Clim. Past Discuss., 9, 1675–1701, 2013
www.clim-past-discuss.net/9/1675/2013/
doi:10.5194/cpd-9-1675-2013


Climate of the Past
Discussions
Open Access



# Post-Pliocene establishment of the present monsoonal climate in SW China: evidence from the late Pliocene Longmen megaflora

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Received: 16 January 2013 – Accepted: 25 January 2013 – Published: 2 April 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

## Abstract

The paleoclimate of the late Pliocene Longmen flora from Yongping County located at the southeastern boundary of the Qinghai-Tibet Plateau was reconstructed using two leaf physiognomy based methods, i.e. Leaf Margin Analysis (LMA) and Climate Leaf Analysis Multivariate Program (CLAMP), to understand the paleoclimate condition and geographical pattern of monsoonal climate in southwestern China during the late Pliocene. The mean annual temperatures (MATs) estimated by LMA and CLAMP are $17.4 \pm 3.3\,^{\circ}$C and $17.4 \pm 1.3\,^{\circ}$C, respectively, compared with $15.9\,^{\circ}$C at present. Meanwhile, the growing season precipitation (GSP) estimated by CLAMP is $1735.5 \pm 217.7$ mm in the Longmen flora, compared with 986.9 mm nowadays. The calculated monsoon index (MSI) of the Longmen flora is significantly lower than that of today. These results appear consistent with previous studies based on the coexistence approach (CA), and further suggest that there was a slightly warmer and much wetter climate during the late Pliocene than the present climate in western Yunnan. We conclude that the significant change of the monsoonal climate might have been resulted from the continuous uplift of mountains in western Yunnan, as well as the intensification of eastern Asian winter monsoon, both occurring concurrently in the post-Pliocene period.

## 1 Introduction

The modern Asian monsoon system is divided into the East Asian monsoon and the South Asian (Indian) monsoon (Molnar et al., 2010). Although they differ in precipitation terms, both are characterized by wet summers and dry winters (B. Wang, 2006). Approximately 60 % of the world's population lives in the regions directly affected by the monsoon system, and therefore its fluctuation can greatly impact human activities worldwide as well as the local economy (B. Wang, 2006). The Asian monsoon has attracted great attention on its evolution, variability and forcing mechanisms (Sun and





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Wang, 2005; Wang et al., 2008; Han et al., 2012). While most work has focused on short term fluctuations in monsoon behaviour, study of the variations in the Asian monsoon in deep time is crucial to contextualise and understand the driving mechanisms underpinning monsoon changes.

Western Yunnan, located at the southeastern boundary of the Qinghai-Tibet Plateau, uniquely experiences both the East Asian monsoon and the Indian monsoon (Y. Wang, 2006). The uplift and east-west extension of the Qinghai-Tibet Plateau has created a series of north-south oriented mountains such as Mt. Gaoligong and Mt. Nu in western Yunnan (Ge and Li, 1999). These high mountains form geographical barriers for the convergence of these two monsoons (Hao et al., 2008) and result in a special regional monsoonal climate (Kou et al., 2006). Consequently, western Yunnan is an ideal region for exploring the evolution of the Asian monsoon climate in deep time. Fossil floral assemblages have been widely used as a proxy for paleoclimate reconstructions due to their direct interaction with the past surrounding environment (Wolfe, 1979, 1993; Mosbrugger and Utescher, 1997; Greenwood, 2005; Jordan, 2011). Thus, the abundance of Neogene floras in western Yunnan (Writing Group of Cenozoic Plants of China – WGCPC, 1978; Bureau of Geology and Mineral Resources of Yunnan Province – BGMRYP, 1990; Ge and Li, 1999) provides important materials for understanding the evolution of monsoonal climate.

