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Leaf physiognomy records the Miocene intensification of the South Asia Monsoon

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ABSTRACT

Our understanding regarding the onset and development of the modern Asian Monsoon System (AMS) and its component parts, the East Asia (EAM), South Asia (SAM) and Western North Pacific monsoons (WNPM), is still incomplete due to its complex nature and differing views about its relationship with major orographic features such as the Himalaya and Tibetan Plateau. Climate data derived from terrestrial and marine sediments from the Neogene suggests the onset and intensification of the SAM to a near-modern state occurred during the Miocene, while

modelling and terrestrial proxies point to a much earlier origin for the proto-EAM and proto-SAM. Angiosperm leaves, particularly dicot leaves, provide a good indication of prevailing climatic conditions as a result of key adaptations in their leaf structure. Here we use climate leaf analysis multivariate program (CLAMP) in conjunction with general circulation models to decode the Lower (~13–11 Ma) and Middle (9.5–6.8 Ma) Siwalik climate signal inherent in the physiognomy of fossil leaves. The reconstructed climate data indicates that the Middle Siwalik was warmer and wetter than the Lower Siwalik, particularly in the cooler part the year. The leaf physiognomy of Lower and Middle Siwalik assemblages is indistinguishable to that of the modern leaf assemblages, which are influenced by today's SAM climate. This shows that the SAM, was already well established as an independent domain during the late middle Miocene (~13–11 Ma) and has changed only a little from the perspective of leaf adaptations since then. A quantitative monsoon intensity index indicates an intensified monsoon during the late Miocene (9.5–6.8 Ma), a finding replicated by climate modelling.

Key words: CLAMP, dicot leaves, Siwalik, Nepal.

1. Introduction

Globally monsoons climates today encompass the low latitudes and can be subdivided according to their location and individual characteristics into the South Asia Monsoon (SAM), Western North Pacific Monsoon (WNPM), East Asian Monsoon (EAM), Indonesia-Australian Monsoon (I-AM), North American Monsoon (NAmm), South American Monsoon, North African Monsoon and South African Monsoon (Yim et al., 2014; Wang et al., 2017) (Fig. 1). In simple terms, the monsoon is defined by seasonal reversals of surface winds, but these reversals are often

associated with distinct rainy summers and dry winter seasons (Webster et al., 1987; Wang et al., 2017). Of the eight regional monsoons listed previously, those that affect Asia, the SAM, EAM and WNPM (Wang et al., 2017), collectively form the Asia Monsoon System (AMS), which is the largest and strongest monsoon system in existence. The SAM and EAM are continental monsoons, while WNPM is an oceanic monsoon (Wang et al., 2017). Predicting the future characteristics of this AMS is complex (Goswami and Krishnan, 2013; Wang et al., 2015) yet vitally important because the AMS supports the lives and livelihoods of millions of people in Asia (Gadgil and Rupa Kumar, 2006). To better understand the complex behaviour of the modern AMS in the future we have to understand its evolution, and tease out its underlying mechanisms and dynamics in deep time. A range of studies using different approaches have been undertaken to try and understand the evolution of the AMS (Quade et al., 1989; Prell et al., 1992; Zhisheng et al., 2001; Dettman et al., 2001; Barry et al., 2002; Guo et al., 2002; Clift et al., 2008; Boos and Kuang, 2010; Molnar et al., 2010; Huber and Goldner, 2012; Betzler et al., 2016; Retallack et al., 2017; Ding et al., 2017; Spicer et al., 2016, 2017; Srivastava et al., 2018; Farnsworth et al., 2019b). However, our understanding regarding its evolution and the interactions between the SAM, EAM and WNPM is still far from satisfactory due to the absence in deep time of proxies that equate unambiguously to the way the modern AMS is characterised (Spicer et al., 2016). Neogene climate data is mainly derived from geochemical proxies which have inherent diagenetic effects and have never characterised the modern AMS as a separate domain as defined by Yim et al. (2014) and Wang et al. (2017).

The evidence of monsoonal climate in Asia dates back to the Eocene (Licht et al., 2014; Shukla et al., 2014; Spicer et al., 2016, Farnsworth, et al. 2019b),

however, its characteristics and driving mechanisms remain controversial (Licht et al., 2014; Farnsworth et al., 2019b). Recently, Spicer et al. (2017) have inferred on the basis of leaf physiognomy that the Paleogene AMS has the characteristics of the Indonesia-Australia monsoon (I-Am) type (confirmed by modelling approaches (Farnsworth, et al. 2019b) and is not typical of the modern AMS. They also inferred that the typical SAM probably evolved as a distinct entity by the late Oligocene. The SAM is tropical in nature and is located south of the Tibetan Plateau, while EAM is subtropical and located east of the Tibetan Plateau. Generally, the SAM is characterised by annual reversal of both zonal and cross equatorial winds, while the EAM is characterised by an annual reversal of the meridional winds (Wang et al., 2017) (Fig. 1).

For the development of an Asian monsoon system, particularly the SAM and EAM, the role of the Tibetan Plateau and Himalaya cannot be ignored as they influence the Asian monsoon directly and indirectly (Ding et al., 2017; Zhang et al., 2018, Farnsworth, et al. 2019b) through mechanical and thermal forcing. Mechanical forcing relates to the physical deflection of air flows by orographic features, which thermal forcing is that produced by temperature contrasts. Recent climate modelling studies have revealed that latitudinal position, along with the relief of the Himalaya and Tibetan Plateau is important in shaping the modern SAM (Zhang et al., 2018). Observation and climate modelling studies have revealed that the Himalaya play a key role in insulating warm and moist near tropical air from the cool and dry extra tropical air (Boos and Kuang, 2010, Farnsworth, et al. 2019b) and the main heat source for generating this monsoon circulation is located in the non-elevated part of northern India (Molnar et al., 2010; Boos and Kuang, 2013). Moreover, a recent climate modelling study has inferred that a monsoon circulation pattern would still

exist, though not having the characteristic of present SAM, in the absence of any topography in south Asia (Acosta and Huber, 2020).

