Hazra, T., Spicer, R. A., Hazra, M., Mahato, S., Spicer, T. E. V., Bera, S., Valdes, P. J., Farnsworth, A. J., Hughes, A., Yang, J., & Khan, M. (2020). Latest Neogene monsoon of the Chotanagpur Plateau, eastern India, as revealed by fossil leaf architectural signatures. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 545, [109641]. <https://doi.org/10.1016/j.palaeo.2020.109641>

Peer reviewed version

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Link to published version (if available):
[10.1016/j.palaeo.2020.109641](https://doi.org/10.1016/j.palaeo.2020.109641)

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Late Neogene monsoon of the Chotanagpur Plateau, eastern India, as revealed by fossil leaf architectural signatures

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ABSTRACT

A fossil leaf assemblage from late Neogene (Pliocene) sediments exposed in Jharkhand of Chotonagpur Plateau, eastern India, is subjected to a CLAMP (Climate Leaf Analysis Multivariate Program) analysis using a new high spatial resolution ($\sim 1 \text{ km}^2$) WorldClim2 gridded climate data and PhysgAsia2 calibration. The CLAMP analysis of 80 different morphotypes of fossil leaves indicates a mean annual temperature (MAT) of $21.9^\circ\text{C} \pm 2.3^\circ\text{C}$; a cold month mean temperature (CMMT) of $16.7^\circ\text{C} \pm 3.5^\circ\text{C}$ and a warm month mean temperature (WMMT) of $26.9^\circ\text{C} \pm 2.9^\circ\text{C}$. Precipitation estimates have high uncertainties but suggest a weak monsoon with a growing season (11.7 ± 1 months) precipitation (GSP) of $201.2 \pm 64.3 \text{ cm}$. The new calibration also provides for the first time in India more detailed insights into the hydrological regime through the return of annual and seasonal vapour pressure deficit (VPD) and potential evapotranspiration (PET) estimates, as well as new thermal overviews through measures of thermicity and growing degree days. The new results confirm the overall warmth of the region. Although rainfall estimates have large uncertainties due to year-round wet soils, measures of VPD and PET show persistent high humidity, but with higher evaporative stress in the summer during late Neogene times.

Key words: Fossil leaves; CLAMP; WorldClim2; late Neogene; Environmental variables; Precipitation seasonality; Jharkhand

1. Introduction

Over the past few decades, understanding the evolution of the Asian monsoon system and its sensitivity to future climate change has become an increasing attraction for the scientific community (Guo et al., 2008; Boos and Kuang 2010, 2013). Determining the evolution of the present Asian monsoon system is crucial not only for knowledge of monsoon history, but also for understanding the mechanism underlying its variations (Ding et al., 2017). Numerous palaeo-records have contributed greatly to our understanding of the monsoon system. During the Neogene the changing orography and extent of the Himalaya-Tibetan plateau edifice (HTE) likely caused profound changes in the regional climate, and must have influenced, to a greater or lesser extent, the characteristics of the Asian monsoons (Molnar et al., 2010; Zhang, 2015; Spicer, 2017). However, Asian orography was not the only change happening in the Neogene as it was a time of marked global cooling and when aridity in the Asian interior became enhanced.

The Indian or South Asian monsoon is a unique climatic phenomenon characterized by seasonal reversal of winds over the Indian subcontinent and nearby areas of Myanmar and Thailand. In summer strong moisture-laden winds blow from the southwest (Southwest Monsoon or SWM), whereas in winter mostly dry and variable winds blow from the northeast (Northeast Monsoon or NEM), primarily caused by the difference in land-sea temperature and associated pressure conditions. Extensive work has been done using different proxies (leaf fossils; pollen; changes in soil carbonate $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$; variations in palaeosols; $\delta^{18}\text{O}$ trend in shells and mammal teeth; geophysical and geochemical data; sediment flux and vertebrate paleontology) to reconstruct the evolution of the Indian summer monsoon (ISM) during the Neogene (Burbank et al., 1993; Clift and Gaedicke 2002; Sanyal et al., 2004; Clift et al., 2008;

Khan et al., 2014; Srivastava et al., 2018). Being directly exposed to, and processors of, the atmosphere fossil leaf architecture and the composition of palaeovegetation are powerful proxies for past climate. Unlike chemical proxies the palaeoclimatic signature contained within the architecture of leaf fossils is not subjected to diagenetic alteration. Furthermore, pre-depositional transport differences of leaf fossils are usually not more than a few hundred metres (Spicer, 1981; Ferguson, 1985; Spicer and Wolfe, 1987) and leaf fossils cannot be reworked intact into younger sediments meaning that the climate signal is both time and site-specific.

