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Palaeoclimatic Estimates for the Late Pliocene Based on Leaf Physiognomy from Western Yunnan, China

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Abstract: Based on leaf physiognomy of the Late Pliocene Tuantian megaflora from the Mangbang Formation of Tengchong County in western Yunnan, a quantitative reconstruction of palaeoclimate was performed with Leaf Margin Analysis (LMA) methodology and the Climate–Leaf Analysis Multivariate Program (CLAMP). The latter produced the following parameters: mean annual temperature (MAT) from 17.2 to 17.7°C; warmest month mean temperature (WMMT) from 25 to 25.5°C; coldest month mean temperature (CMMT) from 9.5 to 10.8°C; length of growing season (GRS) from 9.5 to 9.7 months; growing season precipitation (GSP) from 1834.3 to 1901.2 mm; mean monthly growing season precipitation (MMGSP) from 222.4 to 230.5 mm; precipitation during the three consecutive wettest months (3-WET) from 892.1 to 917.8 mm; precipitation during the three consecutive driest months (3-DRY) from 474.5 to 512.8 mm; relative humidity (RH) from 76.7 to 77.8%; specific humidity (SH) from 10.7 to 10.8 g/kg; and enthalpy (ENTHAL) from 31.8 to 32 kj/kg. However, the MAT obtained from the Chinese LMA regression at 18.7°C, is slightly higher than that from CLAMP. The integrated analysis of these data and three adjacent pollen floras in western Yunnan suggests that the Gaoligong Mountains (a southern portion of the Hengduan Mountains) were only raised to modest altitudes in the Late Pliocene.

Key Words: Hengduan Mountains, leaf physiognomy, monsoon, palaeoclimate, Pliocene, western Yunnan

Yaprak Fizyonomisine Dayalı Geç Pliyosen Paleoiklimsel Tahminleri, Batı Yunnan, Çin

Özet: Batı Yunnan'nın Tengchong ilçesinden Mangbang Formasyonu'na ait Geç Pliyosen Tuantian megaflorasının (yaprak fosili florasının) yaprak fizyonomisi temel alınarak, Yaprak Kenarı Analizi (LMA) yöntemi ve İklim-Yaprak Analiz Değişken Programı (CLAMP) ile paleoiklimin sayısal canlandırması yapılmıştır. Son olarak izleyen parametreler ortaya çıkmıştır: yıllık ortalama sıcaklık (MAT) 17.2–17.7°C; en sıcak ayın sıcaklığı (WMMT) 25–25.5°C; en soğuk ayın sıcaklığı 9.5–10.8°C; büyüme mevsimi uzunluğu (GRS) 9.5–9.7 ayları; büyüme mevsimi yağış miktarı (GSP) 1834.3–1901.2 mm; aylık ortalama büyüme mevsimi yağış miktarı (MMGSP) 222.4–230.5 mm; birbirini izleyen en yağışlı üç ay boyuncaki yağış miktarı (3-WET) 892.1–917.8 mm; birbirini izleyen en kurak üç ay boyuncaki yağış miktarı (3-DRY) 474.5–512.8 mm; bağıl nemlilik (RH) 76.7–77.8%; özel nemlilik (SH) 10.7–10.8 g/kg ve entalpi (ENTHAL) 31.8–32 kj/kg. Ancak, 18.7°C de Çin LMA regresyonundan elde edilen MAT, CLAMP'den elde edilen değerden biraz daha yüksektir. Batı Yunnan'a ait üç komşu polen florası ve bu floralara ait verilerin bütünleştirilmiş analizleri, Gaoligong Dağları'nın (Hengduan dağlarının güney kısmı) Geç Pliyosen'de sadece sınırlı yükselimin olduğunu düşündürmektedir.