Despite inherent ambiguities, available proxy evidence indicates an intensification of SAM took place at ~8 Ma and this has been linked with the uplift of the Himalaya (Quade et al., 1989; Prell et al., 1992; Zhisheng et al., 2001; Dettman et al., 2001; Barry et al., 2002; Guo et al., 2002; Clift et al., 2008; Betzler et al., 2016; Srivastava et al., 2018) and tectonic modification of Indian Ocean gateway (Bialik et al., 2019) during the middle–late Miocene. Unfortunately these studies failed to appreciate the presence of a high (> 4.5 km) mountain range, the Gangdese Arc, that was in existence along the southern edge of what is now the Tibetan Plateau for most of the Cenozoic, and predates the rise of the Himalaya (Ding et al 2014, 2017; Spicer et al., 2020). Long before 8 Ma this significant E-W trending orographic high feature must have imposed similar mechanical and thermal forcing to those attributed to today's Himalaya.

In plants, leaves are directly exposed to, and interact with, their external environment and due to this their morphological traits are especially well 'tuned' through natural selection to deliver maximum photosynthetic gain with minimum economic loss (Givnish, 1984, Bloom et al., 1985). This adaptation of leaf physiognomy (morphological traits) is particularly well expressed in woody dicots and makes them reflective of their prevailing environment and so can be used to distinguish between different monsoon characteristics (Spicer et al., 2016, 2017).

In addition to plant sensitivity to climate the Siwaliks, lying as they do along the base of the Himalaya where northward moving summer air is blocked and forced upwards, are particularly exposed to any changes in the SAM. Plant fossils entombed within Siwalik sediments should, therefore, be capable of recording quite

subtle changes in monsoon behaviour. In this study, we use Miocene leaf physiognomy, recovered from the Siwalik sediments of Nepal (Fig. 2), to decode the climate signal inherent in the preserved leaf morphological traits to answer the following questions:

1. Is an Asian monsoon signature present in Miocene leaf physiognomy along the southern margin of the Himalaya?
2. Did SAM monsoon domain exist as an identifiable entity during the Miocene?
3. Can leaf physiognomy detect and quantify the purported Miocene monsoon intensification?

2. Materials and methods

2.1. Brief geological overview of the studied area

The rise of the Himalaya caused the deposition of fluvial muds, sands, and gravels in the Himalayan foredeep between the Lesser Himalaya in the north and the Gangetic Plains in the south, achieving a thickness of ~6 km. The deposited sediments are termed as Siwalik Group and are now being uplifted themselves as deformation migrates southwards (Ding et al., 2017; Lavé and Avouac, 2000). These sediments have been deposited in a coarsening upward succession since the middle Miocene and extend from Sindh of Pakistan in the west to Arunachal Pradesh in the east (Fig. 2). The Siwalik Group is further sub-divided into three sub-groups based on sediment grain size: mudstone-dominates the Lower, sandstone-dominates the Middle, while conglomerates make up the Upper Siwalik succession (Pilgrim, 1910). In western Nepal, a nearly complete section of ~5500 m of Siwalik sediments is exposed along the Mahendra Highway and the Surai Khola River revealing of all three subgroups, the upper Lower Siwalik, the Middle Siwalik and the uppermost part

of the Upper Siwalik where strata strike WNW to ESE and dip 60°–80° to the north. This complete Siwalik section is popularly termed the Surai Khola section, which is bounded by the Rangsing Khola Thrust (RKT) to the north and the Himalayan Frontal Thrust (HFT) to the south (Fig. 3A). The Siwalik section repeats above the RKT and extends up to the Main Boundary Thrust (MBT).

The Surai Khola section has been studied intensively regarding its geology, lithostratigraphy, palaeontology, facies compositions, isotopic signatures, magnetostratigraphic characteristics, palynology and petrography (Corvinus, 1988, 1990, 1993a, b, 1994; Appel et al., 1991; Corvinus and Nanda, 1994; Corvinus and Schleich, 1994; Rösler and Appel, 1998; Nakayama and Ulak, 1999; Hoorn et al., 2000; Corvinus and Rimal, 2001; Sanyal et al., 2005b; Ojha et al., 2009; Baral et al., 2016). The section has been divided into five formations, namely Bankas (Lower Siwalik), Chor Khola (Middle Siwalik), Surai Khola (mostly to Middle Siwalik), Dobatta, and Dhan Khola (boulder conglomerate) (Corvinus, 1990) (Fig. 3A, B). The sediments of the Bankas Formation were deposited under a low energy floodplain regime of rivers, ponds and swamps, and are dominantly composed of argillaceous material. This formation is characterised by mottled claystones and siltstones with distinct purple and red-brown colours, as well as well-bedded sandstones.

The Bankas Formation is overlain by the Chor Khola Formation, which consists of alternations of mudstones, shales, and sandstones. The mudstones, which are grey and yellow coloured, are intercalated with fine-grained sandstones that become more frequent in the upper part of the formation. These mudstones and sandstones bear the fossiliferous shales.

