Palaeoclimatic estimates for a latest Miocene-Pliocene flora from the Siwalik Group of Bhutan: Evidence for the development of the South Asian Monsoon in the eastern Himalaya

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Abstract

Fossil leaf floras, from the latest Miocene-Pliocene Siwalik Group exposed in Bhutan, sub-Himalaya, are subjected to a CLAMP (Climate Leaf Analysis Multivariate Program) analysis using a high-resolution gridded climate calibration. The CLAMP analysis of 27 different morphotypes of fossil leaves indicates a mean annual temperature (MAT) of 24.1 ºC ± 2.8 ºC; a cold month mean temperature (CMMT) of 18.9 ºC ± 4 ºC and a warm month mean temperature (WMMT) of 27.8 ºC ± 3.3 ºC. The analysis also suggests a weak monsoonal climate (the monsoon index, MSI 46.7; present MSI 52) with growing season precipitation (GSP) of 1819 ± 916 mm (present GSP 2490 mm). Here we also compare palaeoclimate estimates of the latest Miocene-Pliocene Siwalik Group flora from Bhutan (c. 6 to 3.8 Ma) with those of previously investigated Siwalik Group floras from the Miocene-Pleistocene of Arunachal, India and Miocene Siwalik floras of Darjeeling, India which characterise the monsoon signature at the time of deposition. Since all the Siwalik floras of the eastern Himalaya (Darjeeling and Arunachal Pradesh) spanning the mid-Miocene to Pleistocene yield almost the same values we suggest that overall the eastern Himalayan Siwalik climate appears to have been remarkably uniform over the past 15 million years. The MAT result of the Bhutan Siwalik flora differs by just 0.6 °C from Arunachal and 1.2 °C from Darjeeling Siwalik floras. For all Siwalik fossil assemblages, WMMTs, CMMTs and LGSs (length of the growing season) are similar and consistent (WMMTs around 28 ºC, CMMTs around 18 ºC and LGSs around 12 months). Similarly, the mean annual relative humidity (RH) and specific humidity (SH) appear to have been uniformly around 80% and 14 g/kg respectively throughout the Neogene of the eastern Himalayan Siwaliks. Changes in the monsoon index suggest that in both Bhutan and Arunachal sub-Himalaya, there has been little change in the intensity of the monsoon since mid-Miocene time,

while further west in the Darjeeling area precipitation seasonality has increased since the mid-Miocene.

Key words: Fossil leaves; CLAMP; Neogene; Precipitation seasonality; MSI; Eastern Bhutan.

1. Introduction

During the Neogene, the combined Himalaya-Tibet region above an altitude of 2000 m (herein called the Himalaya-Tibet Edifice; HTE), which ostensibly resulted from the collision of the Indian plate with the Eurasian plate, influenced both the regional climate of Asia and the global climate (Wang et al., 2014a, b). Regionally, the HTE is today considered to directly or indirectly control the strength and pattern of the Asian Monsoon System (ASM) (Molnar et al., 2010), although the mechanisms involved remain uncertain (Boos and Kuang, 2010, 2013; Zhang et al., 2015). Monsoon climates are, strictly speaking, a phenomenon of seasonal airflow associated with marked seasonal variations in air mass direction, humidity and associated rainfall (Molnar et al., 2010). The Indian Summer Monsoon (ISM) also referred to as Southwest monsoon or South Asia summer monsoon, is a sub-system of the ASM, is tropical in nature and plays a significant role in the natural development of environmental conditions in SE Asian countries (Guo et al., 2002). A seasonal reversal of the wind system with moist oceanic air from the southwest during summer and cold, dry continental air from the northeast during winter characterises the ISM climate. Alterations in the monsoon regime influence changes in vegetation as well as the climate of an area (Lunt et al., 2010).

To understand future climatic changes and their influence on the environment and biodiversity it is of great importance to gain information about past climates (Haywood et al., 2008). The Himalaya, as distinct from the wider HTE region, acts as unique repository of past ISM variations, situated as it is in the path of the seasonally reversing air flows. Studies of the past climatic history of Bhutan, eastern Himalaya, are significant in this regard due to the presence of enormous altitudinal range and varied climatic conditions reflected in great ecological diversity hosting abundant and diverse flora and fauna (Grierson and Long, 1983). However, we are unaware of previous attempts to understand monsoonal variability and corresponding vegetation change in the Neogene Siwalik sediments of the Bhutan sub-Himalayan zone. The late Cenozoic is particularly interesting in that it spans a time of global transformation from a greenhouse climatic regime to an icehouse state (Zachos et al., 2001).

In the eastern Himalayan Siwalik successions, especially in the Darjeeling and Arunachal Pradesh sectors, several palaeobotanical studies of Siwalik sediments have been undertaken (Antal and Awasthi, 1993; Antal and Prasad, 1996a, 1996b, 1997, 1998; Khan and Bera, 2014a, b; Khan et al., 2014a, b, 2015, 2016, 2017a, b), but in Bhutanese Siwalik strata have received relatively little palaeobotanical attention in relation to phytostratigraphy and palaeoenvironment due to the inaccessibility of most of the fossil bearing locations. Palaeobotanical work that has been carried out so far from the extensive Siwalik successions in the Bhutan sub-Himalaya have mostly focused on fossil plant taxonomy rather than palaeoenvironmental interpretations (Biswas et al. 1979; Banerjee, 1996; Banerjee and Dasgupta, 1996; Prasad and Tripathi, 2000). The documentation of taxa from different fossil localities of the Bhutan Siwaliks is important for the precise reconstruction of floristics and climate. It is, therefore, important to know the composition of fossil flora contained within this group of rocks and how the climate has changed throughout Siwalik deposition to the present day.

Until now we have focused on both floristic reconstructions and foliar physiognomic analysis (Climate-Leaf Analysis Multivariate Program – CLAMP - http://clamp.ibcas.ac.cn) of plant remains contained within the Siwalik Group in eastern India, specifically West Bengal and Arunachal Pradesh (Khan et al., 2014a). However, there is still a lack of information from the Bhutan sub-Himalaya regarding palaeoclimate reconstruction using CLAMP. Here we fill that gap and reconstruct quantitatively the Miocene-Pliocene climate based on physiognomic features of fossil leaf remains. The present study is crucial for a comprehensive quantitative reconstruction of Cenozoic climate evolution among the Himalayan front. In this regard we compared the Bhutan Miocene-Pliocene Siwalik flora to a mid-Miocene leaf flora from the Darjeeling area and Mio-Pleistocene leaf floras from Arunachal Pradesh that have previously been used to derive palaeoclimate estimates (Khan et al, 2014a).