The Pliocene is a key period for the global climate change with a transition from the warmer Miocene to the cooler Pleistocene (McKay et al., 2012). However, our understanding of the Pliocene climate in the Qinghai-Tibetan Plateau is poor. Although paleoclimates derived from several Pliocene floras in western Yunnan have been reconstructed and have provided important information on the character of the monsoon during the Pliocene (Xu et al., 2004; Yao et al., 2012; Supplement Table 1), most of these paleoclimatic studies of the Pliocene floras are based on the coexistence approach (CA) and one type of fossil material, namely palynological material (Kou et al., 2006). The principle of CA is based on the climate interval of the nearest living relatives of each taxon in the flora (Mosbrugger and Utescher, 1997). Although CA clearly





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produces coherent climate trends that match other proxies such as those based on isotopes (Mosbrugger et al. 2005), the climatic range encompassed by the co-existence interval can be large in some circumstances, and when this occurs, the resolution of the technique appears low. An alternative approach is based on the leaf physiognomic spectrum displayed by leaves of woody dicots (Wolfe, 1993; Greenwood, 2005). Methods of this kind only need to classify fossil leaves in a flora into morphotypes without taxonomic identification (Wolfe, 1993). The Tuantian flora, being on the western side of Mt. Gaoligong and Mt. Nu, is the only Pliocene fossil flora in western Yunnan with palaeoclimate reconstructions based on leaf physiognomy (Xie et al., 2012; Fig. A1a).

Here, we examine the late Pliocene Longmen flora on the eastern side of Mt. Gaoligong and Mt. Nu in western Yunnan. The aims of this paper are: (1) to reconstruct quantitatively the paleoclimate by using leaf physiognomy based methods and recently developed calibration datasets; (2) to compare our results with previous results calculated by the taxon based Co-existence Approach; (3) and to discuss the evolution of the Asian monsoonal climate of Yunnan.

## 2 Materials and methods

### 2.1 Geological setting

The fossil site is located in Longmen village, Yongping County, western Yunnan Province (25°30′48″ N, 99°31′11″ E; Fig. A1). Being at the southeastern boundary of the Qinghai-Tibet Plateau, western Yunnan has numerous Neogene coal-bearing basins created by the uplift of the Qinghai-Tibet Plateau (Ge and Li, 1999), and several fossil floras have been reported from these basins (Tao and Kong, 1973; Xie, 2007; Su, 2010). The sediment of Longmen in this study belongs to the Sanying Formation (Ge and Li, 1999), which is assigned to the late Pliocene based on several lines of evidence, such as local geological structure (Compiling Group of the Regional Stratigraphic Table of Yunnan – CGRSTY, 1978; BGMRYP, 1990), stratigraphic correlations (Ge and





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Li, 1999), and fossil record (Tao and Kong, 1973; WGCPC, 1978; Zong et al., 1996; Su et al., 2011). Like other paleofloras uncovered from the Sanying Formation (Tao and Kong, 1973; Tao, 1986; Zhang, 1997), the evergreen sclerophyllous oak (*Quercus* sect. *Heterobalanus*) appears the most abundant in the Longmen flora (Su, 2010).

The Sanying Formation in Longmen village is composed of two units (Bureau of Geology of Yunnan Province – BGYP, 1979). Fossil leaves in this study were collected from the top part of the upper unit. Local stratigraphy has been discussed in Su et al. (2011).

### 2.2 Materials

Several fossil species such as *Litsea* sp. and the evergreen sclerophyllous oak from Longmen village were first reported by the BGYP (1979). Subsequently, Zhou (1992) studied the morphology of fossil leaves in the evergreen sclerophyllous oaks uncovered from Longmen village. During our field work from 2008 to 2010, more than 2000 pieces of specimens have been collected (Su, 2010). Among them, one taxon has been anatomically studied, i.e. *Drynaria callispora* (Polypodiaceae; Su et al., 2011).

Among the collected specimens from the Longmen flora, fossil leaves of woody dicotyledonous species were classified into 22 morphotypes based on leaf morphological characters such as leaf shape, margin form, and the venation (Supplement Plates I–III). All specimens are deposited in the Paleobotany Laboratory, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences.