Anahtar Sözcükler: Hengduan Dağları, yaprak fizyonomisi, muson, paleoiklim, Pliyosen, Batı Yunnan

Introduction

Western Yunnan, encompassing the southern part of the Hengduan Mountains and on the southeastern edge of the Qinghai-Tibet Plateau, displays complicated topography, diverse climates and a high diversity of vascular plant species (Chapin *et al.* 2002). This area has some of the greatest diversity in modern (Wu & Zhu 1987) and fossil (Sun *et al.* 2003a,

b) plants in China. In the Late Cenozoic, the uplift of the Qinghai-Tibet Plateau strongly influenced this region (Hay *et al.* 2002) and this influence is surely recorded in the fossil plants. Additionally, the Late Cenozoic is a key period when the Earth was transformed from a greenhouse climatic regime to an icehouse climate (Zachos *et al.* 2001), and investigations into the fossil plants of this time period can provide proxies for climate change and a suitable candidate for an analogy of the future climate of the Earth.

Tengchong County, with its volcanic landforms, lies in western Yunnan Province (Wang *et al.* 2007) and, through the influence of the southwest monsoon, its modern vegetation supports a subtropical monsoonal evergreen broad-leaved forest (Wu & Zhu 1987). In this region, the study of the megafossils of Cenozoic plant assemblages was initiated by Tao & Du (1982) and continued by Ge & Li (1999). In recent years, further research was conducted into the taxonomy and microstructure of the fossil plants (Sun *et al.* 2003a, b; Wei *et al.* 2005; Yan *et al.* 2007; Wu *et al.* 2009).

Many studies on the quantitative reconstruction of the Cenozoic climate of China have now been carried out, based on pollen, leaf, or seed (fruit) materials (e.g. Xu *et al.* 2004b, 2008; Zhao *et al.* 2004a, b; Kou *et al.* 2006; Yang *et al.* 2007; Xia *et al.* 2009; Yao *et al.* 2009; Hao *et al.* 2010). In this investigation, we collected 1200 specimens of fossil leaves from the outcrop in the Tuantian Basin of Tengchong County (Figure 1). Based on leaf physiognomy, the Late Pliocene palaeoclimatic parameters of western Yunnan were reconstructed quantitatively using Leaf Margin Analysis (LMA) (Wolfe 1979) and the Climate-Leaf Analysis Multivariate Program (CLAMP) (Wolfe 1993). Moreover, the influence of the uplift of the Hengduan Mountains on this area was also investigated. The new data was analyzed in order to better understand the Cenozoic climatic evolution of China, and the climatic origin and high biodiversity of western Yunnan.

Geological Setting and Age

The new materials were collected from an opencast diatomite mine (24°41′13″N, 98°37′59″E) in the Tuantian Basin, 57 km south of Tengchong County and along the Longchuan River (Figure 1). The Tuantian Basin formed in the Cenozoic and accumulated an extensive succession of sediments, which are placed in the Mangbang Formation that comprises three members (Figure 2); the upper and the lower members are clasolite with abundant plant fossils (Ge & Li 1999). The stratigraphic profile within the upper member of the Mangbang Formation exposed at the diatomite mine is about 20 m thick (Figure 2). The plant-bearing sediments are overlain by Quaternary andesite dated at about 2.3 Ma (Jiang 1998). The underlying middle member of the Mangbang Formation is overlain by another basalt, dated at approximately 3.3~3.8 Ma using K-Ar and Rb-Sr isotopic dating (Li *et al.* 2000). Thus, the flora is sandwiched between two dated layers of volcanic rocks within the range of 3.3~2.3 Ma, and hence is Late Pliocene.

Materials and Methods

Materials

The fossil flora of the Mangbang Formation is dominated by large broad leaved angiosperms (Tao 2000). The fossil remains studied here from the upper member of the Mangbang Formation in Yunnan Province (Figure 2), were collected by Sun Bainian, Xie Sanping and other graduate students in 2003 and 2006. The materials are stored at the College of Earth and Environmental Sciences, Lanzhou University, N.W. China. There are about 1200 specimens of plant fossil remains, which include 978 angiosperm leaf specimens; 37 winged fruit specimens; 54 gymnosperm leaf specimens; and 12 fern leaf specimens. The large-leaved specimens remain almost complete and some even have well preserved petioles. They are also mixed with other leaf specimens of different sizes (Xie 2007). This phenomenon seems to show that these fossil leaves were almost intact when fossilized. Thus, this palaeoclimatic estimate can be expected to be accurate and can reflect the local climate of the burial site.