2. Physical setting

Bhutan, a mountainous state lying entirely in the heart of the eastern Himalaya, covers an area of about 96000 sq. km. and is bounded by the Tibetan plateau to the north, the plains of West Bengal and Assam to the south, the sub-Himalayan tract of Arunachal Pradesh in the east and Darjeeling and Sikkim foothills in the west (Fig. 1). In Bhutan mountain ranges vary in height from about 300 m to 7500 m above mean sea level and hosts diverse climates regimes from sub-tropical to temperate to alpine-arctic (Grierson and Long, 1983). The winters are mostly dry and sunny, due to dry air outflows from the Tibetan high-pressure system. The climate is humid and tropical to subtropical in and around the study area in the foothill regions (Biswas et al., 1976; Grierson and Long, 1983).. A hot, humid climate helps maintain a fairly even temperature range between 15 °C and 30 °C year-round, although temperatures sometimes reach 40 °C in the valleys during the summer. Rainfall varies between ca. 1000 – 7800 mm per year supporting thick tropical forest, or savanna.

3. Geological setting

The uplift and erosion of the Himalayan highland during the Neogene resulted in an extensive apron of terrestrial Siwalik sediments deposited all along the Himalayan foreland basin (now foothills) in India, Nepal, Pakistan and Bhutan (Acharyya, 1994). 'Siwalik' sediments, a term introduced by Cautley (1835), generally comprise an enormously thick (~7000 m) succession of Neogene freshwater coarsely bedded sandstone, siltstone, grit, clay and conglomeratic molassic deposits that are exposed all along the length of the Himalayan foothills from the Potwar plateau in the west to the Brahmaputra in the east (Bora and Shukla, 2005; Parkash et al., 1980). These sediments accumulated close to sea level in a long but narrow basin to the south of the rising Himalaya. The Siwalik Group is well known to geoscientists due to its rich fossil vertebrate fauna, ranging in age from middle Miocene to lower Pleistocene (Awasthi, 1992). Considerable data have also been gathered about the megaflora of the Siwalik Group (Pathak, 1969; Antal and Awasthi, 1993; Prasad, 1994a, b, c; Prasad and Pandey, 2008; Khan et al., 2014a). The geographical extent of the Himalayan foothill Siwalik Group has been sub-divided, from west to east, into seven sectors, namely the Jammu sector, the Himachal Pradesh sector, the Uttar Pradesh sector (now Uttarkhand), the Nepal sector, the Darjeeling-Sikkim sector, the Bhutan sector and the Arunachal Pradesh sector (Karunakaran and Ranga Rao, 1976) (Fig. 1). The eastern Bhutan Siwalik sector is the focus of our work presented here.

3.1. Bhutan Siwalik Group

The Himalayan Neogene-Quaternary foreland basin sediments of the Siwalik Group, which comprises a c. 2.2 km thick sedimentary section, is well-exposed on freshly eroded stream banks along the Dungsam Chu near Samdrup Jongkhar at the front of the eastern Bhutan Himalaya (Coutand et al., 2016). The sedimentary section is bounded to the north by the Main Boundary Thrust (MBT), along which the Lesser Himalayan Sequence (LHS) was over thrust on to the Siwalik Group in the late Miocene (Coutand et al., 2014). To the south the Main Frontal Thrust (MFT) juxtaposes the Siwalik Group strata against the Ganges-Brahmaputra plain alluvial sediments (Burgess et al., 2012).

The three lithostratigraphic subgroups of the Siwalik Group, namely the lower, middle, and upper Siwaliks, are recognized on the basis on textural differences, specifically on the proportion of different grain sizes, and crop out in eastern Bhutan. Typically, the coarsest sediments of the lower, middle, and upper Siwalik subgroups correspond to thin-bedded fine to medium-grained sandstones, thick-bedded medium to coarse-grained sandstones, and thin to thick-bedded conglomerates, respectively (Gautam and Rösler 1999; Quade et al. 1995). Accordingly, in eastern Bhutan, the boundary between the lower and middle Siwalik subgroups occurs at the first occurrence of thick coarse-grained sandstones, while the transition between the middle and upper Siwalik subgroups occurs at the first occurrence of thin to thick-bedded conglomerates (Gansser, 1983; Bhargava, 1995; Long et al., 2010, 2011; Coutand et al., 2016) (Fig. 2).

To decipher the sedimentary record through time regarding ages, thicknesses, sedimentary facies, and depositional paleoenvironments, Coutand et al. (2016) performed geochronological (magnetostratigraphy), sedimentological, and palynological analyses on the thick continuous stratigraphic section of the Siwalik Group deposits in eastern Bhutan.

Magnetostratigraphy constrained by vitrinite reflectance data combined with detrital apatite fission track (DAFT) dating indicate that the Siwalik Group was deposited during the latest Miocene and the Pleistocene, between ~7 Ma and ~1 Ma. Magnetostratigraphic results also suggest that the boundaries between the lithological subgroups of the Siwalik Group occur at ~6 Ma for the lower to middle Siwalik subgroups and at ~3.8 Ma for the middle to upper Siwalik subgroups, while the top of the section is dated as ~1 Ma (Coutand et al., 2016).

3.2. Bhutan Siwalik Group facies

Twelve facies identified on the basis of their lithology, sedimentary structures, and trace fossils co-occur in four facies assemblages, which were interpreted in terms of depositional environments (Coutland et al. 2016). Depositional environments include river-dominated and wave-influenced deltaic systems at the base, which, associated with marine trace fossils, glauconite, and some coastal pollen taxa, suggest a marine setting potentially linked to marine incursions from the Bay of Bengal (Coutland et al. 2016). At around 5 Ma, a transition to a sandy and then gravelly alluvial environment occurs. The sporomorphs represent taxa grouped into four main categories (Poaceae, other herbs, angiosperms/gymnosperms, and pteridophytes) from different vegetation types in the proximal Himalayan orogenic system and point to diverse tropical lowlands and rain forest vegetation throughout the ~7–1 Ma time period. The palynological record also indicates that depositional environments and paleoclimate were consistently humid and wet in eastern Bhutan since 7 Ma. An overview of the lithology and stratigraphy of the Siwalik sediments in eastern Bhutan is presented below in Table 1.

4. Materials and methods

4. 1. Fossil leaf assemblage

Numerous well preserved, complete or fragmentary fossil leaf impressions and compressions were collected from two river traverses, namely, the Darranga river traverse in the east and the Lakshini river traverse in the west, both in the eastern part of Bhutan (situated between latitude 26°40'-28°25'N and longitude 88°40'-92°10' E) (Fig. 1).