The major plateaus of the Indian peninsula are the Deccan and Karnataka Plateau in South India, the Chotanagpur Plateau in eastern India and Shillong Plateau in northeastern India. The Chotanagpur plateau is the focus of the work presented here. The Chotanagpur Plateau covers an area of around 75000 km² with an average elevation of 600-800 m above mean sea level (MSL). This eastern Indian plateau was elevated during the Cenozoic, continuing through the Quaternary to the Present resulting in numerous geomorphic features including gorges, rapids, rivers, waterfalls etc. The Rajdanda Formation in the Mahuadanr Valley of Chotanagpur Plateau region of Jharkhand state is a fluvially controlled late Neogene sedimentary deposit from where we have collected a large number of well preserved fossil leaves. Today its climate is influenced by the ISM characterized by distinct wet and dry seasons. The unique geographical position, special climate conditions and abundant botanical resources potentially make the Chotanagpur Plateau an important region of eastern India for studying climate change, as well as investigating the evolution of the South Asia monsoon system. However, until now no quantitative assessment of late Cenozoic monsoon climate and corresponding vegetation in the late Neogene period of the Chotanagpur Plateau has been made. Our study fills this gap.

The Neogene is particularly interesting in that it spans a time of global transformation from a greenhouse to an icehouse climate state (Zachos et al., 2001). In addition, since the economy of the Chotanagpur plateau region is greatly dependent on summer monsoon rains, understanding its past and present variability is of immense importance for predicting future monsoon variability. The main focus of the present work is to examine the late Neogene climate of the Chotanagpur Plateau for the first time and introduce new quantitative proxy palaeo-humidity measurements in order to characterize better the environment at times of global warmth. In the present study we also examine the thermal regime of this region in the light of new high spatial resolution (~1 km) WorldClim2 (Fick & Hijmans, 2017; www.worldclim.org/) calibrations for the non-taxonomic leaf physiognomic proxy known as CLAMP (<http://clamp.ibcas.ac.cn>) and explore new insights into the hydrological regime. We examine not only precipitation and soil moisture capacity, but humidity in terms of specific humidity (SH), relative humidity (RH), vapour pressure deficit (VPD) and potential evapotranspiration (PET). VPD and PET are investigated in respect of annual average values and seasonal variations.

2. Physical setting

The Chotanagpur Plateau, covering an area of about 77,096 km² is located entirely within Jharkhand state and is surrounded by hills, valleys, rivers, streams, and forests. It is flanked by the fertile alluvial Middle Ganga plain in the north, Orissa in the south, West Bengal in the east, and Uttar Pradesh and Chhattisgarh in the west. Geologically, the Chotanagpur Plateau is mainly composed of Archean granites and gneisses, with patches of Gondwana and Dharwar sediments. The forests are one of the richest natural resources of the Chotanagpur Plateau. Based on altitude and

rainfall, the forests vary from tropical moist deciduous to dry deciduous. The region experiences a monsoon type of climate with the average annual rainfall ranging from 100-150 cm and the mean annual temperature varies between 20 °C–29 °C.

3. Regional geological setting

Late Neogene (Rajdanda Formation) sediments of Mahuadanr valley in Jharkhand are exposed along the left bank of Birha River along a length of approximately 2.6 km and a width of 1.5 km. The sediments are deposited over the PreCambrian Chotanagpur gneiss basement (Table 1). The different lithologies in the adjoining areas include pyroclastic sediments, conglomerates, sandstones, and shales. The pyroclastic rock consisting of pumiceous rhyodacite is exposed in the southwestern part of Jhumri nala (Puri and Mishra, 1982). In the northwestern part of the Birha River, volcanic sandstone occurs downstream from a road bridge near Rajdanda. Angular fragments of gneisses, amphibolites and feldspars occur in the volcanic sandstone (Puri and Mishra, 1982). The sedimentary succession includes conglomerate at the base, medium to fine-grained ripple laminated sandstone and clayey shale beds. The conglomerates occur in the southeastern and southwestern extremities of the sedimentary outlier. This unit overlies the granite gneiss basement in the Birha river and Rampur Nala whereas in the Jhumri Mahua Nala it overlies the pyroclastic rocks. The sandstone unit with a thickness of about 3 m is exposed near Rajdanda overlying the pyroclastic rocks.