Associated with the fossil plants, articulated specimens of fossil teleost fish and fossil insects were collected.

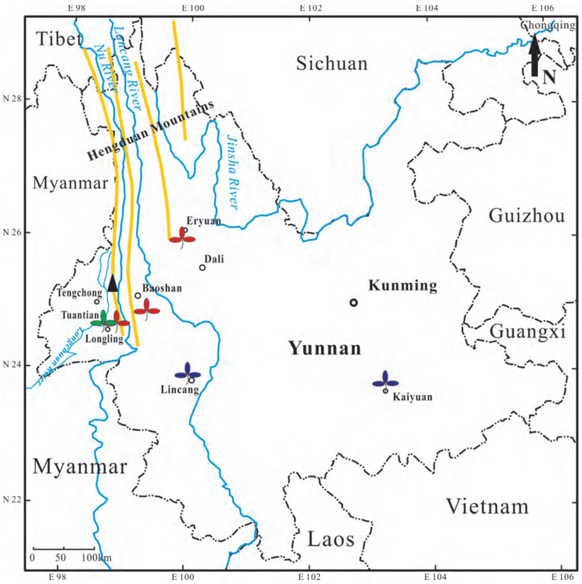

Figure 1. A simplified map showing the present and related fossil localities in Yunnan Province, SW China. Trifoliate leaf symbols (Green indicates this study; red indicates the Late Pliocene pollen floras; blue indicates the Late Miocene megafloras) indicate fossil localities; the yellow lines indicate the Hengduan Mountains; the solid black triangle represents the highest point of the Gaoligong Mountains.

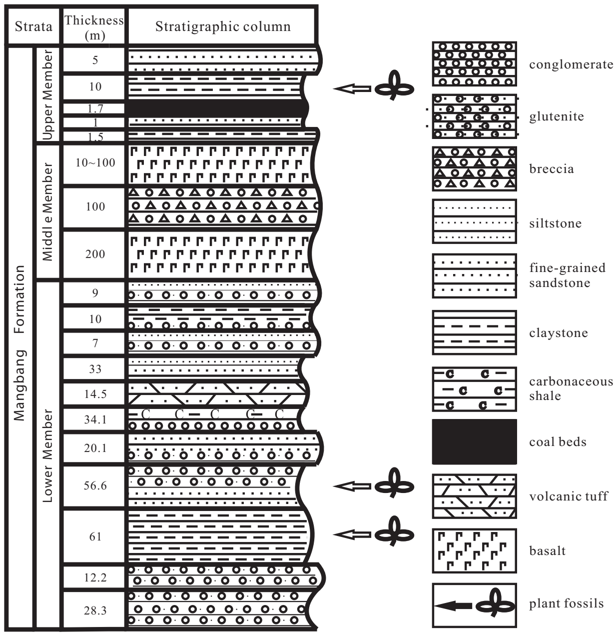

Figure 2. Diagram of the lithostratigraphic column of the Mangbang Formation at the Tuantian diatomite mine, Tengchong County, Yunnan Province. Fossil plant horizons marked with a trifoliate leaf symbol; the studied fossil specimens were collected from the upper member of the Mangbang Formation.

Methods

After cleaning and repairing, 531 specimens of well-preserved angiosperm leaves were photographed with a Ricoh R2 digital camera (5 million pixels). These digital photos of leaf specimens were then subjected to a standard CLAMP analysis using the method advocated by the CLAMP website (http://www.open.ac.uk/earth-research/spicer/CLAMP/Clampset1.html).

