in climate (warm-temperate and humid)
Lacustrine deposit, Khechipiri (27°37′N : 88°20′E), Sikkim Himalaya; Sharma and Chauhan, 1999	~2500 year BP	Mixed broad-leaved forests	Warm and moist
	~1000 year BP	Dominance of *Alnus* over *Quercus* and increase of *Rhododendron*	More humid
Kupup Lake (27°37′N : 88°76′E), Sikkim Himalaya; Sharma and Chauhan, 2001	2000–1800 year BP	Presence of *Pinus*, *Abies*, *Tsuga*, *Quercus*, *Betula*, *Alnus*, *Rhododendron* and *Viburnum*, along with sedges, grasses, Apiaceae and Asteraceae	Cold and moist
	1800–1450 BP	Increase in sedges, grasses and other herbaceous taxa, as well as reduction in *Betula*, *Alnus*, and *Rhododendron* (broad-leaved taxa) increase in broad-leaved taxa	Slightly drier climate
	1450–450 BP	Sudden increase in sedges, grasses, Amaranthaceae and Ranunculaceae and concurrent decrease of arboreal pollen	Cold and moist (MWP)
	~ 450–200 BP		Deterioration in climate (cold and dry)
	Since 200 year BP onwards	Increase in *Quercus*, *Betula*, *Alnus* and Rosaceae	Cold and moist
Paradise Lake (27°30.324′N : 92°06.269′E), Sela Pass, Arunachal Pradesh; Bhattacharyya *et al.*, 2007	~1800 year BP (around AD (CE hereafter) 245)	Conifer/broad-leaved forests	Warm and moist
	~1100 year BP (CE 985)	Sub-alpine forests	More warmer (MWP)
	~550 year BP (~CE 1400)	Decrease in the values of *Tsuga*, *Juniperus* and *Quercus*	Cooler and less moist (LIA)

(*Contd*)

Table 1. (*Contd*)

Area/locality with reference	Period (year BP/cal year BP; unless otherwise stated)	Vegetation dynamics	Inferred climate change
Ganga Lake (27°04′28″–27°04′36″–N : 93°34′04″–93°34′22″E), Itanagar, Arunachal Pradesh; Achyuthan *et al.*, 2013	Five warmer phases, intercepted by cold and moist climatic conditions, occurring throughout the LIA. The warmer events are of shorter duration during the LIA, ultimately indicating that LIA was highly variable and was not a globally synchronous cold period.		
Ziro Lake Basin (27°32′01.22″N : 93°49′49.24″E), Arunachal Pradesh; Ghosh *et al.*, 2014	>19.5 ka	Dense semi evergreen forests	Humid climate
	~19.5–10.2 ka	Moisture loving arboreals	Cooler and drier
	10.2–3.8 ka	Less dense broad-leaved pine forests	Monsoon intensification
	3.8 ka to Present		Warmer and drier
Ziro Valley (27°32′–27°37′N : 93°49′–93°51′E), Arunachal Pradesh; Bhattacharyya *et al.*, 2014	~66 ka	Expansion of Pine–Tsuga savanna	Cool and dry
	~44–34 ka	Expansion of broad-leaved forests	Increased SW monsoon
	~36–34.1 ka	Expansion of broad-leaved/conifer forests	Intensified monsoon
	34–30 ka	C3 dominated vegetation	Increased monsoon
	30–20 ka	C4 vegetation	Cool moist
	20–11 ka	Increase of conifers	Cool dry
Darjeeling foothill region (26°53′30″N : 88°44′23″E), eastern Himalayas; Ghosh *et al.*, 2015	~46.4–41.2 ka	Dominance of C3 plants	Monsoon intensification
	~41.2–31 ka	Increase in deciduous elements	Weak monsoon
	31.0–22.3 ka	C3 expansion	Monsoon intensification
	22.3–18.3	Decline in evergreen elements	Low temperature and precipitation
	18.3–15.6	Expansion of evergreen elements	Enhanced monsoon and temperature
	5.4–4.3 ka	Dominance of evergreen/semi-evergreen taxa	Monsoon intensification
	4.3–3.5 ka	Dominance of deciduous elements	Rainfall minima/weak monsoon
Darjeeling Himalaya (27°01′45.24″N : 88°19′18.71″E); Ghosh *et al.*, 2018	During 364 BCE to 131 CE	Dense broad-leaved evergreen forest	Humid
	Between 131 CE and 624	Thinning of the forest cover	Comparatively drier condition
	During 1118 CE	Broad-leaved forest	Wet phase (increase in monsoonal strength)
	Between 1367 CE and 1802	Dense broad-leaved evergreen forest	Further increases in monsoonal strength
Pankang Teng Tso (PT Tso) Lake (27°46.85′N : 91°58.38′E), Tawang district, Arunachal Pradesh; Mehrotra *et al.*, 2018	~4814 cal year BP	Sub-tropical-temperate species	Less cold and humid
	~4814–2336 cal year BP	Dominance of temperate to sub alpine taxa	Cold and dry
	~2336–1240 cal year BP	Dry temperate forests	–
	906 cal year BP to Present	Sub-alpine forests	–
Northeastern plains			
Deosila Swamp (25°58′14.8″N : 90°57′02.5″E), Goalpara district, Assam; Dixit and Bera, 2011	6340–2970 year BP	Tropical tree savannah-type vegetation	Cool and dry with amelioration
	2970–1510 year BP	Tropical mixed deciduous forest	Warm and humid
	1510–540 year BP	Tropical deciduous sal (*Shorea robusta*) forest established	Warm and more humid (MWP)
	540 year BP onwards	Reduction of forest floristics	Warm and relatively dry (LIA)
Chhayagaon Swamp (26°02′10.5″N : 90°25′20.7″E), Kamrup district, Assam; Dixit and Bera, 2013	12,450–10,810 year BP	Tropical tree-savannah vegetation	Cool and dry (YD cold event)
	10,810–7680 year BP	Open vegetation	Relatively dry and less cool
	7680–6780 year BP	No inferences on vegetation	Some sort of fluvial activity
	6780–1950 year BP	Tropical mixed deciduous forest	Warm and moderately humid (HCO)
	1950–989 year BP	Tropical dense mixed deciduous forest	Warm and more humid (MWP)
	989 year BP onwards	Deterioration of tropical mixed deciduous forest	Warm but relatively dry