The Chor Khola Formation is overlain by the Surai Khola Formation, which is composed of coarse grained, multi-storied 'salt and pepper' coloured sandstones,

deposited by a wide, braided river system. This formation signals increased fluvial energy evidenced by the presence of large mud clasts in the sandstones that during flood conditions, flushed overbank debris into the sand bars.

The Dobatta Formation overlies the Surai Khola Formation and is characterised by a quieter fluvial regime. The Dhan Khola Formation lies at the top of the succession and is characterised by conglomerates composed of pebble and cobble-sized quartzite evidencing extremely high-energy river flow (Fig. 3 B).

2.2. The fossil flora and age of the Surai Khola section, Nepal

The dicot leaf fossils used in this study were excavated from the Bankas and Chor Khola formations within the Surai Khola section in western Nepal (Fig. 2; 27.8° N; 82.9° E, 730 m a.s.l.). The systematics of these fossils have already been published by Awasthi and Prasad (1990), Prasad and Awasthi (1996), Prasad and Pandey (2008). Sanyal et al. (2005a) conducted a magnetostratigraphic study of the Surai Khola section and suggested that the sediments of the Bankas Formation (BF) (Lower Siwalik) were deposited around ~13–11 Ma (late middle Miocene), while the sediments of the Chor Khola Formation (CKH) (Middle Siwalik) were deposited between 9.5–6.8 Ma (late Miocene). In this study, we use 25 and 30 dicot leaf morphotypes recovered from the Bankas (Lower Siwalik) and Chor Khola (Middle Siwalik) formations, respectively. Some of the representative fossil leaf morphotypes are shown in Figs. 3 and 4.

2.3. Methodology

The present study uses the CLAMP (Climate-Leaf Analysis Multivariate Program) methodology (Wolfe, 1993; Yang et al., 2015; <http://clamp.ibcas.ac.cn>) which

exploits the relationship between leaf morphological traits and their prevailing climate. The methodology is robust and immune to diagenetic effects and is taxonomically independent. CLAMP utilises a minimum of 20 woody dicot leaf morphotypes (species) for each site or assemblage scored using 31 numerically scored morphological traits (Table 1) following the protocols given on CLAMP website (<http://clamp.ibcas.ac.cn>). Woody dicot leaves are directly exposed to the atmosphere, and thus prevailing local climatic conditions, and possess adaptations that maximise primary productivity for minimum economic loss incurred by transpiration, respiration and structural investment. The CLAMP technique utilises a multivariate statistical engine (canonical correspondent analysis - CCA) calibrated using data sets from modern vegetation growing under a wide range of climates to decode ancient climatic signals preserved in fossil leaf physiognomy (Spicer et al., 2016, 2017).

For quantitative reconstruction of the Siwalik palaeoclimate we use the PhysgAsia2 calibration that for palaeoaltimetry in Asia has been validated against oxygen isotopes (Currie et al., 2005; Khan et al., 2014; Polissar et al., 2009; Spicer et al., 2003) showing skill and because it contains data from modern vegetation exposed to the Asian monsoons (Srivastava et al., 2012; Khan et al., 2014). In this analysis, we employ a recently introduced high resolution climate-related calibration file (WorldClim2_GridMet_Asia2_24var) based on high spatial resolution (~1 km²) WorldClim2 (Fick and Hijmans, 2017) observed at the same location as in the PhysgAsia2 dataset (Suppl. file). The Siwalik fossil leaf assemblages were positioned passively within the CLAMP physiognomic calibration space defined by these calibration sets to estimate 23 palaeoclimatic variables that show good correlation with the leaf physiognomy (Supplementary material 3). The 23

palaeoclimate variables reconstructed by the CLAMP are mean annual temperature (MAT), cold month mean temperature (CMMT), warm month mean temperature (WMMT), length of the growing season (LGS), growing season precipitation (GSP), mean monthly growing season precipitation (MMGSP), precipitation during the three wettest months (3-WET), precipitation during the three driest months (3-DRY), relative humidity (RH.ANN), specific humidity (SH.ANN), enthalpy (ENTH), minimum temperature of the warmest month (MIN_T_W), maximum temperature of the coldest month (MAX_T_C), mean annual vapour pressure deficit (VPD.ANN), mean summer vapour pressure deficit (VPD.SUM), mean winter vapour pressure deficit (VPD.WIN), mean spring vapour pressure deficit (VPD.SPR), mean autumn vapour pressure deficit (VPD.AUT), potential evapotranspiration (PET.ANN), mean month PET of the warmest quarter (PET.WARM), mean monthly PET of the coldest quarter (PET.COLD), growing degree days > 0°C (GDD_2) and growing degree days > 5°C (GDD_3). To detect the type of monsoon characteristics encoded by the fossil leaves we have coded the modern vegetation sites according to their monsoon type (Fig. 7).

2.4. General circulation model simulations

To investigate spatio-temporal monsoon evolution during the late-to-middle-Miocene we employ a General Circulation Model (GCM) to reconstruct the monsoon signature in the Siwalik region. We utilise HadCM3BL-M2.1aD (Valdes et al., 2017), a fully coupled ocean-atmosphere GCM with dynamic vegetation comprising a 3.75 x 2.5 latitude by longitude spatial grid with 19 vertical levels in the atmosphere and 20 vertical levels in the ocean. HadCM3BL-M2.1aD is part of the HadCM3 family of climate models, and a primary model of the IPCC AR3-5 experiments that has

shown spatio-temporal skill in reproducing the observed Asian monsoon (Sperber et al., 2013) and paleo-monsoon (Farnsworth et al., 2019b), so providing confidence in its thermodynamic and hydrologic response to perturbed forcing.