### 2.3 Methods

Two leaf physiognomy-based methods were applied, namely Leaf Margin Analysis (LMA) and Climate Leaf Analysis Multivariate Program (CLAMP). LMA is a simple way of estimating a single climate variable, namely the mean annual temperature (MAT) (Wing and Greenwood, 1993), whereas CLAMP is used routinely to calculate 11 temperature and precipitation related parameters (Wolfe, 1993). Although the mechanism





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of leaf physiognomy in response to climate has been questioned (Little et al., 2010), both methods are still quite robust in paleoclimate reconstructions (Spicer and Yang, 2010; Peppe et al., 2011). In this study, we did not use any linear regressions to calculate the paleoprecipitation, because none of extant linear regressions could be applied for Chinese paleofloras (Su et al., 2013). For a close comparison, we also recalculated the paleoclimate of the late Pliocene Tuantian flora in western Yunnan from a published account of Xie et al. (2012; site 5 in Fig. A1) using the same calibration dataset in the present study.

### 2.3.1 LMA

LMA is a method based on the single linear regression between the proportion of entire leaves in woody dicots within a flora and mean annual temperature (MAT) (Wolfe, 1993). However, many studies indicate that this correlation shows regional variations worldwide (Gregory-Wodzicki, 2000; Spicer et al., 2004; Adams et al., 2008; Su et al., 2010; Royer et al., 2012). Here we use the equation based on the Chinese dataset (Su et al., 2010) and the standard error of estimated MAT (SE) follows Miller et al. (2006).

$$\text{MAT}\ (^\circ\text{C}) = 1.038 + 27.6 \times P \qquad \text{(Su et al., 2010)}$$

$$\text{SE} = b \times \sqrt{[1 + \varphi(n-1)p(1-p)] \times \frac{p(1-p)}{n}} \qquad \text{(Miller et al., 2006)}$$

$b$ is the slope in the equation, here is 27.6; $\varphi$ is the overdispersion factor with the value of 0.052 from Miller et al. (2006); $p$ is the proportion of woody dicots with untoothed leaves; and $n$ is the total number of woody dicots in a flora.

### 2.3.2 Climate leaf analysis multivariate program (CLAMP)

CLAMP is a multivariate method based on canonical correspondence analysis (CCA). In CLAMP, 31 leaf character states and 11 climate parameters are derived for samples from modern forests to form the calibration dataset; more than two hundred samples





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are available online now (http://clamp.ibcas.ac.cn). In this study, we use the PhysgAsia1 calibration dataset (Jacques et al., 2011b), which supplements the core CLAMP Physg3br dataset with 45 modern Chinese sites. This calibration gives better precipitation estimates for China compared to older calibrations (Jacques et al., 2011b). We scored each leaf character of every morphotype from the Longmen flora by following the definitions on leaf characters on the CLAMP website (http://clamp.ibcas.ac.cn; Table 1). CCA was performed by using the software CANOCO 4.5 (Plant Research International, Wageningen, The Netherlands).

#### 2.3.3 The monsoon intensity index (MSI)

Several indices have been defined to evaluate the intensity of the monsoon (Liu and Yin, 2002; van Dam, 2006; Liu et al., 2011; Xing et al., 2012). However, most indices could not be estimated in this study because the parameters in these indices are not directly available from either LMA or CLAMP. As the monsoon plays the role of the "engine" for the transportation of moisture, the precipitation pattern around a year is closely associated to the intensity of monsoon (B. Wang, 2006). Herein, we use the equation proposed by Xing et al. (2012) to calculate MSIs of the Longmen flora and the Tuantian flora in western Yunnan based on the three precipitation parameters reconstructed by CLAMP:

$$\mathrm{MSI} = (3\mathrm{WET} - 3\mathrm{DRY}) \times 100/\mathrm{GSP} \qquad \text{(Xing et al., 2012).}$$

MSI is the intensity of monsoon climate with a higher value of MSI meaning a bigger difference of precipitation in seasonality and therefore indicating a stronger monsoon climate (Xing et al., 2012). GSP is growing season precipitation (precipitation during months with mean monthly temperature being more than 10 °C). 3WET is the precipitation during the 3 consecutive wettest months. 3DRY is the precipitation during the 3 consecutive driest months.





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## 3 Results

### 3.1 LMA

In the Longmen flora, the proportion of untoothed leaves in woody dicotyledonous species is 59.1 %. Thus the MAT of the Longmen flora resolves as 17.4 ± 3.3 °C.