Siwalik rock types in and around the fossil localities belong to the middle Siwalik (Formation II: Miocene-Pliocene), which is characterised by poorly indurated, medium- to very coarse-grained, multi-storied sandstone bodies, with grey shale intercalations and siltstone, hosting abundant plant fossils (Biswas et al., 1979; Banerjee, 1996) (Fig. 2). The fossil leaf remains are preserved in compact sandstone and dark-coloured carbonaceous shale. The flora is dominated by angiosperms. The compressions have yielded good cuticle the details of which will be published in a separate paper.

The fossils were recovered by splitting large chunks of the massive fossiliferous mudstone with the aid of heavy sledge hammers and chisels. After cleaning, macroscopic images of well-preserved angiosperm leaves were photographed using a digital camera (Canon Power Shot A720IS) (Fig. 3). The recovered leaves were compared with herbarium sheets of modern angiosperm taxa kept in the Central National Herbarium (CAL), Sibpur, Howrah, West Bengal, India. A detailed systematic description of this fossil leaf flora is in preparation. All the fossil specimens, including holotypes, are curated at the Herbarium and Museum, Department of Botany, University of Calcutta, India (CUH).

4.2. Modern flora

To contextualise our fossil finds it is useful to consider the modern vegetation and climate of the Siwaliks in Bhutan.Bhutan has a rich and diverse flora (Grierson and Long, 1983). Over 60% of the common plant species of the eastern Himalayas are found in Bhutan, which is estimated to host 8000 species, among which 2000 species are under 775 genera belonging to pteridophytes, gymnosperms and angiosperms. The N-S trending deep valleys receive moisture-laden winds and heavy precipitation, which supports the development of luxuriant tropical vegetation, in contrast to the comparatively bare slopes of the E-W oriented lateral valleys hosting moist deciduous forests with or without sal (*Shorea robusta*) and pine (*Pinus* spp.). At elevations similar to those inferred for the source vegetation of the Siwalik fossil assemblage (<300 m), modern vegetation close to the fossil locality in Bhutan is characterised as moist tropical to sub-tropical evergreen rain forests (Biswas et al., 1976; Grierson and Long, 1983).

4.3. CLAMP methodology

CLAMP (Climate-Leaf Analysis Multivariate Program), initiated by Wolfe (1990), is a multivariate statistical technique that decodes the climatic signal inherent in leaf physiognomy of woody dicotyledonous flowering plants (Wolfe, 1993; Spicer et al., 2009; Yang et al., 2011). It has developed as a robust, accurate and quantitative tool for direct terrestrial palaeoclimatic determinations based on floral assemblages (e.g. Spicer et al., 2003, 2004). CLAMP exploits the universal relationships that exist between the leaf physiognomy (architecture) of woody dicots and the environment, particularly climate (Yang et al., 2015). It is independent of taxonomy, immune to diagenesis and can be applied to leaf assemblages as old as 100 my (Spicer et al., 2009; Yang et al., 2011).

In CLAMP, 31 architectural character states are scored; these encompass lobing, margin characteristics, size, apex and base form, length to width ratio and shape. Two related training data arrays (a leaf character array derived from modern vegetation and a climate array derived from modern gridded climate data) are used to calibrate CLAMP. Typically variations in leaf form are correlated with 11 climate variables related to temperature, humidity, and precipitation using Canonical Correspondence Analysis (CCA) (ter Braak, 1986). Full details of the method are given on the CLAMP website (http://clamp.ibcas.ac.cn).

CLAMP does not require the species to be identified or referred to modern presumed nearest living relatives, and the term 'morphotype' is used in CLAMP to denote groups of specimens likely to represent leaves of the same ancient species. These morphotypes are often termed operational taxonomic units (OTUs) (Spicer et al., 2004, 2009). The morphotypes were scored according to the standard CLAMP protocols given on the CLAMP website, which are distinct from those used to describe leaves for taxonomic purposes (e.g. Ellis et al., 2009). The scoresheet is available as supplementary material (Table S1).

The PhysgAsia2 and HiResGridMetAsia2 files available from the CLAMP website were used to define a CLAMP physiognomic calibration space within which the Bhutan Siwalik fossil leaf assemblage was passively positioned (Figs. 4, 5, 6). This training set combination, first introduced by Khan et al. (2014a), has been shown to give similar results to those obtained from isotopes when used for palaeoaltimetry (Currie et al., 2016; Xu et al., 2018) and is particularly suited to Asian climates.

In the absence of tested metrics independent of precipitation, to measure the strength of the monsoon we used the monsoon index (MSI) of Xing et al. (2012) because their MSI can be derived from the climate variables returned by CLAMP using the expression: MSI = (3WET-3DRY)*100/GSP. Higher MSI values indicate greater differences in precipitation between the wet and dry seasons, and thus a stronger monsoon.

5. Results

The 31 leaf physiognomic characters of the 27 morphotypes of fossil leaves from the Bhutan Siwalik (Miocene-Pliocene) sediments were scored (Supplementary material; Table S1), and then a standard CLAMP procedure was carried out. Figures 4–6 show the structure of CLAMP physiognomic space. To estimate palaeoclimate, regression models were constructed for each climate variable in Axes 1-4 space, with the position of the fossil site plotted on the regression based on its position projected normally onto the relevant climate vector. Figures 7–11 show, respectively, the regression models for MAT (mean annual temperature), WMMT (warm month mean temperature), CMMT (cold month mean temperature), 3-WET (precipitation during the three consecutive wettest months) and 3-DRY (precipitation during the three consecutive driest months). Regression models for growing season precipitation (GSP), mean monthly growing season precipitation (MMGSP), mean annual relative humidity (RH) and mean annual specific humidity (SH) and mean annual moist enthalpy (ENTHAL) are given as supplementary materials (Figs. S1-S5).

The predicted value for MAT is 24ºC ± 2.8 ºC (1 S.D.) with a mean annual range of temperature of ~ 8°C and growth was possible year-round (Table 2). Seasonality of rainfall is, however, more marked than seasonal temperature variation, with the three consecutive wettest months delivering ~ 9 times the precipitation of the driest three consecutive months and monsoon index is 46.7 (Table 2). Annually rainfall averaged ~ 1800 mm. The quantitative estimates for all eleven CLAMP climate parameters and associated uncertainties derived from the PhysgAsia2 calibration for the Siwalik flora of Bhutan sub-Himalaya as well as of Arunachal and Darjeeling foothills are given in Table 2.