Model boundary conditions (topography, bathymetry and ice sheet configurations; at 0.5 x 0.5° resolution and downscaled to model resolution) for each geologic stage relevant here, Serrevallian (~13 Ma), Tortonian (~9 Ma) and Messinian (~6 Ma), are provided by Getech Plc.. Stage-specific solar luminosity is calculated using the methods of Gough (1981). Atmospheric CO₂ concentrations are prescribed at 400ppm, within the range purported by Foster et al. (2017).

Each simulation is run for 10,422 model years to allow surface and deep ocean equilibrium, as well as no net energy imbalance at the top of the atmosphere. Climate means are calculated from the last 100-years of each simulation. Time varying latitude and longitude plate paleo-rotations are provided for the Siwalik site to allow for accurate comparison within the model. For more information of model setup see, Farnsworth et al. (2019a) and Lunt et al. (2016).

3. Results

3.1. Leaf physiognomy spectra of the Bankas and Chor Khola formations

The whole assemblage foliar spectrum percentage scores for 31 leaf morphological traits of the Bankas and Chor Khola formations are presented in Table 1. Fossil leaves invariably suffer from incomplete preservation, so to determine if the climate signal is likely to be compromised by the absence of data we incorporate a 'completeness statistic' ranging from 0 (not data) to 1 (all traits present for all taxa) in the scoring. The completeness for the Bankas Formation assemblages is 0.80, which is above the minimum of 0.66 required for a reliable analysis. In the Bankas

Formation, the most dominant characters are an elliptic shape represented by 100% of taxa followed by no teeth in 96% of taxa, an acute apex in 77.77% of taxa and an acute base in of 70.83% taxa. Some of the leaf traits which are absent in the assemblage are lobed lamina, regular, round and compound teeth, nanophyll, leptophyll 2 and microphyll 1 size categories, emarginate and round apices, cordate bases and obovate and ovate laminae (Fig. 6).

In the Chor Khola Formation had a completeness statistic of 0.83. The most dominant characters are no teeth (96.66% of taxa) followed by attenuate apex in 92.85% taxa, elliptic shape in 90% taxa and acute base in 72.41% taxa. The leaf traits that are absent are lobed laminae, close, acute and compound teeth, nanophyll, leptophyll 1, leptophyll 2, microphyll 1 size categories, emarginate and acute apices, cordate bases, L:W <1:1 and ovate shape (Fig. 6).

3.2. *Leaf physiognomy and monsoon climates*

The CCA plots are shown in Fig. 7 (A–C). In the physiognomic space defined by the global dataset (Yang et al., 2015), the modern vegetation sites are positioned according to their characteristic physiognomy (Fig. 7 A–C). In this analysis, we have highlighted those sites mainly influenced by the AMS covering all the three sub-systems (SAM, EAM and WNPM) following Wang and Ho (2002), North American monsoon following Adams and Comrie (1997) and Anderson et al. (2000), as well as sites in non-monsoonal climates.

In the CCA axes 1–2 plot (Fig. 7A), the modern vegetation sites segregate according to their prevailing monsoon and non-monsoon domains such as NAmM, SAM, EAM, WNPM, and NM (no monsoon). The fossil sites (red filled circles) are positioned in the domain of AMS and not in or near the domains of NAmM and NM.

This directly indicates that fossils have similar physiognomic characters to those of the modern sites influenced by the AMS. In the CCA axes 1–3 plot (Fig. 7B), the modern sites again segregate into different domains with little overlap, in this perspective the two fossil sites are placed repeatedly in the monsoonal domain of AMS and NAmM. This again shows that the fossil sites have characters of monsoonal climates. In the CCA axes 2–3 plot (Fig. 7C), the modern vegetation once again group themselves as separate domains of the AMS, NAmM and NM. The two fossil sites are clearly placed in the AMS domain suggesting that the fossils as viewed in axes 1-3 space have similar physiognomic characters as found in modern Asian vegetation influenced by the AMS.

3.3. Quantitative palaeoclimate reconstruction of the Bankas and Chor Khola formations derived by CLAMP

For the Bankas Formation, the results indicate a sub-tropical (warm) type of climate having temperature 14.7 ± 3.54 °C in the cooler part of the year, while the MAP is 212.81 ± 64.25 cm. The seasonal rainfall indicates a seasonality between the wettest and driest months whose ratio is 6.5:1 suggesting a monsoonal type of rainfall. Spring (MAM) is the driest, while summer (JJA) is the wettest based on VPD, so is the same pattern as today. PET is highest in the wet summer because of the heat/higher winds associated with convective systems. For the Bankas assemblage, the monsoon intensity index (MSI) as defined by Xing et al. (2012) indicates a value of 41.74% (Table 2)..

In the Chor Khola Formation, the climate was tropical having temperature 18.9 ± 3.54 °C during the cooler part of the year, while the MAP was 232.41 ± 64.25 cm with strong seasonality between the wettest and driest months, with the drier season

getting drier and the wetter season wetter (ignoring uncertainties). The 3WET: 3DRY is now increased to 7:1 indicating a stronger monsoon than the Bankas Formation. VPD is also lower than the Bankas (more humid). Summer is more humid than during Bankas time based on VPD, but spring is still the driest season. PET is again higher in the wet summer because of the heat/higher winds associated with convective systems. In Chor Khola, the MSI indicates a value of 44.56% (Table 2).