Leaf Morphotyping

According to standard CLAMP procedure, the fossil angiosperm leaf specimens were first subjected to morphotypical taxonomy. We conducted the morphotyping with a leaf architectural analysis (Hickey 1973; LAWG 1999) aided by leaf cuticular analysis (Dilcher 1974). Through observation of their general characters, the leaf specimens were divided into eight broad groups, namely: (1) pinnate entire leaves; (2) palmate entire leaves; (3) pinnate toothed leaves; (4) palmate toothed leaves; (5) basal ternate-vein leaves; (6) basal five-veined leaves; (7) small entire leaves; and (8) other leaves: a few individual specimens that could not be assigned to any of the above seven groups. Then these eight groups were subdivided into separate morphotypes based on a detailed study of leaf higher-order veining pattern, tooth type, and further cuticular characters. From this process, we distinguished 52 morphotypes and selected 38 leaf morphotypes with complete physiognomic characters for a CLAMP analysis.

LMA Methodology

LMA is a univariate method to estimate past land temperature based on the proportion of untoothed species in a fossil flora. Since the initial work of Wolfe (1979), it has been used for reconstruction of palaeotemperature in various ecological environments on different continents (Wing & Greenwood 1993; Wilf 1997; Adams *et al.* 2008).

However, Burnham *et al.* (2001) considered that the different relationships of leaf margin characters with temperatures among different ecological environments would induce errors in palaeoclimatic estimates. For example, LMA based on angiosperm fossil leaves deposited in fluvial or lake facies (rather than terrestrial) would underestimate temperature. In addition, although there is a similar trend of the proportion of entire-leaved species increasing with the annual mean temperature among different continents (e.g., North America, Australia, East Asia and Europe), LMA based on the datasets of different continents would lead to different results because of the respective tectonic and vegetation history of those continents (Wilf 1997; Greenwood 2005). For example, application of the Australian dataset of LMA to Australian Cenozoic floras resulted in cooler temperature estimates than those of other LMA regressions (Greenwood *et al.* 2004).

In this study, to get an accurate result, we used multi-dataset LMA regressions (Wolfe 1979, 1993; Wilf 1997; Gregory-Wodzicki 2000; Greenwood *et al.* 2004; Traiser *et al.* 2005; Miller *et al.* 2006; Su *et al.* 2010) to make palaeotemperature estimates and compared among these estimates (Table 1).

CLAMP Methodology

CLAMP, initiated by Wolfe (1990), is a multivariate statistical technique that decodes the climatic signal inherent in leaf physiognomy of woody dicotyledonous plants. It has developed as a robust,

Table 1. Leaf margin analysis based on multi-dataset regressions.

Dataset	Linear regression	MAT (°C)	SD [b] (°C)	Reference
China	MAT= 27.6 × P [a] + 1.038 (r^2= 0.79, n= 50)	18.7	2.1	Su *et al.* (2010)
East Asia	MAT= 30.6 × P + 1.141 (r^2= 0.98, n= 34)	20.7	2.4	Wolfe (1979) Wing & Greenwood (1993)
North and Central America and Japan	MAT= 29.1 × P – 0.266 (r^2= 0.76, n= 106)	18.4	2.3	Wolfe (1993)
North, Central, and South America	MAT= 28.6 × P + 2.240 (r^2= 0.94, n= 9)	20.5	2.2	Wilf (1997)
Europe	MAT=31.4 × P + 0.512 (r^2= 0.60, n= 1835)	20.6	2.4	Traiser *et al.* (2005)
CLAMP3A	MAT= 27.6 × P + 1.295 (r^2= 0.78, n= 173)	19.0	2.1	CLAMP website
CLAMP3B	MAT= 25.0 × P + 3.418 (r^2= 0.87, n= 144)	19.4	1.9	CLAMP website
CLAMP3C	MAT= 27.9 × P – 0.242 (r^2= 0.50, n= 193)	17.6	2.2	CLAMP website
Australia	MAT= 27.0 × P – 2.12 (r^2= 0.63, n= 74)	15.2	2.1	Greenwood *et al.* (2004)
Bolivia (South America)	MAT= 35.9 × P – 2.52 (r^2= 0.93, n= 12)	20.5	2.8	Gregory-Wodzicki (2000)
North and Central America	MAT= 29.0 × P + 1.320 (r^2= 0.91, n= 84)	19.9	2.3	Miller *et al.* (2006)

[a] P denotes the proportion of entire-margined species, the following as the same.