Table 2. Characteristic tree taxa in the Western and Eastern Himalaya reflecting the altitudinal shifts in vegetation

Western Himalaya	Eastern Himalaya
Subtropical taxa (up to 1500–2000 m altitude)	Subtropical taxa (up to 1500 m altitude)
Conifers:	Conifers:
Pinus roxburghii, *P. gerardiana*	*Pinus khasiana*, *Taxus baccata*
Broad-leaved taxa:	Broad-leaved taxa:
Ulmus sp., *Juglans regia*, *Quercus leucotrichophora*, *Alnus nepalensis*, *Rhododendron arboretum*	*Juglans regia*, *Quercus leucotrichophora*, *Q. semecarpifolia*, *Ulmus* sp., *Rhododendron* spp.
Sub-tropical taxa:	Sub-tropical taxa:
Mallotus sp., *Fraxinus* sp., *Bombax ceiba*, *Syzygium* sp., *Emblica officinalis*, *Terminalia* spp., *Ficus* spp., *Grewia* sp., *Mitragyna parvifolia*, *Lannea coromandelica*, *Mallotus philippensis*, *Albizzia* sp., *Bombax ceiba*, *Dalbergia sissoo*, *Cedrela toona*, *Melia azedarach*, *Bauhinia variegata*, *Flacourtia indica*, *Olea* sp., *Sapindus* sp., *Desmodium* spp., *Indigofera* spp., *Toona ciliata*, *Cupressus* sp.	*Lagerstroemia parviflora*, *Shorea*, *Garuga pinnata*, *Terminalia* spp., *Schima wallichii*, *Sterculia, villosa*, *Mallotus philippensis*, *Semecarpus anacardium*, *Symplocos lauriana*, *Syzygium cumini*, *Salmalia* sp., *Ficus* spp., *Litsea monopetala*, *Bauhinia purpurea*, *Emblica officinalis*, *Grewia vestita*, *Bridelia retusa*, *Indigofera* spp., *Aporosa ruxburghii*, *Phoebe lanceolata*, *Albizzia* sp., *Canarium sikkimensis*, *Leea* sp., *Wrightia* sp., *Cassia* sp., *Dillenia* sp., *Duabanga grandiflora*, *Gmelina arborea*
Temperate and alpine taxa (above 1500 m altitude)	*Temperate and alpine taxa* (above 1500 m altitude)
Conifers:	Conifers:
Pinus wallichiana, *Cedrus* spp., *Abies* spp., *Picea smithiana*, *Larix* sp., *Podocarpus* sp., *Juniperus indica*, *J. excelsa*, *J. squamata*, *J. recurva*, *Taxus baccata*	*Pinus wallichiana*, *Cedrus deodara*, *Abies pindrow*, *Picea*, *Juniperus communis*, *Tsuga dumosa*, *Larix griffithiana*, *Salix wallichiana*
Broad-leaved taxa:	Broad-leaved taxa:
Alnus spp., *Betula* spp., *Ulmus wallichiana*, *Quercus* spp., *Carpinus* sp., *Corylus* sp., *Acer* sp., *Rhododendron barbatum*, *R. companulatum*, *Ilex* sp., *Salix* sp., *Aesculus* sp., *Celtis* sp., *Skimmia* sp.	*Alnus nepalensis*, *Betula utilis*, *Corylus*, *Myrica esculenta*, *Rhododendron* spp., *Acer campbelli*, *Castanopsis tribuloides.*