6. Discussion

Megafloras from the Darjeeling, Arunachal Pradesh and Bhutan Siwalik sectors floras contain tropical evergreen elements and thus, the overall species compositions indicate a continuance through time of tropical, warm, humid climate vegetation (Khan et al., 2014a; Prasad and Tripathi, 2000). To investigate climate change and the monsoon signature in the eastern Himalayan region since mid-Miocene times in quantitative terms we compared leaf form across all floras using CLAMP (Table 2).

CLAMP analyses suggest that all the Siwalik fossil assemblages of the eastern Himalaya attest to warm and humid (tropical to subtropical) climates with a distinctive monsoon signature. The CLAMP retrodictions for the Bhutan, Darjeeling and Arunachal Pradesh Siwalik assemblages are, within error, more or less identical as regards to temperature, humidity and enthalpy estimates. This stability in temperature and enthalpy provides an invaluable reference for future isotopic and thermodynamic proxy-based palaeoaltimetric studies. All such studies require baseline (usually sea level) climate metrics from which to calculate past elevations for different parts of the Himalaya-Tibet edifice. Exemplar studies of this approach include Khan et al., 2014a; Currie et al., 2016; Ding et al., 2017; Ingalls et al., 2018; Su et al., 2018 and Xu et al., 2018.

All eastern Himalayan Siwalik assemblages reveal a warm month mean temperature of around 28 °C, a cold month mean temperature of around 18 °C, a length of the growing season of around 12 months, an average annual relative humidity of 80% and a mean annual specific humidity of 14 g/kg. Bhutan Siwalik leaves show mean annual temperature differences of just 0.6 °C from those of Arunachal and 1.2 °C from Darjeeling Siwalik palaeofloras, differences that are far smaller than the uncertainty in the method (± 2.8 °C). The Pliocene assemblage from Arunachal Pradesh appears to represent slightly cooler conditions, notably in winter, than those of the Miocene assemblage of Darjeeling and Mio-Pliocene assemblage of Bhutan, but the difference is within error and may not be real. So, the uniformity of climate variables across all the eastern Himalayan Siwalik samples is notable. The other climate variables such as GSPs and MMGSPs show more variation. The Miocene assemblage from Darjeeling yields the highest GSP and the wettest dry season, but all Siwalik sites suggest distinct seasonality in rainfall.

A common concept for monsoon evolution is that any change in the surface height or extent of Tibet will affect monsoon intensity. Moreover a widely held view is that a Miocene (~23 to 5Ma) uplift of the Tibetan plateau drove widespread speciation across large parts of Asia (Lu et al., 2018). However, an array of geological evidence shows that both an elevated Tibet and the Asian monsoon system predate the Miocene and even the onset of the India-Asia collision (e.g. Wang et al., 2014a; Renner, 2016; Spicer, 2017; Ingalls et al. 2018). Monsoon climates have existed across southern Asia for the whole of the Cenozoic, and probably for a lot longer, but that they were of the kind generated by seasonal migrations of the Inter-tropical Convergence Zone (ITCZ) (Spicer et al., 2017). Climate modeling demonstrates that such monsoons would have existed even in the absence of significant topography over Tibet (Huber and Goldner, 2012). However, the projection of the high (>5 km) Himalaya above the Tibetan highlands at about 15 Ma coincides with the initiation of the circulation system that became modern South Asia Monsoon (Spicer, 2017). Thus, the South Asia Summer Monsoon (SASM) in its modern form appears to have arisen after the mid Miocene, when the rising Himalaya increasingly became an obstacle to north-south airflow. This work, combined with our earlier studies of palaeoclimate in the eastern Himalaya (Khan et al., 2014a) suggest that in the most recent 15 million years elevation of the Himalaya significantly above 5 km has not greatly affected the SASM as it is expressed in the Himalaya foreland basin, at least in the eastern part, and that 5 km may mark a critical elevation for determining modern monsoon circulation over southern Asia.

The modern East Asia Monsoon also appears to be a Neogene phenomenon (An et al., 2001; Guo et al., 2008) beginning in the Early Miocene (~22 Ma), and may be linked with the rise of large parts of northern Tibet (Liu and Dong, 2013), and possibly other parts of Asia, that modified airflow. Other contributory factors include loss of moisture sources in the Asian interior and the development of a strong winter Siberian high as global temperatures declined (Spicer, 2017).

Some measure of the ratio between wet and dry season precipitation has become a preferred proxy for palaeoclimate studies aimed at understanding the history of monsoon climates (e.g. Jacques et al., 2014; West et al., 2015). The ratio of the precipitation in the three consecutive wettest months (3WET) to the three consecutive driest months (3DRY) for Bhutan Mio-Pliocene Siwalik assemblage is 9.1:1. The MSI for the Bhutan flora is 46.7, while that of the modern is 52. The ratio of the 3WET/3DRY for all the Arunachal Siwalik assemblages is >6:1, which defines them as monsoonal (Lau and Yang 1997; Zhang and Wang 2008). However, the present-day ratio for that region is >120:1 based on the same gridded dataset used to calibrate CLAMP. Note though that the 120:1 ratio is based on actual rainfall while the CLAMP predictions are mediated through soil moisture, which for fossil assemblages inevitably is biased towards wet conditions because leaf fossils are almost always preserved in aquatic settings (rivers and lakes).

So, using the physiognomy of the nearby modern Manas vegetation (26.846°N, 91.407°E, elevation 275 m) as if it were a fossil assemblage yields a CLAMP-predicted

3WET/3DRY ratio of 13.3 and a monsoon index (MSI) of 51.2 using the same calibration. The MSI for the Arunachal fossil floras is 47.7, while that of the modern is 53.4. This result suggests that the monsoon in the AP region has remained essentially the same since mid-Miocene times. The Darjeeling fossil wet/dry ratio is 3.8:1 suggesting a more even distribution of rainfall throughout the year due, apparently, to a wetter dry season than further east. The MSI for the Darjeeling fossil flora is 34.2 while that of the present day is 68.1. So, the monsoon indices suggest that in both Bhutan and the Arunachal sub-Himalaya there has been little change in the intensity of the monsoon since mid-Miocene time, while further west in the Darjeeling area there has been monsoon intensification i.e. in Miocene times the monsoon signature appears to have been weaker than now. What is now required is a comprehensive survey of monsoon signatures along the whole length of the Siwalik Group to understand the evolution of the modern rainfall pattern, which today shows increasing wetness in an easterly direction.