[b] Standard deviation abbreviated as SD, $SD = c\sqrt{\frac{P(1-P)}{r}}$, in which c is the slope of regression equation, r is the total number of species in the fossil flora.

accurate and quantitative tool for direct terrestrial palaeoclimate determinations based on land flora (Wolfe 1993, 1995; Spicer *et al.* 2003, 2004). CLAMP results can therefore be an important complement to marine-based climate proxies such as oxygen isotopes and thus open a new window for knowledge of past land climates. In CLAMP, the palaeoclimatic signals are extracted from the relationship between the leaf physiognomy of woody dicotyledonous leaves of modern vegetations and the known climatic conditions, so that palaeoclimatic estimates for the Neogene and Quaternary are more reliable and accurate than those for earlier periods. The CLAMP reference dataset initially contained only a relatively small sample size (Wolfe 1993; Herman & Spicer 1996), but now has developed into two datasets (Physg3ar and Physg3br) with corresponding meteorological datasets (Met3ar and Met3br). Within these, CLAMP3B (Physg3br and Met3ar) is a small reference dataset of 144 samples that excluded the so-called 'subalpine nest' samples, which experienced extreme cold and tend to have very small leaves that lack teeth. A third suite of the CLAMP dataset (Physg3cr and Met3cr) on the CLAMP website is under construction (Spicer *et al.* 2009). In our investigation, we used the first two dataset suites (CLAMP3A & CLAMP3B) to make a palaeoclimatic construction (Table 3).

Abbreviations of climate parameters used in CLAMP include: MAT, mean annual temperature; WMMT, warmest month mean temperature; CMMT, coldest month mean temperature; GRS, length of the growing season; 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, relative humidity; SH, specific humidity and ENTHAL, enthalpy.

Results

Leaf Margin Analysis

As noted above, we distinguished 38 morphological types, in which some leaf morphotypes had teeth only on the apical part, such as some *Fagus* species that scored 0.5. From this we got 24.5 entire-leaf morphotypical species and calculated the proportion of untoothed species at about 64%. Applying this percentage to multi-dataset regressions with different origins, we obtained the MAT results (Table 1).

The multi-dataset regressions showed different MAT ranging from 15.2 to 20.7°C with the standard deviation (SD) from 1.9 to 2.8°C (Table 1). The Australian and East Asian datasets show the minimum and maximum estimates, and the other estimates are moderate results ranging from 17.6 to 20.6°C (Table 1). If statistically uncertain data ($r^2 < 0.7$ or $n < 20$) are excluded, the MAT would range from 18.4 to 20.7°C, and average 19.4°C.

CLAMP

The 31 leaf physiognomic characters of the 38 morphotypes were scored and summed up to a percentage (Table 2), and then a standard CLAMP procedure was carried out. Finally, 11 climate parameters based on two datasets were estimated (Table 3).

Compared to the LMA estimates, CLAMP calculated a lower MAT. This may be a result of the difference between the LMA and CLAMP methodologies (Liang *et al.* 2003; Uhl *et al.* 2006, 2007). Table 3 shows that the two CLAMP datasets produced very similar results, showing an internal consistency within the methodology. CLAMP3B yielded a slightly lower MAT and a GRS about one month shorter than that of CLAMP3A, but the difference in temperature of warmest and coldest months (DT) of CLAMP3B is higher than that of CLAMP3A. Climatic parameters predicted from CLAMP3B related to water, including GSP, MMGSP, 3-WET, 3-DRY and RH, are rather higher than those from CLAMP3A, but the estimates of SH and ENTHAL based on CLAMP3B are lower than those of CLAMP3A (Table 3).