grow in the region between 2000 and 500 year BP; however, *Quercus* and *Betula* fluctuated sharply and simultaneously *Pinus* improved, indicating a gradual deterioration of climate.

Mixed broad-leaved oak forests dominated the vegetation ~2500 BP around the Jore-Pokhari area in Darjeeling under a warm temperate and humid climate[72]. Subsequently, between 1600 and 1000 BP, a short-term oscillation occurred and the climate turned towards cooler with an increase in the conifers and reduction of broad-leaved tree taxa. Between 1000 and 300 year BP, with the increase of *Quercus*, *Betula*, *Alnus* and *Rhododendron* and a simultaneous decrease of *Pinus*, amelioration in climate (warm-temperate and humid) was suggested.

Palynological data from a lacustrine deposit around Khechipiri (Sikkim Himalaya) revealed that around 2500 years ago, mixed broad-leaved forests occurred in the region under a warm and moist climate[73]. Later, the climate became more humid around 1000 years ago when *Alnus* overshadowed *Quercus* and *Rhododendron* also increased.

From Kupup Lake (4000 m), a cold and moist climate was suggested to exist in the alpine zone of Sikkim Himalaya[74], with the presence of *Pinus*, *Abies*, *Tsuga*, *Quercus*, *Betula*, *Alnus*, *Rhododendron* and *Viburnum*, along with sedges, grasses, Apiaceae and Asteraceae between 2000 and 1800 BP. Subsequently, between 1800 and 1450 year BP, with the increase in sedges, grasses and other herbaceous taxa, as well as the reduction in *Betula*, *Alnus* and *Rhododendron*, slightly drier climatic condition was indicated. Between 1450 and 450 year BP, an increase in broad-leaved taxa indicates that the climate turned towards cold and moist, correlating with the MWP (CE 750–1200). Between ~450 and 200 year BP (CE 1500–1750), a sudden increase in the values of sedges (Cyperaceae), grasses (Poaceae), Amaranthaceae and Ranunculaceae, and also with a concurrent decrease of arboreal pollen, a deterioration in climate towards cold and dry was observed, correlating with the LIA. Since 200 year BP onwards, *Quercus*, *Betula*, *Alnus* and Rosaceae increased under a cold and moist climate, characteristic of the present alpine zone in the Eastern Himalaya.

Palynological studies from the Paradise Lake, Sela Pass in Arunachal Pradesh[75] indicated conifer/broad-leaved forests around the study area under a warm and moist climate ~1800 year BP (~CE 245). Subsequently,

~1100 year BP (CE 985), with an increase in *Tsuga*, *Abies*, *Picea*, *Pinus* and *Juniperus*, as well as other broad-leaved taxa, sub-alpine forests came into existence by transforming the existing conifer/broad-leaved forests. The changing vegetation scenario could be indicating a comparatively warmer climate, corresponding to the MWP. In addition, the glaciers also seemed to have receded and the tree-line might have been closer to the site. The climate turned towards cooler and less moist ~550 year BP (~CE 1400) with the decrease in the values of *Tsuga*, *Juniperus* and *Quercus*, corresponding to the LIA. This is followed by amelioration in the climatic conditions, more or less equivalent to that of the present-day climate.