3.4. Quantitative palaeoclimate reconstruction derived by GCM

The GCM-derived estimation indicates a nearly tropical climate for all the three time slices namely, Serravallian, Tortonian and Messinian. The length of the growing season again supports the near-tropical climate. The MAP is higher in the Serravallian than the Tortonian and Messinian. All the three reconstructed time slices indicate a strong seasonality in 3-WET and 3-DRY seasons and have ratio higher than the 6:1 indicating a monsoonal type of climate. PET is again higher in the wet summer because of the heat/higher winds associated with convective systems (Table 2).

4. Discussion

4.1. Leaf physiognomy and climate during Bankas and Chor Khola deposition

We have already stated that leaf morphological traits are strongly correlated with their prevailing climatic conditions and this correlation is independent of taxonomic affinity, which makes the CLAMP methodology robust for estimating deep time climates (Wolfe, 1993; Yang et al., 2015; Spicer et al., 2016, 2017). The similarity of leaf physiognomy between the Bankas and Chor Khola formations reveals the overall similarity of their environmental conditions - a humid warm monsoonal climate

(table 2). Some of the physiognomic features which are dominant and present in both the formations occur in nearly the same proportions. These are: no teeth, mesophyll 1, acute base, L:W 2-3:1 and elliptic shape. The dominance of entire margins (no teeth) in both the assemblages is typical for warm climates. The elliptic shape of the lamina in association with a length to width ratio of 2-3:1 indicates the occurrence of a tropical climate with high humidity and good moisture supply. The acute base is the result of rapid lamina growth of the leaf and is also a characteristic feature of tropical climates having warm and humid conditions (Wolfe, 1993). The most important and dominant leaf morphological trait exclusively present in the Chor Khola Formation is the attenuate apex (Table 1). The attenuate apex is associated with areas of high rainfall and is an adaptation to drain a leaf rapidly, primarily to prevent fungal growth in humid climate (Wolfe, 1993). Therefore, the dominance of attenuate apex (92.85%) in the Chor Khola Formation indicates a high rainfall regime in contrast to the Bankas Formation where this character is represented by only 22.22% taxa (Table 1).

4.2. Quantitative palaeoclimate data derived from leaf physiognomy of Bankas and Chor Khola formations

4.2.1. Thermal regime

The estimated climate derived from leaf physiognomy indicates an increasing warming in MAT and CMMT, while the WMMT remains the same in both Bankas and Chor Khola formations (Table 2). This may be due to the fact that at close to 28°C the polynomial four-dimensional regression used to predict the WMMT arches over, so any change in the WMMT vector score will not give a meaningful difference in

predicted WMMT. The significant increase of 4.2°C in temperature during the cooler part of the year suggests that the Chor Khola climate was warmer and had less temperature seasonality than the Bankas. A similar finding was also evident in previous reconstructions based on the Coexistence Approach methodology, which relies on the fossil taxa possessing the same relationship with climate as their nearest living relatives (Srivastava et al., 2018), as well as in previous modelling (Wu et al., 2014). The Chor Khola depositional interval had a warmer winter climate and was accompanied by more open vegetation, as evidenced by the dominance of deciduous taxa in contrast to the Bankas fossil flora where evergreen taxa were dominant and likely formed a closed canopy of wet evergreen forest year-round (Srivastava et al., 2018). The minimum temperature of the warmest month (minTempW_1) and maximum temperature of the coldest month (maxTempC_1) also show the similar trend as shown by the WMMT and CMMT (Table 2).

4.2.2. Rainfall regime

The rainfall estimation derived from leaf physiognomy indicates a higher MAP in the Chor Khola time i.e. 232.41 ± 64.25 cm than Bankas time where rainfall is 212.81 ± 64.25 cm, but when uncertainties are taken into account the difference may not be real. The results also indicate that the summer rainfall experienced by the Chor Khola palaeovegetation was likely higher (120.94 ± 40.03 cm) than that experienced by the Bankas vegetation (104.91 ± 40.03 cm), but again note the large uncertainties. Rainfall during the dry season was nearly the same in both the formations (Table 2). This indicates that a strong seasonality of rainy summer and dry winter seasons was present during the deposition of the Bankas and Chor Khola

formations though the rainfall seasonality was likely more during deposition of the Chor Khola Formation, although the uncertainties for each overlap..

The most reliable indicators of humidity are the specific humidity (SH) and vapour pressure deficit (VPD) which are independent of the temperature. The SH refers to the amount of water in grams present within a kilogram of dry air and is a measure of absolute water content of the air. The VPD is a measure of the pressure exerted by moisture in a parcel of air relative to what it would be if that air parcel was saturated with water. Low VPD suggests that the airmass is close to saturation and thus resists transpirational loss of water from plants and thus is a measure of plant susceptibility to heat stress. The estimated data of SH indicates that the airmass dominating the Chor Khola palaeovegetation bears marginally more water vapour than that of the Bankas palaeovegetation and this is most likely due to the higher wet season rainfall. This conclusion is supported by the summer VPD which is markedly lower for Chor Khola (4.89 ± 3.49 hPa) than Bankas (VPD.sum 9.484 ± 3.49 hPa), and confirms the wet season, like now, was in the summer and supports the higher overall rainfall estimate for Chor Khola time.