### 3.2 CLAMP

By using the CLAMP calibration dataset (PhysgAsia1), the Longmen flora plots inside the physiognomic ordination space, and it resides within the cloud of modern Chinese samples (Fig. 1), which indicates that PhysgAsia1 is suitable for paleoclimate estimation of the Longmen flora. For temperature related parameters, those of the Longmen flora seem comparable with the present conditions (Table 2). For example, MAT and CMMT of the Longmen flora are 17.4 ± 1.3 °C and 8.9 ± 2.6 °C, respectively. The modern values for these parameters at Yongping are 15.9 °C and 8.2 °C, respectively. The length of the growing season (months with temperature > 10 °C, GROWSEAS) is similar to that of the present with 9.3 ± 0.7 months being predicted for the Longmen flora compared to 10 months at present. However the WMMT of the Longmen flora is estimated to have been much higher than nowadays.

Unlike the temperature variables, the difference between the late Pliocene and modern precipitation parameters in Longmen appears quite significant (Table 2). The largest difference for a precipitation related parameter is that of 3-DRY, the predicted value for the Longmen flora is about three times higher than that of the present day, with 184.5 ± 41.2 mm and 69.5 mm, respectively. The GSP of the Longmen flora is nearly twice as high as that nowadays, with 1735.5 ± 217.7 mm and 986.9 cm, respectively. Both 3-WET and RH estimates for the Longmen flora are higher than the present day values.





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## 3.3 MSI

The MSI of the Longmen flora is 35.5, whereas the MSI of Yongping County at present is 55.4 (Table 2).

# 4 Discussion

## 4.1 Warmer temperature during the late Pliocene

For the Longmen flora, LMA and CLAMP both give consistent results for MATs with estimated values 17.4 ± 3.3 °C and 17.4 ± 1.3 °C, respectively. Both values are about 1.5 °C higher than the present MAT. LMA is based on the single linear regression between leaf margin and MAT (Wolfe, 1979; Wing and Greenwood, 1993), whereas CLAMP is a multivariate method with 31 leaf characters included (Wolfe, 1993). Therefore, the results of these two methods are independent from each other (Spicer et al., 2009). These higher Pliocene temperatures are also found at Tuantian, which is approximate 100 km southwest of the Longmen flora (Table 2). These results combined both show that the MAT in western Yunnan during the late Pliocene was slightly higher than that of today. Meanwhile, CMMT stayed similar between the late Pliocene and the present day.

It is interesting to note that WMMT shows a dramatic difference with a temperature 4.4 °C higher in the late Pliocene than that of today in Yongping. Similarly, WMMT of the Tuantian flora is 24.3 ± 1.5 °C, comparing to 19.8 °C at present (Table 2). The significant decrease of WMMT to today's values between the late Pliocene and now might be related to an increase in altitudes in western Yunnan. During the late Pliocene, the altitude of western Yunnan might not have been as high as the present day, an interpretation that is supported by prior evidence from plant fossils (Kou et al., 2006; Xie et al., 2012), testate amoebae (Yang et al., 2006), and basin analysis (Fan et al., 2006). Altitude correlates negatively with temperature (Y. Wang, 2006). Therefore, a lower

WMMT is observed nowadays. Meanwhile, much heavier precipitation during the late Pliocene (Table 2) means that the wet and warm airflow in summer forms the rain and by the release of latent heat by condensation heats the atmosphere, a higher temperature could be observed.

In this study, results of leaf physiognomic methods are consistent with results of the Coexistence Approach (CA). The Longling flora, at about 120 km southwest to the Longmen flora was studied using CA (Kou et al., 2006; Supplement Table 1). MAT of the Longling flora was reconstructed to have been 18.6–22.1 °C compared to 15.0 °C at present. Therefore, all results based on independent approaches indicate a higher temperature during the late Pliocene than at present in western Yunnan.