Palynological studies, supplemented with phytoliths and stable carbon isotopic records, suggest that a dense C3 species-dominated moist semi-evergreen forest existed around the Ziro Lake Basin, Arunachal Pradesh until LGM[76]. Between 10.2 and 3.8 ka, an expansion of the forest cover occurred in the region under an ameliorating climate with intensified southwest monsoon. Further, shrinkage in forest cover as a result of a rising trend in dryness is observed by a slight increase in C4 species after 3.8 ka. Co-existence approach on pollen data revealed that prior to the LGM, the mean annual temperature (MAT) and mean annual precipitation (MAP) were approximately 19.3 ± 0.001°C and 1925 ± 15 mm respectively. Between 10.2 and 3.8 ka, MAT was about 19.4 ± 0.5°C, while MAP was 1901 ± 41.3 mm. Between 3.8 and 1.2 ka and onwards, a slight increase in MAT (~0.3°C) was observed with further decrease in MAP to 1861 ± 33.4 mm. During pre- and post-LGM times, MAT was more or less similar in the Ziro Lake Basin, which increased gradually after 3.8 ka and was ~1.2°C higher than today. Prior to the LGM, MAP was higher than the present day by 94 mm, between 10.2 and 3.8 ka by 70 mm and since 3.8 ka onwards by 30 mm, showing a tendency of gradual decline and a consequent increase in dryness.

On the basis of geochemical as well as epiphyllous lichen (EL) studies from the Ganga Lake in Itanagar, Arunachal Pradesh, five warmer phases intercepted by cold and moist climatic conditions were suggested[77], which occurred throughout the LIA. They further suggested that warmer events are of shorter duration during the LIA, ultimately indicating that LIA was highly variable from region to region and was not a globally synchronous cold period.

Mixed broad-leaved/conifer forests and pine-grass-savannah occurred in and around the Ziro Valley, Arunachal Pradesh at variable densities since 66,000 year BP (ref. 78). Between ~44,000 and 34,000 year BP, intermittent phases of expansion and decline of oaks, as well as decline and increase of pines and grasses probably occurred under increased warm–moist conditions, which could be linked to the interstadial phase during the last major glacial cycle in the Himalayan region. The impact of expansion of the glacier is felt with a peak at around 20,000 year BP (LGM); the tree-line had moved to lower altitudes due to increased aridity and low temperature. During this time, the existence of savannah type of vegetation is also evident by the increase of C4 taxa.

Based on co-existence approach on pollen data and other proxies, significant oscillations in precipitation during the late part of MIS 3 (46.4–25.9 ka), early and middle part of MIS 2 (25.9–15.6 ka), and 5.4 to 3.5 ka was suggested. Between 46.4 and 31 ka (middle to late MIS-3), a comparatively low monsoonal activity and slightly higher temperature than that around 31 ka onwards was observed from the Darjeeling Himalaya[79]. Simultaneous expansion of deciduous trees and chloridoid grasses also imply a drier and warmer phase. An increase in evergreen elements over deciduous taxa, and wet-loving panicoid grasses over dry-loving chloridoid grasses owing to higher precipitation and slightly cooler temperature occurred during late MIS 3 to mid MIS 2 (between ~31 and 22.3 ka). Expansion of C4 chloridoid grasses, Asteraceae and Amaranthaceae in the vegetation and the lowering of temperature and precipitation after ~22.3 ka indicate shrinking of forest cover, which characterizes the onset of the LGM till ~18.3 ka. A restoration in the forest cover marked the end of the LGM. Later, between 5.4 and 4.3 ka, a strong monsoonal activity supported a dense moist evergreen forest that subsequently declined between 4.3 and 3.5 ka. A further increase in deciduous elements and non-arboreals might be a consequence of reduced precipitation and higher temperature during this phase. A comparison between monsoonal rainfall, MAT and palaeoatmospheric CO_2 with floral dynamics since the last ~50 ka, indicates that these fluctuations in plant succession were mainly driven by monsoonal variations.

Considerable variations exist globally for the warm (moist) MWP and cool (dry) LIA periods with respect to their timing, duration, and hydroclimatic dynamics, although, a humid climatic phase at the beginning of the last millennium; a pre-MWP less humid phase, where MWP was wetter than the former phase and a wet LIA in the Darjeeling, Eastern Himalaya were identified[80]. A dense broad-leaved evergreen forest also occurred in the region under a humid climate during 364 BCE to 131 CE. However, thinning of the forest cover was noticed under comparatively drier conditions between 131 and 624 CE. Furthermore, a wet phase (increase in monsoonal strength) was observed during 1118 CE, which further increases between 1367 CE and 1802.

Based on multi-proxy (pollen, environmental magnetism and stable isotope data) records, a cold–humid climate around 4625 year BP was suggested, followed by a cold–dry climate, favouring sub-alpine vegetation at around 4.2 ka from the catchment of Pankang Teng Tso (PT Tso) Lake (altitude 3935 m amsl) of Tawang District of Arunachal Pradesh[81].