7. Conclusions

Palaeoclimate estimates of the Bhutan Mio-Pliocene flora provide valuable insights into monsoon climatic evolution throughout the eastern Himalayan Siwalik belt during late Cenozoic time. The results indicate that the Bhutan Siwalik flora experienced a monsoonal tropical warm humid climate. By comparing it with other neighboring eastern Himalayan Siwalik floras, we conclude that overall the eastern Himalayan Siwalik climate estimates appear to have been remarkably uniform over the past 15 million years and may indicate that once the Himalaya achieved elevations in excess of 5 km it made little difference to the climate of the eastern Himalaya foreland basin.

Acknowledgments

MK and SB acknowledge the UGC-CAS VII, Department of Botany, and University of Calcutta for necessary facilities. RAS and TEVS acknowledge support from NERC/NSFC BETR Project NE/P013805/1. MK., MB and SB express their sincere thanks to Dr. Sanjib Biswas and the authorities of Oil and Natural Gas Commission (ONGC), Dehra Dun, India, Mrs. Rupali Dasgupta and the late Manju Banerjee for supplying leaf remains studied in the present investigation. Thanks are also due to the authorities of Central National Herbarium, Sibpur, Howrah for permission to consult the Herbarium.

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Table Captions

Table 1. Lithology and stratigraphy of the Siwalik Group in eastern Bhutan (after Kumar, 1982; Biswas et al., 1979; Banerjee, 1996; Coutand et al., 2016).

Table 2. CLAMP results and associated uncertainties from the entire eastern Himalayan Siwalik fossil leaf assemblages (Khan et al., 2014a). Abbreviations: MAT - mean annual temperature, WMMT - warm month mean temperature, CMMT - cold month mean temperature, LGS - length of the growing season where growth is regarded to take place when the mean daily temperature >10 °C (note - values > 12 months reflect the uncertainty in the estimates), GSP - growing season precipitation, MMGSP mean monthly growing season precipitation, 3-WET - precipitation during the three consecutive wettest months, 3-DRY - precipitation during the three consecutive driest months, RH - mean annual relative humidity, SH mean annual specific humidity, ENTHAL - mean annual moist enthalpy, MSI - monsoon index, SD - standard deviation.

Figure Captions

Figure 1. A-B: A. Maps showing the seven sectors of Siwalik belt (modified *aftaer* Karunakaran and Ranga Rao, 1976); B. Map of Bhutan showing the location of the study areas.

Figure 2. Lithosuccession of Siwalik sediments of Bhutan (*after* Banerjee, 1996)

Figure 3. A-I: Leaf impressions and compressions recovered from the Miocene-Pliocene Siwalik sediments of Bhutan sub-Himalaya. Physiognomic characters such as lobing, margin characteristics, size, apex and base form, length to width ratio and shape of the recovered leaf remains used in CLAMP analysis (Scale Bar = 1 cm for all figures).

Figure 4. CLAMP PhysgAsia2 plot for CCA Axes 1 v 2 showing the location of the fossil site relative to the cloud of modern calibration (training set) sites of modern vegetation.

Figure 5. CLAMP PhysgAsia2 plot for CCA Axes 2 v 3 showing the location of the fossil site relative to the cloud of modern calibration (training set) sites of modern vegetation.

Figure 6. CLAMP PhysgAsia2 plot for CCA Axes 1 v 3 showing the location of the fossil site relative to the cloud of modern calibration (training set) sites of modern vegetation.

Figure 7. CLAMP PhysgAsia2 regression model for Mean Annual Temperature (MAT). The position of the Bhutan fossil flora along the second order polynomial regression relating the MAT vector scores for modern vegetation against the observed MATs for those sites is shown as a red closed circle with uncertainties (1 s.d.) reflecting the scatter of the residuals about the regression line indicated by the associated bars.

Figure 8. CLAMP PhysgAsia2 regression model for Warm Month Mean Temperature (WMMT). Site and uncertainty represented as in Fig. 7.

Figure 9. CLAMP PhysgAsia2 regression model for Cold Month Mean Temperature (CMMT). Site and uncertainty represented as in Fig. 7.

Figure 10. CLAMP PhysgAsia2 regression model for precipitation during the three consecutive wettest months (X3-WET). Site and uncertainty represented as in Fig. 7.

Figure 11. CLAMP PhysgAsia2 regression model for precipitation during the three consecutive driest months (X3-DRY). Site and uncertainty represented as in Fig. 7.

Supplementary material Captions

Table S1. CLAMP scoresheet for the Bhutan Siwalik Miocene-Pliocene assemblage.

Fig. S1. CLAMP PhysgAsia2 regression model for growing season precipitation (GSP). Site and uncertainty represented as in Fig. 7.

Fig. S2. CLAMP PhysgAsia2 regression model for mean monthly growing season precipitation (MMGSP). Site and uncertainty represented as in Fig. 7.

Fig. S3. CLAMP PhysgAsia2 regression model for mean annual relative humidity (RH). Site and uncertainty represented as in Fig. 7.

Fig. S4. CLAMP PhysgAsia2 regression model for mean annual specific humidity (SH). Site and uncertainty represented as in Fig. 7.

Fig. S5. CLAMP PhysgAsia2 regression model for mean annual moist enthalpy (ENTHAL). Site and uncertainty represented as in Fig. 7.

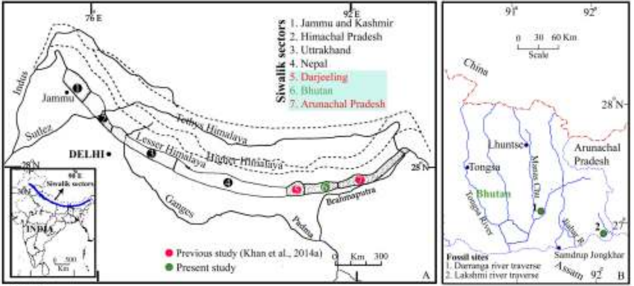
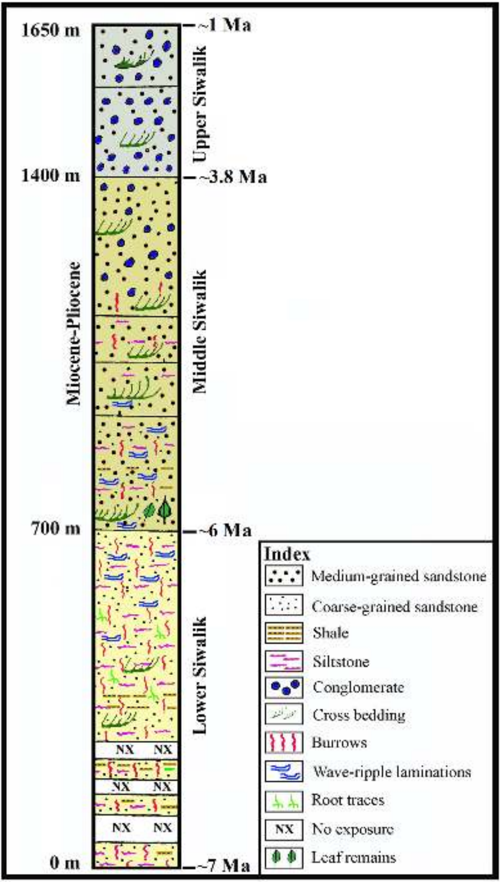