Spring VPD (VPD.spr) is nearly the same for both the formations and has higher values (10.32 to 10.67 with an error of ± 3.95) suggesting a high moisture stress environment in the pre-monsoon season as in the modern-day climate of the fossil localities (Table 2). The VPD.win also has same values in both the formations but is lower than the VPD.spr and this is most likely due to the presence of moisture brought by the Westerlies and residual moisture from the previous summer and autumn (Table 2).

PET, like VPD, defines the ability of the atmosphere to remove water from a surface and combines the effect of temperature and wind and also indicates the

ease with which transpiration can take place. A low value for PET indicates a wet regime. The lower value of PETWarm derived from the Chor Khola fossils again indicates high rainfall in the warm season as compared to the higher value of PETWarm derived from the Bankas Formation fossils (Table 2). During the cold season evapotranspirational stress is higher in Chor Khola time (94.56 ± 13.83 mm/day) than for Bankas (75.14 ± 13.83 mm/day), in part probably due to the warmer temperatures.

The overall hydrological regime indicates the presence of higher rainfall and greater rainfall seasonality in the Chor Khola time than during the period of Bankas Formation deposition. Although the CLAMP rainfall uncertainties overlap this conclusion is supported by the other more precise humidity metrics and a result obtained by the Co-existence Approach (Srivastava et al., 2018).

4.2.3. Leaf physiognomy, monsoon signature and tectonics of the Himalaya

Previous biotic and abiotic proxies from both marine and land sediments have tried to decode the existence of the Asian monsoon during the Neogene, but they have provided only indirect and incomplete evidence such as increased rainfall seasonality, increased aridity, the presence of summer monsoon winds or increased precipitation, but none of them have neither quantified nor characterised the presence of AMS as an independent domain as defined by the Yim et al. (2014) and Wang et al. (2017). Climate modelling has played an important role in exploring the significance of major orography (the Himalaya and Tibetan Plateau) in influencing the characteristics of the SAM (e.g. Boos and Kuang, 2010, 2013). The inferences derived from it are complemented by a recent climate modelling study (Acosta and Huber, 2020).

Leaf morphological traits of evergreen taxa must have characters that confer functional efficiency in all the seasons throughout the year. In deciduous taxa traits have to confer functional efficiency during the growth period, but even then adaptations expressed during leaf expansion can provide insights into environmental conditions during the period of dormancy (Spicer et al., 2004). Overall, woody dicot leaf morphological traits represent adaptations to the prevailing local long-term climate conditions. For leaves exposed to monsoon climates the seasonal environmental fluctuations tend to be extreme, varying from water-saturated to desiccating, and such leaves display highly characteristic trait spectra specific to different monsoon types. CLAMP is robust in segregating both modern and ancient vegetation influenced by different monsoonal and non-monsoonal climates (Spicer et al., 2016, 2017).

We have utilised this methodology to decode the monsoon signature inherent in the fossil leaves of the Chor Khola and Bankas formations. We categorise modern vegetation sites into those influenced either by the SAM, EAM, WNPM and NAMM, and no monsoon (Fig. 7A–C). In axis 1–2 space (Fig. 7A) the modern vegetation sites segregate clearly into two main monsoon domains, namely AMS domain (positive vector scores on axis 2) consisting of SAM sites (light pink shading) EAM sites (light pink and dark pink shading) and WNPM sites (purple shading), a NAMM domain generally with negative axis 2 vector scores, and an intermediate domain occupied by vegetation exposed to non-monsoonal climates. Note that our two Siwalik leaf fossil assemblages from the Bankas and Chor Khola formations are positioned well within the AMS domain (Fig.7A) in the light pink shaded area characterized by SAM sites and some EAM (warmer) sites, and quite separate from the NAMM and non-monsoonal domains. In the CCA axes1–3 plot (Fig. 7B), again

the two sites are positioned within the AMS domain but appear to have some mixing with the NAmM. However, in the CCA axes 2–3 plot (Fig. 7C), it is clear that this is a perspective artefact and that the two fossil assemblages are within the AMS domain, and more specifically they are closely allied to the SAM group admixed with EAM sites from southern China. This indicates that fossil assemblages exhibit leaf trait spectra typical of modern continental Asian monsoon climates, not those of the oceanic monsoon, and the trait spectra are most similar to those of the modern SAM and warmer, wetter EAM sites.

CCA plot 1–3 (Fig. 7A–C) indicate that the modern vegetation sites representing the SAM are tightly clumped and less scattered than those of the NAmM, EAM and WNPM. With the available data this suggests quite specific leaf trait adaptations to the strong modern SAM. Moreover, some of the forest sites of EAM are intermixed within the cloud of SAM suggesting a similar adaptations among some sites of the EAM. Closer inspection shows that these EAM sites are those in southern and southwestern China, including where the SAM and EAM interact. The same CCA plot for axes 1–2 with climatic vectors indicates that overlapping sites of SAM and EAM are strongly influenced by the summer monsoon rainfall (Supplementary CCA plot 1–3). In all the CCA plots (Fig. 7A–C), the Bankas fossil assemblage is exclusively positioned closest to the SAM sites, while the Chor Khola fossil assemblage is positioned nearer where the SAM and EAM overlap. This directly indicates that the Bankas fossil leaf assemblage has similar physiognomic characters as found in the modern vegetation sites mainly influenced by the SAM suggesting that the modern SAM, or something very similar to it, was already well established during the late middle Miocene (~13–11 Ma). This inference is also supported by the previous studies from the terrestrial and marine archives (Zaleha,

1997; Clift and Gaedicke, 2002; Clift et al., 2008; Gupta et al., 2015; Betzler et al., 2016). Moreover, the Chor Khola fossil assemblage is positioned near the overlapping sites of SAM and EAM which are strongly influenced by the summer monsoon rainfall (X3WET) (Supplementary CCA plot 1–3) indicating the presence of an intensified summer monsoon during the late Miocene (9.5–6.8 Ma). The dominance of an attenuate apex (92.85%) in the Chor khola leaf fossil assemblage again supports a high rainfall regime (section 4.1, Table 1).