The studied sedimentary section is exposed over a length of about 100 m and extends to a maximum thickness of 5 m in the left bank of Rampur Nala. The lithology in the studied section includes mostly shale and sandstone. The structural dip of the sedimentary beds varies from 2-5° towards NW. The type of shale varies from

arenaceous to clayey. The colour of the clayey shale varies from grey to black whereas the arenaceous variety has a brownish hue. 'Papery shales' with fine millimeter scale laminations also occur frequently. Yellowish brown sandstones occur interbedded between the shale layers and they mostly pinch out and occur as lenses in places. Rounded to elliptical shaped armored mudballs with coated sand grains occur embedded in this sandstone unit. The mudballs are formed from the mudclasts derived from previously deposited clays, which during transportation developed a round shape and a sandy coating. In places flame structures occur where the shale layer protrudes into the overlying sand layer as upwardly pointing fingers or wedges. The upper 0.5 m of the studied sedimentary unit comprised of shale is highly fossiliferous with abundant fossil flora and fauna including angiospermic leaf impressions and compressions, fruit remains, flowers, fossil fish and bird remains. Carbonised wood fragments are also found within the interbedded yellowish sandstone lenses. The excellent preservation of fossil plant and animal remains suggests a reducing condition during the time of deposition. Clusters of euhedral and anhedral pyrite occur within the fossiliferous shale layer also indicate the presence of a reducing lacustrine environment with fluvial incursions (possibly during flood events) that experienced euxinic conditions during deposition (Kumar et al., 2000; Bajpai et al. 2001).

Various workers (Prakash et al., 1987; Bande & Srivastava, 1990; Srivastava & Bande, 1990, 1992; Srivastava et al., 1992; Singh & Prasad, 2007, 2008, 2009a-c, 2010; Singh & Chauhan, 2008) have considered the age of the Rajdanda Formation to be 'late Tertiary' (Pliocene) based on the study of megafossils and palynological analysis. Prakash et al. (1987) suggested a same age of the Rajdanda Formation. They assigned a Pliocene age to these sedimentary deposits based on the presence of fossil

Sindora wood as *Sindora* is an index fossil of Pliocene age (Guleria 1992). The district resource map as published by the Geological Survey of India of Palamau, Jharkhand, also assigns a Pliocene age to the Rajdanda Formation.

4. Materials and methods

4. 1. Fossil leaf assemblage

Numerous well-preserved fossil leaf, flower, seed and fruit remains were collected from the Pliocene Rajdanda Formation in the Mahuadanr Valley (23.3965 °N, 84.1066 °E; altitude 353 m above sea level) within the Chotanagpur Plateau region of Latehar District of Jharkhand, eastern India (Figures 1-8). Here we focus only on the leaf impressions and compressions. The fossiliferous beds are exposed along the bank of Birha River and its tributary Jhumari Nala between Rajdanda and Mahuadanr Village (84.12 °N, 23.412 °E) about 116 km south of Daltenganj in Jharkhand (Figures 1-3). Rocks in and around the fossil localities belong to the Rajdanda Formation (Pliocene), which is lithologically characterized by sandstones, mudstones, shales, and clays (Figures 4, 5). The fossil leaf remains are preserved in compact sandstone and dark-coloured carbonaceous shale (Figures 5, 6). The fossil assemblage is dominated by angiosperms. The recovered well-preserved compression fossils have yielded good cuticular features, the details of which will be published in a separate article.

The fossil leaf remains were recovered by splitting large chunks of the fossiliferous mudstone with the aid of hammers and chisels. After cleaning, macroscopic images of well-preserved angiosperm leaves were photographed using a digital camera (Canon Power Shot A720IS) (Figures 7, 8). A detailed systematic description of this fossil leaf assemblage is in preparation. All the fossil specimens, including holotypes, are

kept at the Herbarium and Museum, Department of Botany, Sidho-Kanho-Birsha University, India (SKBUH).

4.2. Modern flora of Jharkhand

Jharkhand is known for its greenery. Literally the word 'Jharkhand' indicates 'area of land covered with forests'. The total recorded forest area of the state is 23,605 km² which is 29.6% of the state's geographical area. The total forest and tree cover put together constitutes about 33% of the geographical area of the state.