76 E
92 E
Siwalik sectors
1. Jammu and Kashmir
2. Himachal Pradesh
3. Uttrakhand
4. Nepal
5. Darjeeling
6. Bhutan
7. Arunachal Pradesh
Indus
Jammu
Sutlez
DELHI
Tethys Himalaya
Lesser Himalaya
Higher Himalaya
28 N
Ganges
Brahmaputra
Padma
Previous study (Khan et al., 2014a)
Present study
Km 300
INDIA
Siwalik sectors
A
91
92
0 30 60 Km
Scale
China
28 N
Lhuntse
Tongsa
Arunachal Pradesh
Bhutan
Manas Chu
Tongsa River
27
Samdrup Jongkhar
Assam
Fossil sites
1. Dantanga river traverse
2. Lakshmi river traverse
B

Figure 1



1650 m
~1 Ma
Upper Siwalik
1400 m
~3.8 Ma
Miocene-Pliocene
Middle Siwalik
700 m
~6 Ma
Lower Siwalik
NX
0 m
~7 Ma
Index
Medium-grained sandstone
Coarse-grained sandstone
Shale
Siltstone
Conglomerate
Cross bedding
Burrows
Wave-ripple laminations
Root traces
No exposure
Leaf remains

Figure 2

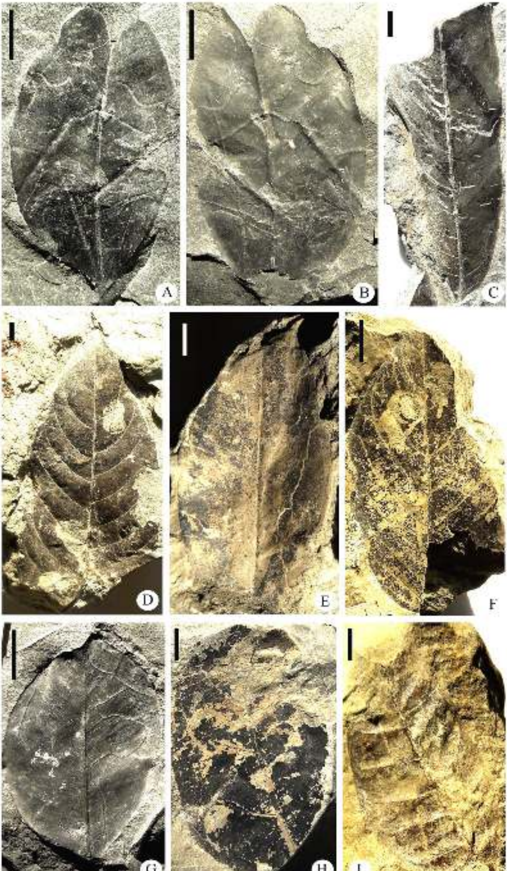


Figure 3

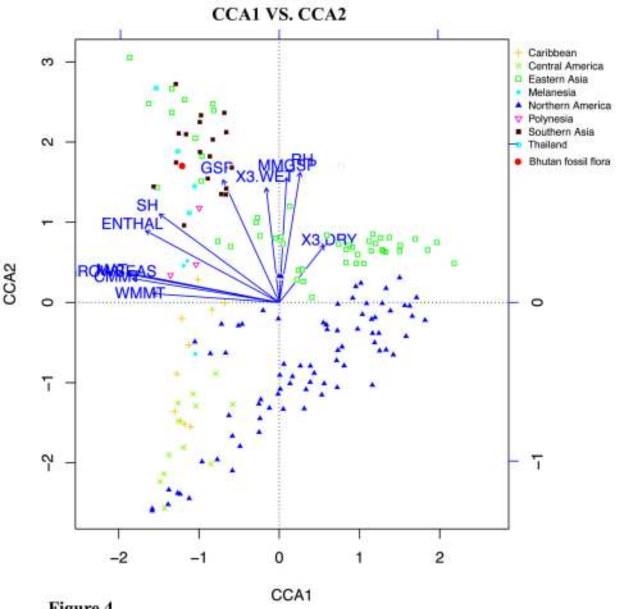
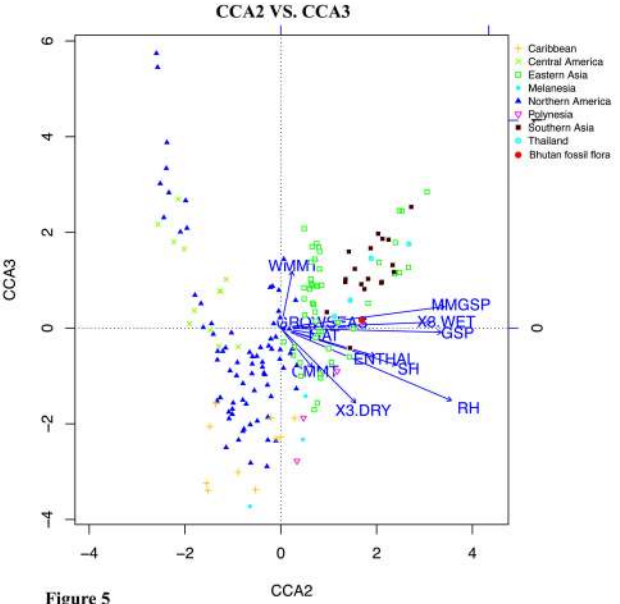

CCA1 VS. CCA2
Caribbean
Central America
Eastern Asia
Melanesia
Northern America
Polynesia
Southern Asia
Thailand
Bhutan fossil flora
GSP
X3.WET
MMGSP
RH
SH
ENTHAL
X3.DRY
WMMT
CMMT
CCA1
CCA2