Discussion

To get an overall understanding of the Late Pliocene climatic situation in western Yunnan, we present the results of this investigation in association with other studies (Xu 2002; Xu *et al.* 2004a, b; Kou *et al.* 2006; Wu 2009) to discuss monsoon climate

Table 2. Scored percentage of 31 leaf physiognomic characters for the CLAMP.

Leaf character	Percentage
Lobed	0
No teeth	64
Regular teeth	33
Close teeth	16
Round teeth	17
Acute teeth	18
Compound teeth	13
Nanophyll	0
Leptophyll 1	0
Leptophyll 2	2
Microphyll 1	5
Microphyll 2	19
Microphyll 3	29
Mesophyll 1	27
Mesophyll 2	13
Mesophyll 3	4
Emarginate apex	8
Round apex	21
Acute apex	52
Attenuate apex	27
Cordate base	28
Round base	45
Acute base	27
L:W<1:1	1
L:W 1–2:1	31
L:W 2–3:1	48
L:W 3–4:1	15
L:W N 4:1	5
Shape obovate	5
Shape elliptic	57
Shape ovate	38

evolution. Additionally, to date in Yunnan Province, only two studies (Xia *et al.* 2009; Jacques *et al.* 2011) have quantitatively reconstructed Neogene climatic parameters using the methodologies of LMA, CA and CLAMP, and we will compare our results to theirs.

Tuantian was much warmer in the Pliocene than it is at present (Xie *et al.* 2006), when MAT, WWMT, and CMMT are 14.9°C, 21.4°C and 10.2°C (Table 4), respectively. For the CLAMP results, as the CLAMP website suggested, it is usually better to use the smaller 144-site dataset unless winter temperatures below freezing are suspected. Notably, it was expected that the small dataset (CLAMP3B) could obtain a more accurate prediction than the full dataset (CLAMP3A) in this investigation. Therefore, the following discussions of palaeoclimate are based on the CLAMP3B estimates (Table 4).

In the LMA results, although the mean MAT is 19.4°C, it might be more accurate using the recently developed Chinese LMA regression (Su *et al.* 2010) and North and Central American and Japan LMA regression (Wolfe 1993), as suggested by Su *et al.* (2010). This might be tested in a future study.

Palaeoclimatic Parameters Related to Temperature

Wu (2009) calculated a MAT of 16.4–19.8°C (Table 4) for the Tuantian megaflora using the Coexistence Approach (CA); the MATs in the present study calculated by LMA and CLAMP (Tables 1 & 4) were within this temperature range. The MAT from LMA is the highest, which follows a pattern from the two Miocene Xiaolongtan and Lincang megafloras (Xia *et al.* 2009; Jacques *et al.* 2011). This phenomenon probably relates to the low latitude locations of these megafloras, but other factors cannot be excluded before the underlying mechanisms are identified. Royer & Wilf (2006) investigated the possibility that gas exchange may cause the correlation between toothed leaves and cold climates in LMA, but for CLAMP, the mechanism for empirical correlations between leaf physiognomical traits and climate parameters remains unknown. So the reason/s for the difference between LMA, CLAMP and CA remain far from certain. The Late Pliocene MAT obtained from the Tuantian megaflora is higher than that of today (Table 4), which is in accordance with the Cenozoic

Table 3. Climatic predictions for the Tuantian Basin in the Late Pliocene using CLAMP.

Climatic parameters	CLAMP3A [a]		CLAMP3B [b]	
	Prediction	SD [c]	Prediction	SD [c]
MAT (°C)	17.7	1.7	17.2	1.2
WMMT (°C)	25.0	1.8	25.5	1.6
CMMT (°C)	10.8	2.5	9.5	1.9
GRS (month)	9.7	0.9	9.5	0.7
GSP (mm)	1834.3	318.0	1901.2	335.9
MMGSP (mm)	222.4	36.7	230.5	36.9
3-WET (mm)	892.1	138.1	917.8	140.3
3-DRY (mm)	474.5	89.9	512.8	93.0
RH (%)	76.7	8.2	77.8	7.4
SH (g / kg)	10.8	1.0	10.7	0.9
ENTHAL (kj / kg)	32.0	0.4	31.8	0.3