Northeast plains

Due to the paucity of records from the Eastern Himalaya, some relevant works having good age control and also having global climatic correlations are being discussed from the nearby northeastern plains to complement the dataset from the eastern region. The northeastern plain, which encompasses the Brahmputra River Valley, is an extension of the Indo-Gangetic Plain. The northeastern plains are being considered here because the region is also under the influence of ISM, similar to that of the Eastern Himalaya.

Tropical tree savannah-type of vegetation is suggested around the Deosila swamp, Rangjuli Reserve forest in the Goalpara District of Assam, between 6340 and 2970 year BP under a relatively less cool and dry climatic condition with a little ameliorating trend. This finding, in the initial phase, matches with the HCO and is the first such record from northeast India. Between 2970 and 1510 year BP, tropical mixed deciduous forests succeeded the tree savannah-type of vegetation under a warm and humid climate. Subsequently, between 1510 and 540 year BP, tropical deciduous sal (*Shorea robusta*) forest established in the region under a warm and more humid climate, possibly indicating an active SW monsoon, corresponding to the MWP. Since 540 year BP onwards, the reduced forest floristics suggested a change in the climate, which turned towards relatively dry, probably attributable to weak monsoonal rainfall, correlatable with the LIA[82]. Tropical tree-savannah vegetation between 12,450 and 10,810 year BP under a cool and dry climate from Chhayagaon Swamp of the Kamrup district, Assam[83], corresponds to the YD cold. Between 10,810 and 7680 year BP, a relatively dry and less cool climate prevailed, which is again followed by some fluvial activity between 7680 and 6780 year BP. A tropical mixed deciduous forest succeeded the fluvial activity under a warm and moderately humid climate between 6780 and 1950 year BP, signifying an increase in monsoon precipitation that correlates well with the peak of HCO. Between 1950 and 989 year BP, a tropical dense mixed deciduous forest established under a warm and more humid climate, corresponds to the MWP. Since 989 year BP onwards, deterioration of the tropical mixed deciduous forests took place, indicating a forest clearance, under a warm but relatively dry climatic regime. A detailed pollen-based review of the palaeoclimatic studies during the Late Pleistocene–Holocene was done from northeast India[84].

Comparison and correlation of past vegetation dynamics and inferred climate change

Late Pleistocene

During the Late Pleistocene (~77 ka), the steppe vegetation occupied the region under a cold-arid climate[60], whereas in the Eastern Himalaya too, savannah vegetation with few scattered trees of *Pinus* and *Tsuga* occurred in the region under a cold and dry climate during the Late Pleistocene (~66 ka)[78]. In the Western Himalaya, during 77–34 ka, five warm–moist fluctuations and four during 30–10 ka (30–28, 21–18.375, 16 and 10 ka BP) have been recognized[60]. In the Eastern Himalaya, between ~44,000 and 34,000 year BP, alternating phases of expansion and decline of oaks, as well as decline and increase of pines and grasses probably occurred under increased warm–moist conditions, which could be linked to the interstadial phase during the last major glacial cycle in the Himalayan region. At around 20,000 year BP (the LGM), the impact of the expansion of glacier is felt and the tree-line had moved to lower altitudes due to increased aridity and low temperature. During this time, existence of savannah type of vegetation is also evident by the increase of C4 taxa in the Eastern Himalaya. Open grasslands around the Darjeeling Himalaya was also suggested under a cold and dry climate during the LGM (~20,000 year BP)[71]. In the Eastern Himalaya, during the late part of MIS 3 (46.4–25.9 ka), and early and middle part of MIS 2 (25.9–15.6 ka), significant oscillations in precipitation was observed, based on co-existence approach on pollen data and other proxies[79]. They further indicated that middle to late MIS 3 (46.4–31 ka) was characterized by a comparatively low monsoonal activity and slightly higher temperature than that during 31 ka onwards. Between 31 and 22.3 ka (late MIS 3 to mid MIS 2), higher precipitation and slightly cooler temperature led to an increase in evergreen elements over deciduous taxa, and wet-loving panicoid grasses over dry-loving chloridoid grasses. After around 22.3 ka, shrinking of forest cover, expansion of C4 chloridoid grasses, Asteraceae and Amaranthaceae in the vegetation, with the lowering of temperature and precipitation, characterized the onset of the LGM, which continued till around 18.3 ka in the Darjeeling Himalaya. However, a dense C3 species-dominated moist semi-evergreen forest existed around the Ziro Lake Basin, Arunachal Pradesh until the LGM[76]. Prior to the LGM, the mean annual temperature (MAT) and mean annual precipitation (MAP) were approximately 19.3 ± 0.001°C and 1925 ± 15 mm respectively. MAP was higher than the present day by 94 mm. The quantification of palaeoclimatic records from the Western Himalaya, however, is wanting.