Figure 4



CCA2 VS. CCA3
Caribbean
Central America
Eastern Asia
Melanesia
Northern America
Polynesia
Southern Asia
Thailand
Bhutan fossil flora
WMMT
MMGSP
X8.WET
GSP
GRO.VS.EAS
MAT
ENTHAL
SH
CMMT
X3.DRY
RH
CCA2
CCA3

Figure 5

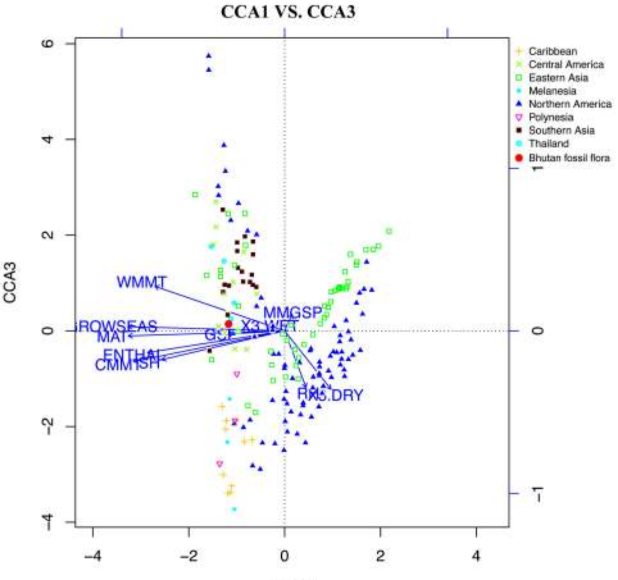

CCA1 VS. CCA3
Caribbean
Central America
Eastern Asia
Melanesia
Northern America
Polynesia
Southern Asia
Thailand
Bhutan fossil flora
WMMT
MMGSP
GROWSEAS
X3.WET
MAT
GSP
ENTHAL
CMMTSH
RH
X3.DRY
CCA3
CCA1

Figure 6

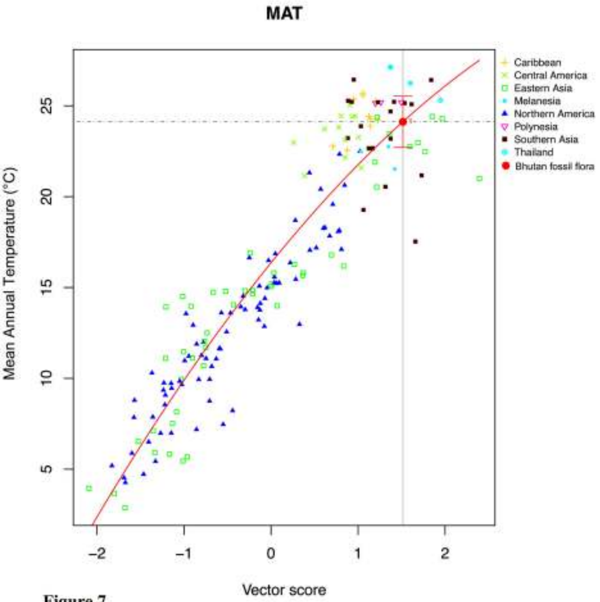

MAT
Mean Annual Temperature (°C)
Vector score
Caribbean
Central America
Eastern Asia
Melanesia
Northern America
Polynesia
Southern Asia
Thailand
Bhutan fossil flora
25
20
15
10
5
−2
−1
0
1
2

Figure 7

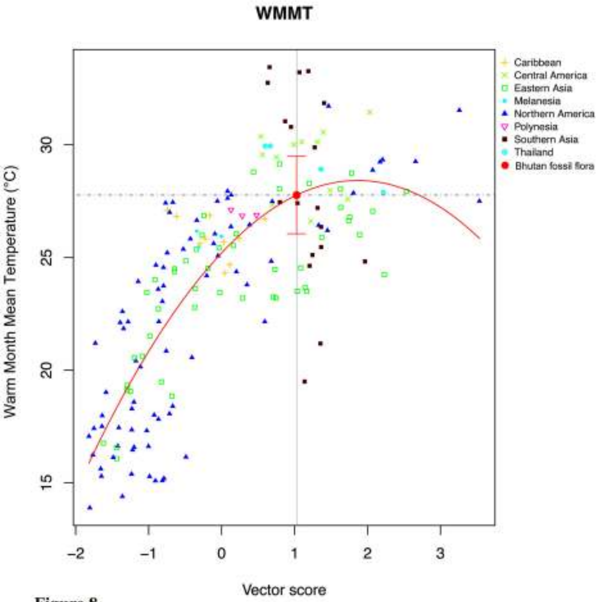

WMMT
Caribbean
Central America
Eastern Asia
Melanesia
Northern America
Polynesia
Southern Asia
Thailand
Bhutan fossil flora
Warm Month Mean Temperature (°C)
15
20
25
30
−2
−1
0
1
2
3
Vector score

Figure 8

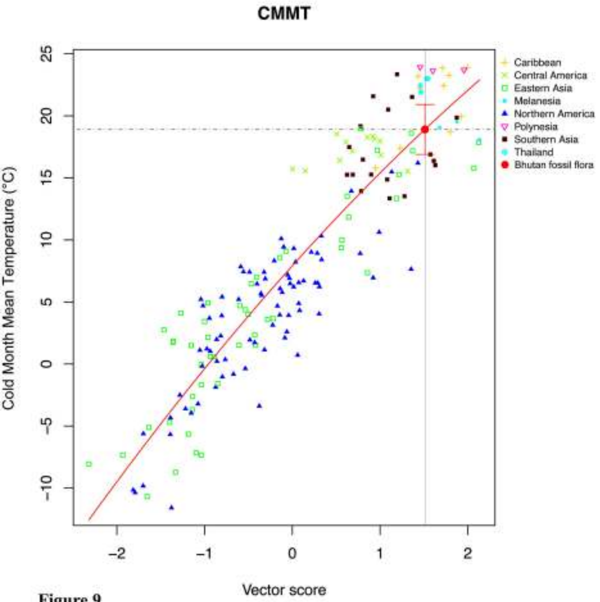

CMMT
Cold Month Mean Temperature (°C)
Vector score
Caribbean
Central America
Eastern Asia
Melanesia
Northern America
Polynesia
Southern Asia
Thailand
Bhutan fossil flora