[a] CLAMP3A denotes the CLAMP analysis based on the dataset of Physg3ar and Met3ar.
[b] CLAMP3B denotes the CLAMP analysis based on the dataset of Physg3br and Met3br.
[c] SD is the abbreviation of standard deviation.

cooling trend (Zachos *et al.* 2001) and also agrees with previous investigations based on Late Pliocene pollen floras in western Yunnan (Xu 2002; Xu *et al.* 2004a, b; Kou *et al.* 2006) (Table 4).

CLAMP obtained higher WMMT, DT and lower CMMT than those from CA (Table 4), with a different pattern from the two Miocene megafloras (Xia *et al.* 2009; Jacques *et al.* 2011). The WMMT and DT calculated by both CLAMP and CA for the Tuantian megaflora were higher than those of today, but the CMMT calculated by CLAMP was 0.7°C lower and the one from CA was 2.5°C higher than that of today (Table 4). Interestingly, the adjacent Longling pollen flora (Xu 2002) (Figure 1) showed a similar temperature pattern to the CA results (Wu 2009) with higher WMMT, CMMT and DT in the Pliocene than those of today. Eryuan and Yangyi, located in the northeastern Gaoligong Mountains (the southern portion of the Hengduan Mountains: Figure 1), however, showed another temperature pattern. They possessed higher WMMT, lower CMMT and higher DT in the Pliocene than those of today (Table 4). As the temperature pattern of the four floras differed in CMMT, it is suggested that in the Late Pliocene, the Gaoligong Mountains were elevated to a certain height, and the winter monsoon then influenced Eryuan and Yangyi much more than Longling and Tuantian. We also note that the Late Pliocene MAT and CMMT decreased with a latitude increase from Longling through Tuantian and Yangyi to Eryuan (Table 4), which indicates that the Gaoligong Mountains were not then high enough to break the latitude-based temperature zonation.

Palaeoclimatic Parameters Related to Water

CLAMP produced a slightly lower GSP in the present study than that of today (Table 4), probably indicating that the Late Pliocene fossil plants in the Tuantian Basin enjoyed approximately similar rainfall to the present flora. Interestingly, the CLAMP obtained a much higher MAP (greater than or equal to GSP) (Table 4) in the present study than that from CA (Wu 2009), showing a similar pattern to that from

Table 4. Palaeoclimatic parameters and modern equivalent based on four Pliocene floras from western Yunnan.

Location	Time	MAT (mid-value) (°C)	WMMT (mid-value) (°C)	CMMT (mid-value) (°C)	DT (mid-value) (°C)	MAP (mid-value) (mm)	GSP (mm)	3-WET (mm)	3-DRY (mm)
Eryua[n] a	Pliocene	13.3–18.6 (15.95)	24.6–27.5 (26.05)	1.9–12.1 (7.0)	14.2–16.6 (15.4)	619.9–1484.3 (1052.1)	N/A	N/A	N/A
Yangyi [b]	Pliocene	13.3–20.9 (17.1)	22.5–27.5 (25.0)	1.9–12.6 (7.25)	12.3–25.8 (19.05)	797.5–1254.7 (1026.1)	N/A	N/A	N/A
Tuantian [c]	Pliocene	17.2	25.5	9.5	16	≥1901.2	1901.2	917.8	512.8
Tuantian [d]	Pliocene	16.4–19.8 (18.1)	21.3–25.1 (23.2)	10.8–14.6 (12.7)	11.3–16.3 (13.8)	1225.7–1638.3 (1432.0)	N/A	N/A	N/A
Longling [b]	Pliocene	18.6–22.1 (20.35)	22.8–27.5 (25.15)	9.7–15.1 (12.4)	12.3–18.1 (15.2)	815.8–1254.7 (1035.25)	N/A	N/A	N/A
Eryuan [e] (26°00′N, 99°49′E)	Modern	15.1	20.1	8.7	11.4	1079	1049.8	596.2	54.7
Yangyi [e] (24°57′N, 99°15′E)	Modern	15.5	21	8.2	12.8	966	909.5	500.3	56.5
Tuantian and Longling [f] (24°41′N, 98°50′E)	Modern	14.9	21.4	10.2	11.2	2110	2035.2	1243.8	74.8