The forest cover of Jharkhand is tropical moist to dry deciduous (Mishra 2013). The detailed forest types of this state of eastern India and its floristic composition are described in Champion and Seth (1968). Northern tropical dry deciduous forests are found throughout Jharkhand where the mean annual temperature varies between 24 °C–27 °C and mean annual rainfall varies between 750 mm–1300 mm. Dry Peninsular Sal forest type is found on shallow soil derived from crystalline and metamorphic rocks. This type of forest is found in districts of East Singhbhum, West Singhbhum, Seraikela, Kharswan and parts of Ranchi and Hazaribag. The dominant species are *Shorea robusta*, *Anogeisus*, *Boswellia*, *Terminalia*, *Pterocarpus*, *Lagerstroemia*, *Diospyros*, *Adina*, *Acacia*, *Buchanania*, *Madhuca* etc. Northern dry mixed deciduous type of forests are dominated by woody trees such as *Acacia*, *Anogeisus*, *Boswellia*, *Bombax*, *Linea*, *Garuga*, *Hymenodictyon*, *Disopyros*, *Madhuca*, *Albizia* etc. Some species form more or less consociation depending on edaphic conditions. Some Examples of edaphic climax associations are: Aegle forest found in the Palamu district on stiff clay alluvial soil with manganese, while dry bamboo brakes occur in dry soil both on the hills as well as on the alluvium of the Palamu region where the dominant species is *Dendracalamus strictus*.

Tropical moist deciduous forest is dominated by moist sal forest. Moist Peninsular Sal forest is dominated by *Shorea robusta*. The other associated species are *Syzigium cumini* with *Dendrocalamus strictus* growing in the mid region, and *Phoenix acualis* is found in the undergrowth. Moist mixed deciduous forest is found in the Singhbhum region of Jharkhand, with dominating species such as *Albizia procera*, *Adina sp*, *Bombax sp*, *Terminalia tomentosa*, *T. belerica*, *Dilenia pentagyna* etc.

4.3. CLAMP analysis

The key leaf physiognomy (architecture) based palaeoclimate proxy for assessing a range of climate variables related to temperature, precipitation and humidity is known as CLAMP (Climate Leaf Analysis Multivariate Program) (<http://clamp.ibcas.ac.cn>) (Wolfe, 1993; Kovach & Spicer, 1996; Yang et al. 2011, 2015). CLAMP, initiated by Wolfe (1990), is a non-taxonomic, robust, accurate and quantitative tool that decodes the climatic signal inherent in leaf physiognomy of woody dicotyledonous flowering plants (Spicer et al., 2003, 2004, 2009; Yang et al., 2011). It exploits the universal relationships that exist between the dicot leaf architecture and an array of environment variables, particularly climate (Yang et al. 2015). In CLAMP, 31 architectural character states encompassing lobing, margin, size, apex, base, length to width ratio and shape and 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 different climate variables related to temperature, humidity, and precipitation using Canonical Correspondence Analysis (CCA) (ter Braak, 1986). This multivariate statistical engine decodes these relationships and, by scoring fossil leaf character traits the same way as for living vegetation growing under known climatic regimes, estimates of past conditions can be obtained.

Our previous CLAMP analyses on Siwalik fossil leaf assemblages of eastern Himalaya (Figure 9) have been based on modern gridded climate observations recorded between 1961 and 1990 at a spatial resolution of $0.16^\circ \times 0.16^\circ$ (New et al. 2002). This calibration dataset is known as HiResGridMetAsia2 (<http://clamp.ibcas.ac.cn>) which is a moderately high spatial resolution modern gridded climate data. Subsequently, Hijmans *et al.* (2005) provided climate surfaces, referred to as the “WorldClim version 1 database”, for global land areas (excluding Antarctica), consisting of long-term average monthly temperature and precipitation. Recently, Fick & Hijmans, 2017 presented a refined and expanded version of this dataset. The new version is referred to as the “WorldClim version 2” (<http://worldclim.org/version2>), a new dataset of spatially interpolated monthly climate data for global land areas at a very high spatial resolution (approximately 1 km²). They included monthly temperature (minimum, maximum and average), precipitation, solar radiation, vapour pressure and wind speed, aggregated across a target temporal range of 1970–2000, using data from between 9,000 and 60,000 weather stations.