These higher temperatures are also observed from the late Miocene floras (Supplement Table 1), for example, the Xiaolongtan flora from southeastern Yunnan (Xia et al., 2009), the Lincang flora from southwestern Yunnan (Jacques et al., 2011a), and the Xianfeng flora from central Yunnan (Fig. A2; Xing et al., 2012), based on different methods, namely, CA, LMA and CLAMP. Results of all methods show a slight decrease of MATs between the late Miocene and the present (Supplement Table 1). Moreover, the significantly higher WMMT during the late Miocene (Xu et al., 2008), is similar to the trend of WMMT cooling from the late Pliocene to today as shown in this study.

Overall, the cooling trend from the late Miocene to present in Yunnan Province (Fig. A2) is similar to the trend of global cooling since the late Miocene (Zachos et al., 2001). The lower temperature in western Yunnan at present might be also associated with regional uplift (Kou et al., 2006), leading to a higher altitudes and a cooler temperatures.

### 4.2 Geographical precipitation pattern

Paleoclimate reconstructions show that the precipitation during the late Pliocene was greater than that at present in western Yunnan (Fig. A2). GSPs between the late Pliocene and nowadays are comparable, because the length of the growing season (mean monthly temperature higher than 10 °C, GROWSEAS) in the late Pliocene





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Longmen flora is 9.3 ± 0.7 months, and GROWSEAS of the present day is 10 months. For the Longmen flora, GSP is 1735.5 ± 217.7 mm, nearly twice as high as that in the present day (Table 2). As far as the wet season is concerned, 3-WET is 800.3 ± 139.0 mm in the Longmen flora, whereas this value is 588.6 mm in Yongping County today (Table 2). A similar drying is seen in the dry season. 3-DRY decreases sharply from 184.5 ± 41.2 mm in the Longmen flora to 69.5 mm in Yongping County today. Conditions wetter than now are also observed in the late Pliocene Tuantian flora: the GSP in the Tuantian flora is 1625.7 ± 217.7 mm compared to 1381.1 mm in the present day. Meanwhile, precipitation during the three driest consecutive months (3-Dry) in the present day is only half of that during the late Pliocene. However, no drying trend is seen in the wet season because the late Pliocene and modern values are similar. In this study, we could not compare the precipitation values estimated by CLAMP and CA, simply because the precipitation co-existence intervals in CA are wide (Kou et al., 2006), and the observed modern rainfall values are within the reconstructed intervals for the palaeo-precipitation parameters (Supplement Table 1).

The Longmen flora is located on the eastern side of the Mt. Gaoligong and Mt. Nu, whereas the Tuantian flora is in the western side (Fig. 2). Today, both fossil localities are largely influenced by the Asian monsoon, which is characterized by a wet summer and a dry winter, and a series of north–south oriented mountains in western Yunnan such as Mt. Gaoligong and Mt. Nu play a vital role in determining moisture distribution. For example, precipitation on the western slope of Mt. Gaoligong is significantly higher than that on the eastern slope (B. Wang, 2006). During the late Pliocene, 3-WETs in both Longmen flora and Tuantian flora are quite similar to each other (Table 2), and indicate a different pattern of moisture distribution and a possibly different topography.

We also noticed that the precipitation of the late Pliocene Longling flora is lower than the present day (Kou et al., 2006). Longling is on the western slope of the Gaoligong Mountain where the Indian monsoon delivers high moisture levels. The East Asian summer monsoon impacts the eastern side of western Yunnan, but it is not as strong as the Indian monsoon in the western side of western Yunnan (Fig. 2). Consequently, precipitation of Longling during the late Pliocene was lower than the present day, and Yongping is drier than Longling nowadays.

### 4.3 The evolution of the Asian monsoon in western Yunnan

This study indicates that the Asian monsoon during the late Pliocene is not as strong as at the present day in western Yunnan. According to the MSI proposed by Xing et al. (2012), the intensity of the monsoon in both the Longmen flora and the Tuantian flora are lower than those of the present day (Table 2). In both floras, 3-DRYs contribute to the difference of MSI between the late Pliocene and the present day. For 3-DRY, the Longmen flora and the Tuantian flora are 184.5 ± 41.2 mm and 209.9 ± 41.2 mm, respectively, compared to 69.5 mm and 111.6 mm at present.