Late Pleistocene–Early Holocene transition and Early Holocene

The palynological studies from the Western Himalaya suggest that between 12.2 and 11.8 k year BP, an extremely weak monsoon was indicated, corresponding with the YD interstadial (cold event), which supported the spread of Chenopodiaceae-dominated vegetation around the Tso

Kar Lake (4527 m amsl) in the arid Ladakh area of the NW Himalaya[61]. Further, they indicated a jump in humidity, in response to the increased summer monsoon, with *Artemisia*-dominated steppe and wet alpine meadows having Gentianaceae, after the late glacial/Early Holocene transition. Weakening of SW monsoon between ~12,880 and 11,640 year BP was suggested, which correspond with the YD cold event, around the Chandra Valley in Lahaul[68]. They further indicated a short spell of cold and dry climate with a gradual decrease in SW monsoon intensity between ~10,398 and 9778 year BP, which is closely linked with the Bond Event-7. A prominent decrease in local (meadow) and regional (alpine steppe) vegetation was noticed, indicating a major climatic shift towards cold and dry conditions, corresponding to the YD cold event, which intensified progressively till 11,640 year BP (ref. 69). They further suggested a significant wet and warm phase prior to 12,880 year BP (preceding the YD cold event), depicting the Ållerød interstadial (warm phase).

In the Eastern Himalaya, an amelioration in the climate (intensification of southwest monsoon) was suggested between 10.2 and 3.8 ka with expansion of forest around the Ziro Lake Basin of Arunachal Pradesh[76]. They further quantified the MAT and MAP and indicated that between 10.2 and 3.8 ka, MAT was about 19.4 ± 0.5°C, whereas MAP was 1901 ± 41.3 mm (higher than the present day by 70 mm) around the area of study. Similarly, the signatures of the YD cold event between 12,450 and 10,810 year BP was also suggested from the Kamrup district of Assam (northeast India), suggesting a tropical tree-savannah vegetation under a cool and dry climate[83].

Middle Holocene

The palaeoclimatic records from the Western Himalaya suggest that a warm and wet HCO period prevailed around the Lahaul Valley, NW Himalaya between 6732 and 3337 year BP, wherein the expansion of broad-leaved taxa and the effective growth of meadow vegetation took place[69]. A warm and humid climate with increased monsoon precipitation also occurred around the Jammu region, supporting mixed broad-leaved/conifer forests between 5296 and 2776 year BP (ref. 49), corresponding to the HCO. However, prominent cold–dry events were suggested during ~8810 to 8117 year BP, that roughly corresponds to the global 8.2 ka cold event and ~4808 to 4327 year BP, closely preceding the global 4.2 ka cold-arid period from the Lahaul Valley, NW Himalaya[69].

The HCO is well recorded from the Eastern Himalaya as well; rather a prolonged warm and humid phase (10.2 to 3.8 ka) has been observed in the Zero Valley, Arunachal Pradesh[78]. From the northeastern plains too, a warm and moderately humid climate with increased monsoon precipitation was indicated between 6780 and 1950 year BP (ref. 83), correlatable with the peak of HCO.

Late Holocene

A warm and moist climate between 1158 and 647 year BP was suggested, which is correlatable with the MWP, from the Lahaul Valley, NW Himalaya[68]. A cold–dry event ~CE 1303 to 1609 year was also indicated, corresponding to the LIA. A relatively warm and moist MWP was suggested between 1.75 and 0.9 k year BP, which supported both the conifers and broad-leaved taxa along with fair amount of *Rhododendron* around the Pindari Valley, Kumaun Himalaya[59]. Furthermore, between 0.9 and 0.2 k year BP, which corresponds to the LIA, the climate changed drastically, affecting the vegetation, showing a comparative decline in both conifers and broad-leaved taxa (except *Quercus* and *Rhododendron*) in the area. Between 962 and 300 year BP, a warm and more humid climate occurred around the Triloknath glacier valley of Lahaul (Himachal Pradesh)[70], which supported increased growth of the broad-leaved forests, the early part of which coincides with the MWP. A pulsatory cool climatic phase ~350 years ago (CE 1650) was indicated, more likely reflecting the impact of the LIA, which is also evidenced by a sharp decline in the broad-leaved forests. The vegetation succession and associated climate change from the Western Himalaya indicate amelioration of climate (warm–moist) between 1700 and 850 year BP (CE 250–110), which corresponds partly with the MWP. The warm–moist climate turned drier, correlatable with the LIA ~850 year BP (CE 750–1200) around the Gangotri Glacier[55]. They also indicated a shift in the vegetation pattern, with a sharp increase in *Ephedra*; *Artemisia* and members of Asteraceae (steppe elements), as well as a decrease in ferns and *Potamogeton* during the drier climate. The signal of MWP was also indicated around 865 year BP onwards from the Jammu region[50], wherein the broad-leaved taxa expanded and dominated over the conifers under a warm and humid climate with increased monsoon precipitation.