One most important advantage of using WorldClim2 for CLAMP calibration is that 24 environmental variables related to temperature, precipitation and humidity, mapped onto the same grid, exhibit strong correlations with leaf form. The previous CLAMP calibration datasets (HiResGridMetAsia2 and WorldClim version 1 database) were limited to eleven climate variables related to mainly temperature and precipitation. Of the thirteen new environmental variables five are temperature related and are: the compensated thermicity index (THERM.), growing degree days above 0 °C (GDD_0), growing degree days above 5 °C (GDD_5), minimum temperature of the warmest month (MIN_T_W) and maximum temperature of the coldest month

(MAX_T_C) (Table 2). The new eight humidity related metrics are: 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), mean annual potential evapotranspiration (PET.ANN), mean monthly potential evapotranspiration during the warmest quarter (PET.WARM), and mean monthly potential evapotranspiration during the coldest quarter (PET.COLD) (Table 4). Precipitation-related climate variables are the same using both HiResGridMetAsia2 and WorldClim2 calibration datasets (Table 3) but due to interpolation and temporal sampling differences the values differ between the two data sets. Tables 2-4 summarize all CLAMP-derived metrics presented here. The 31 leaf physiognomic characters of the 80 morphotypes of fossil leaves from the Jharkhand Pliocene sediments were scored and analysed using standard CLAMP protocols. Supplementary materials (Figure S1–S3) show the structure of CLAMP physiognomic space in the context of the new WorldClim2 calibration. The CLAMP scoresheet for the Jharkhand fossil assemblage is also available as supplementary material (Table S1). The new WorldClim2-based climate training set (WorldClim2_GridMet_Asia2) and the accompanying modern leaf physiognomic (PhylogAsia2 calibration) data files are given in the supplementary materials (Tables S2 and S3 respectively).

5. Results

5.1. Composition of the fossil flora

The late Neogene fossil assemblage recovered from Jharkhand shows that there has been some compositional change since the Pliocene at species level, but the general

character of the vegetation does not alter in that the fossil leaf forms are similar to those typical of modern moist tropical to subtropical forests. The late Neogene fossil flora consists of mainly woody dicot taxa assignable to the following modern genera such as *Lagerstroemia*, *Eucalyptus*, *Dipterocarpus*, *Citrus*, *Woodfordia*, *Albizia*, *Psidium*, *Terminalia*, *Desmodium*, *Acronychia*, *Mangifera*, *Myrtaceae*, *Ficus* etc. collectively indicative of a tropical to subtropical humid environment. In addition, some fossil leaves remain unidentified. A full taxonomic treatment of the Jharkhand Pliocene flora, including formal descriptions of new species, is in preparation. Earlier, various workers (Prakash et al., 1987; Bande & Srivastava, 1990; Srivastava & Bande, 1992; Srivastava et al., 1992; Singh & Prasad, 2007, 2008, 2009a-c, 2010; Singh & Chauhan, 2008) described some fossil taxa comparable to modern *Citrus aurantium*, *Acronychia laurifolia*, *Cassia nodosa*, *Erythrina lithospora*, *Butea frondosa*, *Citrus medica* etc. from the same horizon and suggested that the late Neogene fossil flora of Jharkhand had a tropical to subtropical moist aspect. It is interesting to note that the nearest living relatives of the fossil flora still grow in the vicinity of a tropical to subtropical evergreen-deciduous forests of the Chotanagpur Plateau today. Thus, it is evident that evergreen to moist deciduous forests has flourished since the Pliocene in the Chotanagpur Plateau region and that the climate around this basin was tropical to subtropical during the time of deposition. Determining quantitatively how similar the Pliocene climate was compared to the modern is the main objective of this study.

5.2. CLAMP-derived climate variables and their predicted values

The quantitative estimates for all 24 CLAMP climate parameters derived from the new high spatial resolution WorldClim2_GridMet_Asia2 calibration for the late

Neogene flora of Jharkhand of the Chotonagpur Plateau, eastern India, are given in Tables 2–4. Figures 10–21 illustrate the CLAMP regression models for the new WorldClim2_3br calibration and the position of the Jharkhand fossil site within those regression models. The regression models illustrate the relationship between leaf physiognomy (architecture) and the individual climate variable and thus the precision of the CLAMP predictions. They also indicate the position of the value for fossil assemblage for each climate variable relative to those for modern vegetation. All regression models are derived from the leaf physiognomy (architecture)/climate relationships in four-dimensional space as used in earlier CLAMP analyses (Herman & Spicer, 1996, 1997; Spicer & Herman, 2010). The PhysgASia2 and WorldClim2_GridMet_Asia2 gridded climate data were used to define a CLAMP physiognomic calibration space within which the Jharkhand fossil leaf assemblage was passively positioned (Supplementary materials; Figures S1–S3). Figures 10–17 show, respectively, the regression models for MAT, WMMT, CMMT, GROWSES, MIN_T_W, MAX_T_C, GDD_0, GDD_5, THERM., ENTHAL, GSP, MMGSP, 3-WET, 3-DRY, RH and SH. Regression models for VPD.ANN, VPD.WIN, VPD.SPR, VPD.SUM, VPD.AUT, PET.ANN, PET.WARM and PET.COLD are given in figures 18–21 respectively.