[a] All palaeoclimate parameters were taken from the estimates of Kou *et al.* (2006).
[b] All palaeoclimate parameters were taken from the estimates of Xu (2002).
[c] All palaeoclimate parameters taken from this study.
[d] All palaeoclimate parameters were taken from Wu (2009).
[e] These modern climatic data derived from the website (http://www.data.ac.cn/). The value of Eryuan is based on that of Dali meteorological station and the value of Yangyi is based on that of Baoshan meteorological station.
[f] The modern climate data based on the statistics of Longling Meteorological Bureau. Considering Tuantian is geographically closer to Longling than to Tengchong, we take the modern climate data of Longling meteorological station as the analog of the Tuantian megaflora.

the two Miocene floras (Xia *et al.* 2009; Jacques *et al.* 2011) in southern China. Thus, the divergence of precipitation estimates between CLAMP and CA may indeed be due to some limitations of CLAMP (Yang *et al.* 2007) in estimating precipitation in a water-sufficient environment, where water condition was not a limiting factor that controlled the survival and growth of plants, and further shaped the leaf form.

Moreover, 3-DRY in the Late Pliocene was 438 mm higher than at present, whereas in contrast 3-WET was 326 mm lower than today (Table 4), implying that the seasonality of rainy and dry seasons of western Yunnan in the Late Pliocene was not as pronounced as it is now. Since the seasonal assignment of rainfall is thought to be related to the monsoon system, which is caused and strengthened by mountain uplift (Liu & Yin 2002), the seasonality of rainfall might also be related to the phased uplift of the Himalaya-Tibetan Plateau (An *et al.* 2001). The uplift height of the Himalaya-Tibetan Plateau can influence atmospheric circulation pattern and monsoon intensification (Liu & Yin 2002). Therefore, the weaker seasonality of rainfall indicated in this investigation suggests that in the Late Pliocene the Himalaya-Tibetan Plateau had not yet been elevated to a height sufficent to produce a more intense monsoon than today, but this does not rule out that the monsoon system might have been more intense than earlier periods (Jian *et al.* 2001; Qiang *et al.* 2001).

At present, Longling and Tuantian, situated in the southwestern Gaoligong Mountains, receive much more precipitation than Yangyi and Eryuan to the northeast (Figure 1), and this reflects frontal rains on the southwestern side of the range (Table 4). However, in the Late Pliocene, Longling, Yangyi and Eryuan retained roughly the same MAP, as suggested by Kou *et al.* (2006), excluding Tuantian (probably due to differences between pollen flora and megaflora). This perhaps demonstrates that the Gaoligong Mountains and maybe the whole Hengduan Mountain range were not yet elevated at that time to their present altitudes.

Conclusions

Based on our analysis of four Late Pliocene floras from western Yunnan, some preliminary conclusions can be drawn:

(1) The Tuantian Basin in the Late Pliocene exhibited a much higher MAT with a higher DT than those of today; the area possessed an approximately similar MAP to the present, but with much less seasonality;

(2) The Himalaya-Tibetan Plateau was not high enough to provoke a stronger monsoon in the Late Pliocene than it does now. The drastic uplift of the Himalaya-Tibetan Plateau occurred mostly since the Late Pliocene;

(3) The Gaoligong Mountains (and maybe the Hengduan Mountains) probably had been elevated to a certain altitude in the Late Pliocene, but their height was still relatively limited.

The new data provide valuable insights into climatic evolution during the Cenozoic in southwestern China, and into the climatic origin and high biodiversity of plants in western Yunnan.

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