In the Eastern Himalaya, a comparatively warmer climate ~1100 year BP (CE 985) was suggested[75], which corresponds with the MWP, around the Paradise Lake, Sela Pass, Arunachal Pradesh, which turned towards cooler and less moist ~550 year BP (CE 1400), corresponding to the LIA. The LIA event was also suggested from Itanagar (Arunachal Pradesh)[77], but highly variable and not a globally synchronous cold period, but rather cold and moist. A cold and moist climate ~1450–450 BP (CE 500–1550) was suggested from Sikkim Himalaya[74], corresponding to the MWP. However, deterioration of climate (cold-dry) ~450–200 BP (CE 1550–1750) was also noticed, which is correlatable with the LIA. The palaeoclimatic studies undertaken from the Darjeeling region[80]

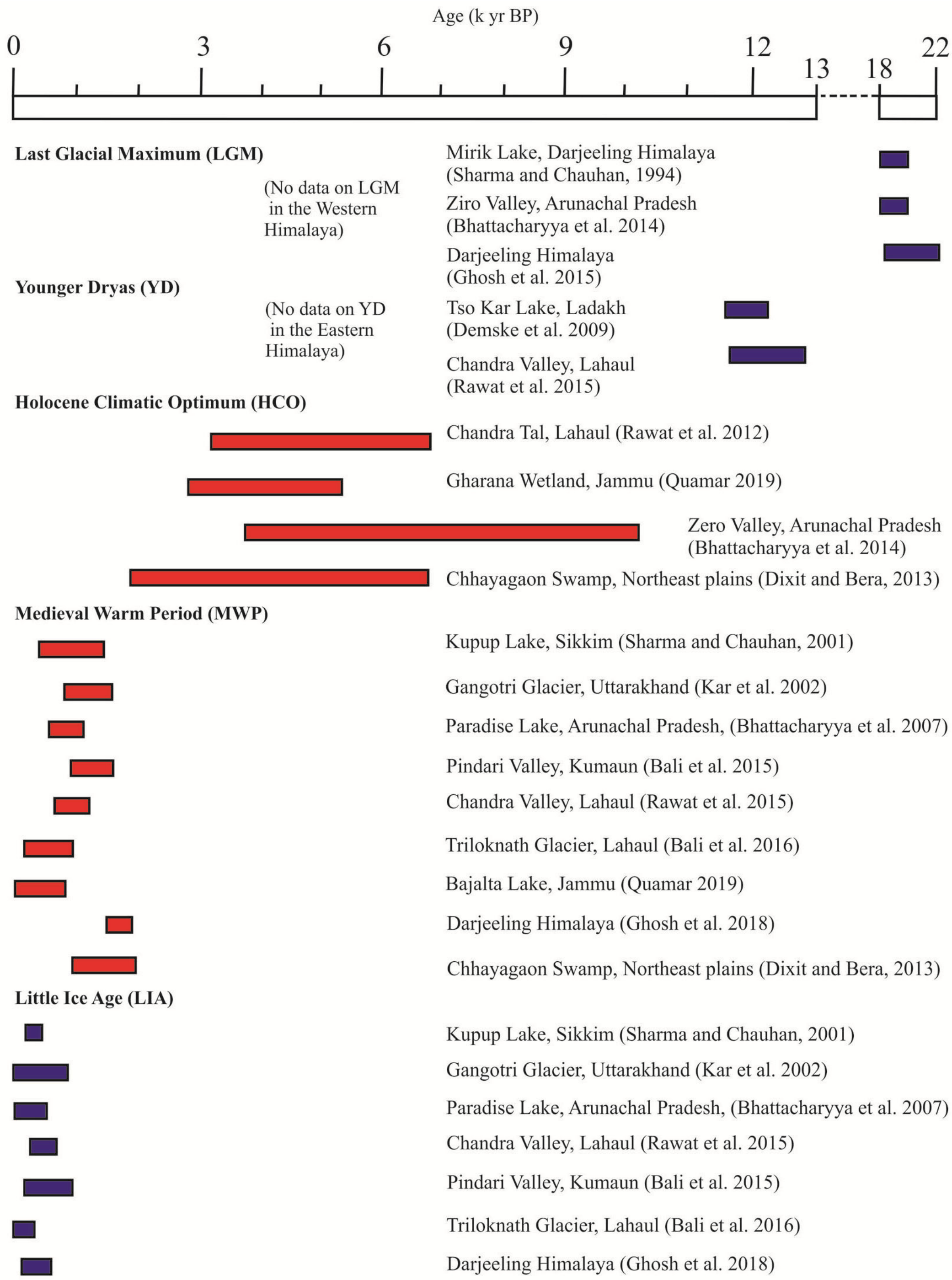

Figure 4. Vegetation-based timings and durations of major global climatic events from the Western and Eastern Himalaya (and the Northeast plains).

suggested that a humid climate during 364 BCE to 131 CE, is correlatable with the MWP, wherein a dense broad-leaved evergreen forest occurred. Comparatively drier conditions supported thinning of the forest cover between 1367 CE and 1802, comparable with the LIA. MAT and MAP were quantified from Arunachal Pradesh, in the Eastern Himalaya[76], and between 3.8 and 1.2 ka onwards, MAT was observed ~0.3°C and MAP to be 1861 ± 33.4 mm around the Ziro Lake Basin. Further shrinkage in forest cover was indicated after 3.8 ka as a result of a rising trend in dryness and a slight increase in C4 species. Similarly, from the northeastern plains, the signal of LIA was indicated since 540 year BP onwards, as evidenced by the reduced forest floristics, probably attributable to weak monsoonal rainfall[82]. The signal of MWP was reported between 1950 and 989 year BP, supporting a tropical dense mixed deciduous forest under a warm and more humid climate[83].

The palaeoclimatic records and associated vegetation dynamics from the Western and Eastern Himalaya show a broad compatibility with regards to the major global climatic events of the late Pleistocene–Holocene. There are, of course, disparities in the timings and durations of the climatic events between the two regions, which can be attributed to the wide geographical distance, influence of altitude, topography, local climatic factors, besides the effects of ISM and WDs. Generally, prolonged warm-humid phases are observed in the Eastern Himalaya, while the cold-arid phases are better marked in the Western Himalaya. The timings and durations of the major global climatic events from both the Western and Eastern Himalaya are shown in Figure 4.