6. Discussion

6.1. Thermal regime

The temperature related climate metrics for late Neogene plant assemblage from the Jharkhand region of Chotonagpur Plateau, eastern India are: MAT, WMMT, CMMT, LGS, THERM., MIN_T_W, MAX_T_C, GDD_0 and GDD_5, (Table 2). The compensated thermicity index (THERM is expressed by following equation: THERM.

$= \{(T + m + M) \times 10\} \pm C$, where $T = \text{MAT}$, $m = \text{MIN_T_W}$, $M = \text{MAX_T_C}$ and C is a 'compensation value'. C depends on continentality, which is simply a measure of the difference between the WMMT and the CMMT. The method for calculating C is given in the Worldwide Bioclimatic Classification System

(www.globalbioclimatics.org) (Rivas-Martinez et al. 1999). This thermicity index equilibrates the large differences in temperature occurring between cold winters and hot summers in continental climates compared to those small differences in oceanic climates in the extratropical zones of the world (northern and southern 27° parallels). The predicted value for THERM. is 521.7 ± 74.8 °C (1 S.D.), while the minimum temperature of the warmest month (MIN_T_W) is 22.7 ± 2.9 °C, the maximum temperature of the coldest month (MAX_T_C) is 22.1 ± 3.5 °C, and the mean annual temperature (MAT) is 21.9 ± 2.3 °C. With a mean annual range of temperature of ~10 °C and warm winters, growth was possible year-round (Table 2).

GDD_5, a measure of the cumulative heat available to plants, is the sum of mean monthly temperature for months with mean temperature >5 °C multiplied by the number of days above that temperature. The estimated values of temperature related CLAMP-derived metrics using the new WorldClim2_GridMet_Asia2 CLAMP calibration confirms the Jharkhand fossil flora represents a thermal regime that may be broadly characterized as 'tropical'.

6.2. Precipitation regime

Table 3 shows the estimated precipitation regime derived from the Jharkhand fossil leaf physiognomy. In general, the wetter the climate the less well leaf physiognomy predicts the precipitation regime (Fig. 16). The regression model shows more scatter

when the precipitation is high (Fig. 15) but, bearing this in mind, the precipitation estimates a growing season (11.7 ± 1 month) precipitation (GSP) of 201.2 ± 64.3 cm. CLAMP also returns estimates for precipitation during the three wettest (3WET) and three driest months (3DRY). Some measure of the ratio between wet and dry season precipitation has become a preferred proxy in palaeoclimate studies aimed at understanding the history of monsoon climates (West et al., 2015). The Jharkhand fossil leaf physiognomy exhibits adaptations to seasonal rainfall; seasonality more marked than that for temperature variation, with the three consecutive wettest months delivering ~4 times the precipitation of the driest three consecutive months. This suggests that the Chotanagpur Plateau region of eastern India experienced a ‘monsoonal’ climate in the late Neogene period, albeit one less marked than at present. 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: $MSI = (3WET - 3DRY) \times 100 / GSP$. Higher MSI values indicate greater differences in precipitation between the wet and dry seasons, and thus a stronger monsoon. The monsoon index (MSI) for the Jharkhand leaf flora is 32.5, while that of the nearby modern Sunderbans vegetation (21.9497 °N, 89.1833 °E) is 56.7.

6.3. Humidity regime

Until recently CLAMP has routinely returned only two humidity measures: mean annual relative humidity (RH.ANN) and mean annual specific humidity (SH.ANN). SH is simply the amount of water in grams contained within a kilogram of dry air and as such is a measure of the absolute water content of the air. Relative humidity is the

ratio of SH to its saturation value at ambient temperature and pressure and is highly temperature dependant. Present day leaf physiognomy appears to code for SH.ANN quite well in that the CLAMP regression model shows relatively little scatter compared to that of RH.ANN (Fig. 17). As the scatter in Figure 17 shows, leaf form does not correlate well with RH, so CLAMP predictions of RH carry a lot of uncertainty.

Another, better, measure of humidity is vapour pressure deficit (VPD). VPD is important for plants in that it reflects the force opposing transpiration. VPD reflects the ease of losing water to the atmosphere and, as such, affects transpiration as well as evaporation. Like SH, VPD is not measured in relation to temperature. It is the difference between the actual water vapour pressure and the water vapour pressure at saturation. At saturation ($VPD = 0$ hPa) water will condense out to form clouds, dew or films of water on surfaces, including leaves. VPD has a simple nearly straight-line relationship to the rate of evapotranspiration and other measures of evaporation.