Our climate model simulations for three geological time slices, the Serravallian (12.6 Ma), Tortonian (~9.4 Ma) and Messinian (~6.25 Ma), also indicate the presence of the AMS since at least the late middle Miocene (Fig. 7D–F). However, the model indicates an opposing trend with increasing temperature and precipitation and decreasing seasonality (monsoon strength) from the middle-to-late Miocene. As $p\text{CO}_2$ does not vary between each stage-specific simulation its influence might be masked from a decreasing trend from the Middle Miocene Climatic Optimum (MMCO) towards the late Miocene. Likewise, topographic features at the local scale in the Siwalik region may not be well represented within the model due to model resolution constraints. Further sensitivity analysis is required to fully understand this behaviour.

Previous climate modelling studies have revealed that major Asian orographic features (Himalaya and Tibetan Plateau) are important in modulating the modern (Boos and Kuang, 2010, 2013; Zhang et al., 2018) and ancient AMS (Farnsworth et al., 2019b). A recent climate modelling study argues that Asian orographic features are important in shaping the characteristic AMS circulation pattern (Acosta and Huber, 2020), but that even in the absence of relief Asia would experience a distinct monsoon caused by its unique size, position and land-sea contrasts. Spicer et al.

(2016, 2017) suggested that Paleogene leaf fossil assemblages across India and China primarily show the characteristic features of the Indo-Australian type of monsoon (I-AM), which is independent of topography. Only one late Oligocene fossil assemblage from India exhibited some characteristics of the SAM (Srivastava et al., 2012). A combination of inferences drawn from CLAMP studies based on the Paleogene (Spicer et al., 2016, 2017), and the Miocene assemblages investigated here, indicates that the characteristics of modern SAM emerged late in the Paleogene and by the mid Miocene the SAM along the central southern margin of the Himalaya was very similar to that experienced in that area today. To examine if the spatial extent of this early SAM was similar to that of today requires further study along the entire length of the Siwaliks and further afield. For instance, both Farnsworth, et al. (2019b) and Acosta and Huber (2020) have underpinned the importance of the Iranian plateau as a primary gate keeper to sustaining warm, moist tropical air in the AMS from that of cool, dry northerlies that would destabilise the monsoon. Variations in its height and extent are still relatively unconstrained throughout the Miocene and could be an important factor in sensitive regions such as the Siwaliks and should be a area of future investigation.

The collision of Indian and Eurasian plates resulted in the onset of the rise of the Himalaya, and this had begun by the early Eocene (Ding et al., 2017). However, major rapid uplift only began the early Miocene when the northern part of the Indian Plate broke off throughout its length along the Main Central Thrust (MCT) in the south and the Trans-Himadri Fault in the north (Valdiya, 2002). This likely resulted in rapid surface rebound. Ongoing compression gave rise the thrusting up of the basement complex along the MCT as inferred from fission track dating of apatites and zircons, along with $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende ages and U-P zircon and Th-Ph

monazite ages from the granites of different parts of the Greater Himalaya (Daniel et al., 1987; Hubbard and Harrison, 1989; Metcalfe, 1993; Sorkhabi et al., 1993; Noble and Searle, 1995; Harrison et al., 1997). These data constrain the thrust movements to have taken place between 25–21 Ma, mostly between 23–22 Ma (Valdiya, 2002). Moreover, monazite from mylonitic migmatite schist of the MCT zone in Nepal indicates metamorphism beginning at 22 Ma and ending at 18 Ma (Coleman, 1998).

As the Himalaya grew the Himalayan foredeep developed, within which the Siwalik sediments accumulated. The complete absence of heavy minerals indicative of metamorphics in the pre-Siwalik succession (Dharmasala-Dumri) reveals that until the early Miocene the Greater Himalaya underwent minimal erosion (Valdiya, 2002). The early Miocene Qiabulin flora (21–19 Ma) from just south of the Yarlung-Tsangpo Suture Zone in the central Himalaya yielded an elevation of ~2.3 km, but by 19 Ma the Qiabulin area had risen to above 4 km (Ding et al., 2017). As the Lesser Himalaya rose along the Main Boundary Thrust (MBT) to the south of the Greater Himalaya this loading created even more accommodation space within the Siwalik basin.

The magnetostratigraphy of the Siwalik basin from Potwar (Pakistan), Jammu, Himachal Pradesh and Arunachal Pradesh (NE India and eastern Nepal) constrains the Lower, Middle and Upper Siwalik succession to be 18.3 Ma, 11 Ma, 5.3 Ma and 0.22 Ma, respectively (Johnson, N.M. et al., 1982; Johnson, G.D. et al., 1983; Tandon et al., 1984; Ranga Rao et al., 1988; Appel et al., 1991; Ranga Rao, 1993; Gautam and Appel, 1994; Sangode et al., 1996; Gautam and Fujiwara, 1999; Chirouze et al., 2012). The sudden appearance of garnet and staurolite in the Lower Siwalik (18.3–11 Ma) suggests the exhumation of low-grade of metamorphic rocks from the Greater Himalaya, and this is corroborated by isotopic data which suggests

that the Mount Everest region was uplifted to ~5000 m by ~15 Ma (Gébelin et al., 2013). Similarly, the presence of kyanite and staurolite, along with epidote in the Middle Siwalik again suggests the uplift and exhumation of the Greater Himalaya (Chaudhri, 1984), which is again corroborated by isotopic data which reveals that the height of the Greater Himalaya at northern part of central Nepal was ~5500 m between 11–9 Ma (Garzzone et al., 2000).