The MSI during the late Miocene was slightly lower than that during the late Pliocene in Yunnan (Fig. A2). MSIs of the Xiaolongtan flora, the Lincang flora and the Xianfeng flora are 31.3, 31.0 and 28.6, respectively. The lower MSIs during the late Miocene are mainly due to the higher GSP and 3-DRY (Xing et al., 2012). The GSPs of all the three late Miocene floras estimated by CLAMP are higher than the two late Pliocene floras. It indicates that in Yunnan there was an amplification of the Asian monsoon from the late Miocene to the late Pliocene, and a significant intensification of the Asian monsoon from the late Pliocene to the present. A Quaternary pollen record from Heqing in northwestern Yunnan further supports this conclusion (Xiao et al., 2010).

However, the MSI could not distinguish the East Asian monsoon from the Indian monsoon, which both impact western Yunnan. The evolution of both monsoon systems could be explored further by examining the distribution of precipitation throughout the year.

Very interestingly, both GSP and 3-WET in Yongping decrease more than those in Tengchong from the late Pliocene to the present day (Fig. A2). Today, during the summer the Indian Monsoon affects Tengchong because it is situated on the western side of Gaoligong and Nu Mountains (Fig. 3), but it barely reaches Yongping because it is on the eastern side (Fig. 3). Judging from the similar GSPs and 3-WETs exhibited by the





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Longmen flora and Tuantian floras during the late Pliocene, Mt. Gaoligong and Mt. Nu may not have acted as such a strong barrier to monsoonal air flow. The simplest way by which this may have happened is that it was lower than now, and this interpretation is evidenced by previous studies (Fan et al., 2006; Kou et al., 2006; Yang et al., 2006; Xie et al., 2012).

As far as the 3-DRY climate parameter is concerned, all the three precipitation parameters show the greatest decrease over time (Fig. A2), and it indicates the significant intensification of the Asian winter monsoon since the Pliocene. Our finding is supported by studies on loess sediments in northwestern China (An et al., 2001; Xiong et al., 2003). This intensification of the East Asian winter monsoon is interpreted to be associated with the development of the Northern Hemisphere ice sheet at high latitudes since the late Pliocene, which lead to the onset of Northern Hemisphere glaciation and the strengthening of a drier airflow from the Siberia High (Meyers and Hinnov, 2010). The dry airflow may have penetrated to some parts of western Yunnan such as Yongping along lower parts of the predominantly north–south alignment of the mountains, creating much drier winter at present than in the past (Fig. 3).

## 5 Conclusions

In this study, we used methods based on the relationship between leaf physiognomy and climate to quantitatively reconstruct the paleoclimate of the late Pliocene Longmen flora in western Yunnan. In combination with results of previous paleoclimatic studies, we conclude that:

1. Both temperature and precipitation in the late Miocene and the Pliocene of Yunnan are higher than at the present day;

2. The uplift of a series of mountains such as Mt. Gaoligong and Mt. Nu since the late Pliocene contributes to the creation of the modern spatial pattern of precipitation in western Yunnan;





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3. In Yunnan, the Asian monsoon intensified slightly from the late Miocene to the late Pliocene, and strengthened significantly from the late Pliocene to the present day. A significant intensification of the East Asian winter monsoon in western Yunnan occurred during the Quaternary, leading to a much drier winter today than in the Neogene.

**Supplementary material related to this article is available online at: http://www.clim-past-discuss.net/9/1675/2013/cpd-9-1675-2013-supplement.zip.**

*Acknowledgement.* We thank W.-T. Yu, Y. Yang, G.-F. Li and F.-M. Zhang for their assistance in fossil collections. This work is supported by National Natural Science Foundation of China (No. 41030212 to ZKZ, No. 31100166 to TS, No. 41272007 to FMBJ), the 973 Project (No. 2012CB821900 to ZKZ), the Foundation of the State Key Laboratory of Paleobiology and Stratigraphy, Nanjing Institute of Geology and Paleontology, Chinese Academy of Sciences (No. 123106 to TS), the West Light Foundation of the Chinese Academy of Sciences (to TS), the CAS 135 program (XTBG-F01 to ZKZ), a CAS Senior Visiting Professorship (2009S1-20) to R. A. Spicer, as well as US NSF (No. EAR-0746105 to YSL).