Conclusion

(1) The Late Pleistocene (~77 ka) in the Western Himalaya is characterised by steppe vegetation under a cold-arid climate. Around 66 ka in the Eastern Himalaya, a *Pinus-Tsuga* savannah vegetation flourished under cool-dry climatic conditions.

(2) Between 77–34 ka and 30–10 ka, a number of warm-moist fluctuations are recorded in the Western Himalaya; whereas similar climatic vicissitudes are also discernible in the Eastern Himalaya during 44–34 ka and 25–15 ka.

(3) The impact of the LGM and prevailing aridity is visible in both the regions, as evidenced by the spread of steppe and savannah vegetation during that phase.

(4) The YD cold event is well marked in the Western Himalaya characterized by Chenopodiaceae-dominated vegetation. The YD, *sensu stricto*, has not been observed in the palynological records from the Eastern Himalaya. However, from the northeastern plains, the YD event is visible between 12.4–10.8 ka, represented by a tree-savannah vegetation.

(5) A general warming, with the initiation of Holocene, is perceptible in both the sectors. The HCO is well recorded from the different parts (and altitudes) of Western Himalaya. Moreover, in the Eastern Himalaya, a long phase of warm-humid conditions is present during 10.2–3.8 ka.

(6) The arid events of 8.2 ka and 4.2 ka are better present in the Western Himalaya. These are somewhat missing in the eastern part, probably due to prolonged wetter conditions during the Holocene; however, the 4.2 ka event has been observed in one record.

(7) The evidences of MWP and LIA are present in a number of areas in both regions. However, the MWP and LIA phases were found to be wetter in the eastern sector.

(8) The ISM is not only the exclusive climate system in the Eastern Himalaya, but it is the dominating force in the western sector as well. However, the WDs have some influence in the arid, rain-shadow zone of Trans Himalaya, which has helped in the sustenance of alpine meadows and steppe vegetation during the weak phases of the summer monsoon.

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