Because of this, plant distribution (Huffaker, 1942) and leaf physiognomy are more strongly reflective of VPD.ANN than RH. ANN (Figs. 17, 18). This suggests strong leaf trait adaptations are necessary to overcome transpiration depression at low VPDs. VPD also is strongly correlated with stomatal conductance (Oren et al. 1999; Katul et al. 2009). Annual mean VPD (VPD.ANN) as well as seasonal VPD estimates (spring – VPD.SPR; summer – VPD.SUM; autumn – VPD. AUT; and winter – VPD.WIN) are also given by CLAMP. Figures 18, 19 and 20 show that, at low VPD values, leaf form correlates very well with VPD, while in high VPD situations transpiration can take place easily without the need for specific leaf trait spectra to increase transpiration. Thus, there is more scatter in the CLAMP regressions at high VPDs. So, unlike precipitation, CLAMP estimates of VPD in moist regimes are generally more

precise than in dry regimes. High VPD values are found in arid environments while low VPDs reflect air close to saturation and thus a high resistance to transpiration. Table 4 shows that the Jharkhand late Neogene leaf assemblage indicates low VPDs (<7 hPa) in spring, autumn and winter.

Beside VPD, another useful measure of humidity is potential evapotranspiration (PET). PET expresses the ability of the atmosphere to remove water through evapotranspirational processes assuming no limits on plant water supply. PET combines the energy available for evaporation and the capacity of the lower atmosphere to move evaporated water vapour away from the land surface, for example by winds and convective processes. PET is lower on cool cloudy days because there is less solar radiation to provide the energy for evaporation. Like VPD, PET indicates the ease with which transpiration (a process that is essential for moving water and nutrients from the soil to the leaves) can take place. Because of this, and as with VPD, leaf physiognomy correlates well with PET (Figs. 20, 21), particularly at low PET values, i.e. wet regimes. PET estimates for the warmest month (PET.WARM, Fig. 21) and coldest month (PET.COLD, Fig. 21) are given, as well as the mean annual PET (PET.ANN, Fig. 20). Our fossil assemblage falls in the lower half of the regression, showing that it experienced similar PETs to modern vegetation in the more humid half of the training set. The PET.WARM and PET.COLD values also show that any dry season was in the summer, presumably because higher temperatures and convective winds favored greater evaporation.

Our new insights into annual and seasonal atmospheric humidity in the warm late Neogene Jharkhand support the concept of a very humid regime. It appears humidity was high year-round, but with most evaporative stress occurring in the summer. Note that this does not mean that summer rainfall was less than winter, just that evaporative

stress was higher due to higher temperatures. PET never exceeds rainfall even in the summer growth period, leading to year-round moist soils. So, CLAMP analysis suggests that the late Neogene fossil assemblage in Jharkhand on the Chotonagpur Plateau, eastern India experienced a monsoonal tropical to subtropical warm humid climate.

Acknowledgments

TH, MH, SM and MAK gratefully acknowledge the Department of Botany, Sidho-Kanho-Birsha University for providing infrastructural facilities to accomplish this work. RAS and TEVS were supported by NERC/NSFC BETR Project NE/P013805/1. SB acknowledges the Centre of Advanced Study (Phase-VII), Department of Botany, University of Calcutta for providing necessary facilities.

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Table Legends

Table 1. Lithostratigraphic succession of the exposed rocks in the Mahuadanr area of Jharkhand (after Puri and Mishra, 1982)

Table 2. Temperature-related CLAMP-derived metrics, their acronyms, descriptions and units, derived from WorldClim2 gridded data at $\sim 1 \text{ km}^2$ spatial resolution

Table 3. Precipitation and moist enthalpy CLAMP-derived metrics, their acronyms, descriptions and units, derived from WorldClim2 gridded data at $\sim 1 \text{ km}^2$ spatial resolution

Table 4. Humidity-related CLAMP-derived metrics, their acronyms, descriptions and units, derived from WorldClim2 gridded data at $\sim 1 \text{ km}^2$ spatial resolution

Figure Legends

Figure 1. Geological map of Mahuadanr and adjoining areas, Latehar District of Jharkhand (a part of the district resource map of Palamu district, Bihar published under the direction of Director General, Geological Survey of India, Kolkata)

Figure 2. Map showing the fossiliferous locality near Mahuadanr, Latehar District, Jharkhand