The rate of sedimentation in the Siwalik basin also reveals the uplift history of the Himalaya, but tempered by climate. The rate of deposition varies from sector to sector across the Siwalik basin over the time. Time/thickness measurements indicate that on average it was 10 cm per 1000 year in the Lower Siwalik and 30 cm per 1000 year in the Middle Siwalik of the Potwar Basin, Pakistan (Johnson et al., 1982), 30–40 cm per 1000 years during the Middle Siwalik in Himachal Pradesh, India, and 33 cm per 1000 year in the lower–middle Siwalik of eastern Nepal, peaking at 9–10 Ma when the rate was 48–50 cm per 1000 year (Gautam and Fujiwara, 1999).

All these data from the Himalayan region indicates that the Greater Himalaya attained their modern elevation within the last 15 Ma (Garzzone et al., 2000; Rowley et al., 2001; Saylor et al., 2009), and parts of the Himalaya such as Mount Everest had achieved 5000 m by 15 Ma (Gébelin et al., 2013). This suggests that height of the Himalaya between 15–11 Ma was exceeded that of the Gangdese and sufficient to amplify the monsoonal climate from that produced by the pre-existing Gangdese uplands to something similar to that of the modern SAM. Future high resolution modelling is required to better understand the extent of their relative influences. Further rise of the Greater Himalaya during the late Miocene likely caused the intensification of SAM between 10–6 Ma (Flynn and Jacobs, 1982; Barry et al., 1985, 2002; Quade et al., 1989, 1995; Prell et al., 1992; Harrison et al., 1993; Tanaka,

1997; Hoorn et al., 2000; Dettman et al., 2001; Sanyal et al., 2004).. Along with the high orography of the Himalaya, the closure of Indian Ocean Gateway to the Mediterranean Sea also likely strengthened the SAM during the late Miocene (Bialik et al., 2019).

5. Conclusions

Building on earlier work that showed that a weak SAM-like monsoon was present to the south of the Himalaya in late Oligocene time (Srivastava et al., 2012) fossil leaf physiognomy indicates that adaptations to a near-modern SAM was established during at least the late middle Miocene (~13–11 Ma) in the Siwaliks of Nepal, and that this intensified to become even more like the modern SAM later in the Miocene (9.5–6.8 Ma). These changes coincide with the Himalaya rising to exceed the height of the pre-existing Gangdese mountains, and point to the growth of the Himalaya having a major role in SAM development. GCM simulations of the middle and late Miocene show agreement that a monsoon climate was a persistent feature of the Siwaliks with a monsoon climate already established. However there is disagreement in the intensification of the monsoon climate from the middle Miocene to the late Miocene with the GCM showing a decreasing trend in both monsoon precipitation and temperature. Model disagreement could be systematic of model boundary conditions and/or coarse model resolution relative to that required to simulate the local Siwalik conditions, which could be highly sensitive to the rapidly increasing height of the Himalaya in the middle to late Miocene .

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Legends

Fig. 1. World map showing the approximate eight rectangular domains (NAmm – North American Monsoon, SAmM - South American Monsoon, NAmM – North Africa Monsoon, SAfM – South Africa Monsoon, SAM – South Asia Monsoon, EAM – East Asia Monsoon, WNPM – Western North Pacific Monsoon and I-AM – Indonesia-Australia Monsoon) of regional monsoons (modified after Yim et al., 2014).

Fig. 2. Physiographic map of Asia showing the Surai Khola fossil locality (white circle), Siwalik range, different mountain ranges, Tibetan Plateau and Asian monsoon system circulation pattern.

Fig. 3. Showing geological map and lithology of the studied area. A. Geological map of Surai Khola, Nepal showing different formations (after Corvinus and Rimal, 2001). B. Lithology of the Surai Khola section of Nepal showing different formations and fossil bearing horizons (green leaves) (modified after Corvinus and Rimal, 2001).

Fig. 4. Fossil leaves from Lower Siwalik. A–F. Fossil leaves recovered from the Bankas Formation (~13–11 Ma) showing morphological traits.

Fig. 5. Fossil leaves from the Middle Siwalik. A–F. Fossil leaves excavated from the Chor Khola Formation (9.5–6.8 Ma) showing morphological traits.

Fig. 6. Bar diagram showing leaf morphological traits. The bar diagram showing the percentage score of 31 leaf morphological traits of fossil leaves recovered from the Bankas Formation (Lower Siwalik) and the Chor Khola Formation (Middle Siwalik).

Fig. 7. CCA plots of leaf morphological traits and climate modelling. A–C. CCA plots showing the relationship between leaf morphological traits exhibited by

modern and fossil forests in the physiognomic space according to their prevailing climates in their respective regions. Individual sites are coded according to the legend. Sites are grouped into Asian monsoons (light pink shading, dark pink and purple shading and North American monsoon (blue shading) separated by non-monsoonal sites. Note that there are apparent outliers from these groups depending on axes views. D–F. Climate models of different geological ages showing the summer monsoon area (green) and water body (blue).