Figure 9

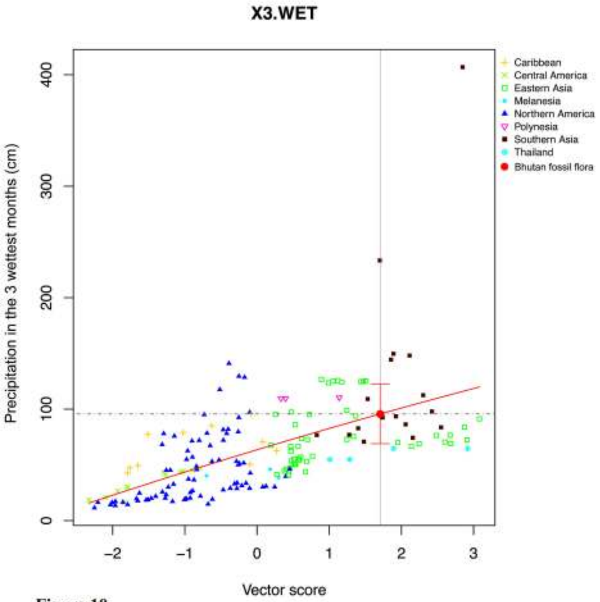

X3.WET
Precipitation in the 3 wettest months (cm)
Vector score
0
100
200
300
400
−2
−1
0
1
2
3
Caribbean
Central America
Eastern Asia
Melanesia
Northern America
Polynesia
Southern Asia
Thailand
Bhutan fossil flora

Figure 10

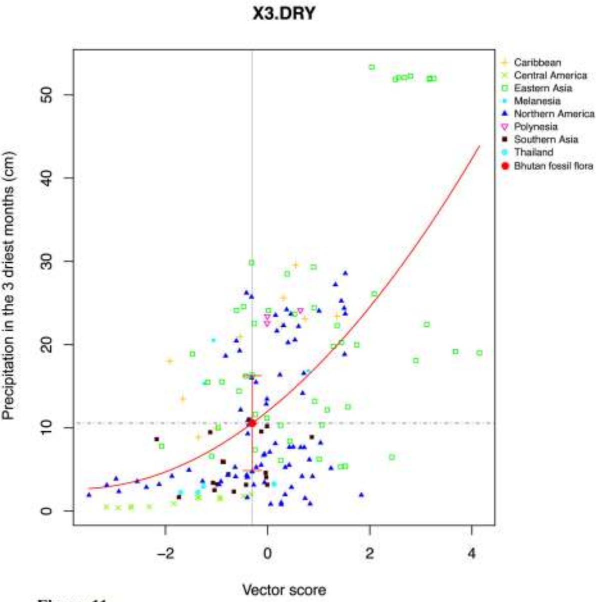

X3.DRY
Precipitation in the 3 driest months (cm)
Vector score
0
10
20
30
40
50
−2
0
2
4
Caribbean
Central America
Eastern Asia
Melanesia
Northern America
Polynesia
Southern Asia
Thailand
Bhutan fossil flora

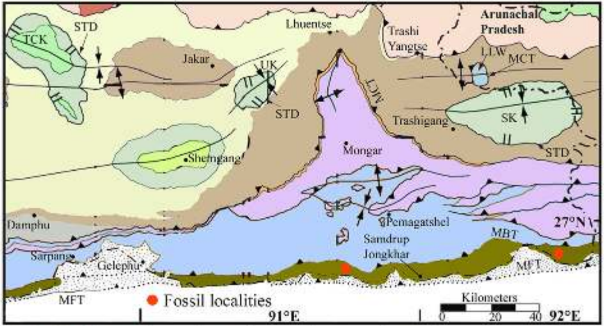
Figure 11

Table 1

Group	Sub-groups (Formations and Epoch)	Lithology	Age (Ma)
S I W A L I K	Upper Siwalik (Formation III: Pliocene-Pleistocene)	Thick beds, wedges and lenticular bodies of conglomerate comprising pebbles of quartzite in sandy matrix and interbeds of grey coarse grained, massive, micaceous sandstone, silty claystone with occasional lenses of lignite. …………………………Gradational……………………………………	~1 Ma
	Middle Siwalik (Formation II; late Miocene-Pliocene)	Interbedded sequence of sandstone, siltstone, claystone and mudstone, thick-bedded medium to coarse-grained sandstone, containing wood pieces, leaf impressions and compressions and calcareous concretions. …………………………Gradational……………………………………	~3.8 Ma
	Lower Siwalik (Formation I: late Miocene)	Dark grey claystone, shale, mudstone and subordinate thin-bedded fine to medium-grained sandstone, carbonaceous shale and pockets of coal.	~6 Ma ~7 Ma

Table 2

Eastern Himalayan Siwalik fossil leaf assemblages (mid-Miocene to early Pleistocene)	**MAT** (°C)	**WMMT** (°C)	**CMMT** (°C)	**LGS** (Months)	**GSP** (cm)	**MMGSP** (cm)	**3 WET** (cm)	**3 DRY** (cm)	**RH** (%)	**SH** (g/kg)	**ENTHAL** (kJ/kg)	**MSI**	**References**
Darjeeling Miocene	25.3	28.3	17.8	12.9	242.3	24.5	111.7	28.8	80.9	14.4	354.1	34.2	Khan et al. 2014a
Arunachal Pradesh Middle Miocene	25.2	27.8	21.2	12.4	174.1	13.9	96.1	7.3	81.1	14.9	355.8	51	Khan et al. 2014a
Pliocene	23.6	28.1	16.9	12.1	198.1	17.9	99.4	13.7	78.8	14.0	351.3	43.2	Khan et al. 2014a
Late Pliocene to early Pleistocene	25.3	28.0	20.8	12.5	189.8	15.8	101.6	8.9	82.3	14.9	356.1	48.8	Khan et al. 2014a
Bhutan Miocene to Pliocene	**24.1**	**27.8**	**18.9**	**12.1**	**181.9**	**15.4**	**95.7**	**10.6**	**80.2**	**14.4**	**353.3**	**46.7**	**Present study**
Uncertainty (1 S.D.)	2.8	3.3	4	1.3	91.6	8.8	52.8	11.5	10.7	2.1	10.3	-	



Eastern Himalayan Siwalik fossil leaf assemblages	MAT (°C)	WMMT (°C)	CMMT (°C)	LGS (Months)	RH (%)	SH (g/kg)	ENTHAL (kJ/kg)	MSI
Darjeeling Miocene	25.3	28.3	17.8	12.9	80.9	14.4	354.1	34.2
Arunachal Pradesh Mio-Pleistocene	24.7	27.9	19.6	12.3	80.7	14.6	354.4	47.7
Bhutan Miocene to Pliocene	24.1	27.8	18.9	12.1	80.2	14.4	353.3	46.7