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**Table 1.** Percentages of 31 leaf characters in the Longmen flora.

| Leaf character | | Percentage (%) |
|---|---|---|
| Lobed | Lobed | 0.0 |
| Teeth of the leaf | No teeth | 59.1 |
| | Teeth regular | 38.6 |
| | Teeth close | 2.3 |
| | Teeth round | 18.2 |
| | Teeth acute | 22.7 |
| | Teeth compound | 4.5 |
| Size of the leaf | Nanophyll | 0.0 |
| | Leptophyll I | 0.0 |
| | Leptophyll II | 0.0 |
| | Microphyll I | 10.2 |
| | Microphyll II | 37.5 |
| | Microphyll III | 28.4 |
| | Mesophyll I | 17.0 |
| | Mesophyll II | 4.5 |
| | Mesophyll III | 2.3 |
| Apex of the leaf | Apex emarginate | 0.0 |
| | Apex round | 28.9 |
| | Apex acute | 44.7 |
| | Apex attenuate | 26.3 |
| Base of the leaf | Base cordate | 11.1 |
| | Base round | 13.5 |
| | Base acute | 75.4 |
| Length to width ratio of the leaf | L : W < 1 : 1 | 2.3 |
| | L : W1–2 : 1 | 12.9 |
| | L : W2–3 : 1 | 60.6 |
| | L : W3–4 : 1 | 19.7 |
| | L : W > 4 : 1 | 4.5 |
| Shape of the leaf | Obovate | 4.5 |
| | Elliptic | 90.9 |
| | Ovate | 4.5 |





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**Table 2.** Comparisons on climatic parameters between the late Pliocene and the present day in Longmen and Tuantian. MAT = mean annual temperature; WMMT = warm month mean temperature; CMMT = cold month mean temperature; LGS = length of the growing season; GSP = growing season precipitation (precipitation during months with mean monthly temperature being more than 10 °C); MMGSP = mean monthly growing season precipitation; 3WET = precipitation during the 3 consecutive wettest months; 3DRY = precipitation during the 3 consecutive driest months; RH = relative humidity; SH = specific humidity; ENTHAL = enthalpy.

| | Longmen, Yongping | | | Tuantian, Tengchong | | |
|---|---|---|---|---|---|---|
| | LMA | CLAMP | Present[1] | LMA[2] | CLAMP[2] | Present[1] |
| MAT (°C) | 17.4 ± 3.3 | 17.4 ± 1.3 | 15.9 | 18.7 ± 2.6 | 15.3 ± 1.3 | 14.9 |
| WMMT (°C) | | 25.8 ± 1.5 | 21.4 | | 24.3 ± 1.5 | 19.8 |
| CMMT (°C) | | 8.9 ± 2.6 | 8.2 | | 7.7 ± 2.6 | 7.6 |
| GROWSEAS (months) | | 9.3 ± 0.7 | 10 | | 8.1 ± 0.7 | 9 |
| GSP (mm) | | 1735.5 ± 217.7 | 986.9 | | 1625.7 ± 217.7 | 1381.1 |
| MMGSP (mm) | | 187.6 ± 25.3 | 98.7 | | 186.8 ± 25.3 | 153.5 |
| 3-WET (mm) | | 800.3 ± 139 | 588.6 | | 787.4 ± 139 | 790 |
| 3-DRY (mm) | | 184.5 ± 41.2 | 69.5 | | 209.9 ± 41.2 | 111.6 |
| RH (%) | | 81.1 ± 6 | 75 | | 81.6 ± 6 | 79 |
| SH (%) | | 11.1 ± 1.2 | | | 10.3 ± 1.2 | |
| ENTHAL ($kJ\,kg^{-1}$) | | 334.4 ± 5.4 | | | 329.2 ± 5.4 | |
| MSI | | 35.5 | 52.6 | | 35.5 | 49.1 |

[1] Data are from Yunnan Provincial Meteorological Bureau (YPMB) (1984).
[2] The standard error of LMA was estimated by following Miller et al. (2006). We recalculated the paleoclimate of the Late Plicoene Tuantian flora with the new calibrated CLAMP dataset (PhysgAsia1) by leaf physiognomic data providing in Xie et al. (2012).