Figure 3. Type section from the riverbank exposure showing stratigraphic units

Figure 4. Composite graphic log of 3 m of exposed sedimentary section using software SedLog 3.0 version

Figure 5. Enlarged view of the fossiliferous horizon bearing leaf remains

Figure 6. Field outcrop showing nearly 10m of horizontally bedded strata

Figure 7. A-L: Leaf impressions recovered from the late Tertiary exposures (Rajdanda Formation: Pliocene) in the Mahuadanr Valley of the Chotanagpur Plateau region of Jharkhand, eastern India. 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 8. A-I: Leaf impressions recovered from the Pliocene exposures (Rajdanda Formation) in the Mahuadanr Valley of the Chotanagpur Plateau region of Jharkhand, eastern India. 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)

Figure 9. Physiographic map showing the present fossil locality and previous evidence (¹ & ³Spicer et al., 2014; ²Herman et al., 2017; ^{4, 6} & ⁹Khan et al., 2014; ⁵Khan et al., 2019; ⁷Srivastava et al., 2012; ⁸Yang et al., 2007; ¹⁰Xie et al., 2012; ¹¹Shukla et al., 2014; ¹²Su et al., 2013) of Cenozoic climate change in Southeast Asia using fossil leaf physiognomy (Map source: ArcGIS online)

Figure 10. CLAMP WorldClim2_GridMet_Asia2 regression models for mean annual temperature (MAT) and warm month mean temperature (WMMT). The position of the Jharkhand fossil flora along the second order polynomial regression relating the MAT and WMMT vector scores for modern vegetation against the observed MATs and WMMTs for those sites is shown as red closed circles with uncertainties (1 s.d.)

reflecting the scatter of the residuals about the regression line indicated by the associated bars

Figure 11. CLAMP WorldClim2_GridMet_Asia2 regression models for cold month mean temperature (CMMT) and length of the growing season (temp. >10 °C) (GROWSES). Site and uncertainty represented as in Fig. 10

Figure 12. CLAMP WorldClim2_GridMet_Asia2 regression models for minimum temperature of the warmest month (MIN_T_W) and maximum temperature during the coldest month (MAX_T_C). Site and uncertainty represented as in Fig. 10

Figure 13. CLAMP WorldClim2_GridMet_Asia2 regression models for growing degree days when temperatures are above freezing (GDD_0) and growing degree days when temperatures are above +5 °C (GDD_5). Site and uncertainty represented as in Fig. 10

Figure 14. CLAMP WorldClim2_GridMet_Asia2 regression models for Compensated Thermicity Index (THERM) and mean annual moist enthalpy (ENTH). Site and uncertainty represented as in Fig. 10

Figure 15. CLAMP WorldClim2_GridMet_Asia2 regression models for growing season precipitation (GSP) and mean monthly growing season precipitation (MMGSP). Site and uncertainty represented as in Fig. 10

Figure 16. CLAMP WorldClim2_GridMet_Asia2 regression models for precipitation in the three consecutive wettest months (3WET) and precipitation in the three consecutive driest months (3DRY). Site and uncertainty represented as in Fig. 10

Figure 17. CLAMP WorldClim2_3brc regression models for mean annual relative humidity (RH.ANN) and mean annual specific humidity (SH.ANN). Site and uncertainty represented as in Fig. 10

Figure 18. CLAMP WorldClim2_GridMet_Asia2 regression models for mean annual vapour pressure deficit (VPD.ANN) and mean winter vapour pressure deficit (VPD.WIN). Site and uncertainty represented as in Fig. 10

Figure 19. CLAMP WorldClim2_GridMet_Asia2 regression models for mean spring vapour pressure deficit (VPD.SPR) and mean summer vapour pressure deficit (VPD.SUM). Site and uncertainty represented as in Fig. 10

Figure 20. CLAMP WorldClim2_GridMet_Asia2 regression models for mean autumn vapour pressure deficit (VPD.AUT) and Potential evapotranspiration (PET.ANN). Site and uncertainty represented as in Fig. 10

Figure 21. CLAMP WorldClim2_GridMet_Asia2 regression models for potential evapotranspiration during the warmest month (PET.WARM) and potential evapotranspiration during the coldest month (PET.COLD). Site and uncertainty represented as in Fig. 10

Supplementary Materials Captions

Table S1. CLAMP scoresheet for the Jharkhand Pliocene assemblage

Table S2. A new high spatial resolution (~1 km) WorldClim2 gridded climate data

Table S3. Modern leaf physiognomic (PhysgAsia2 calibration) data

Figure S1. 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 S2. 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 S3. 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.