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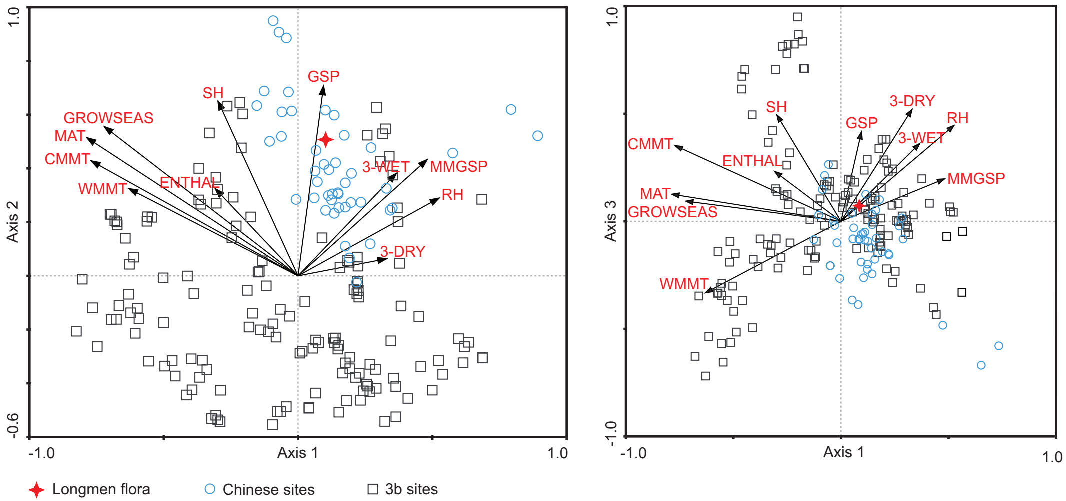


**Fig. 1.** Position of the Longmen flora in the physiognomic space of the calibrated CLAMP dataset – PhysgAsia1.

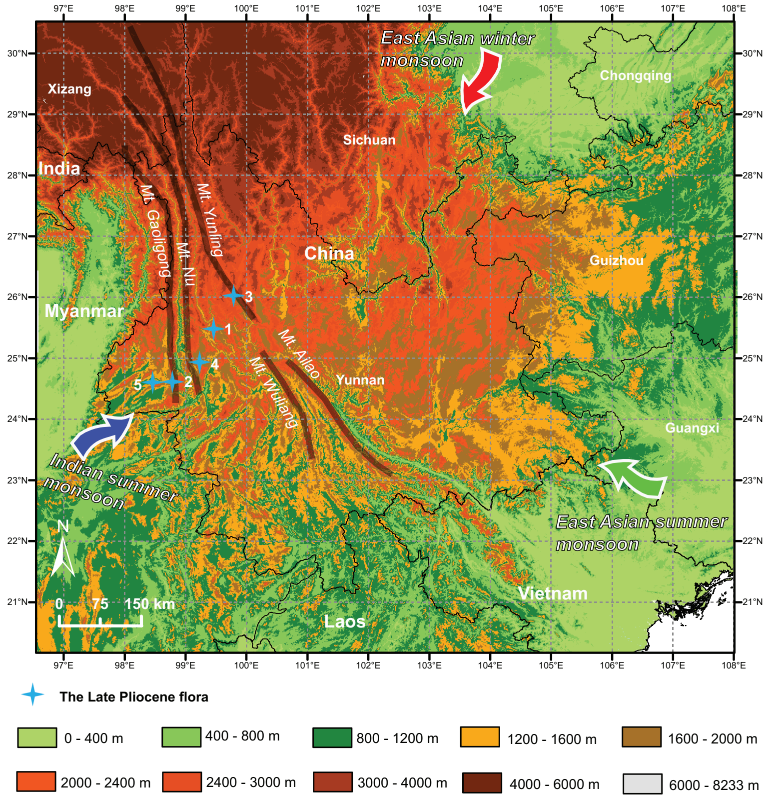


**Fig. 2.** The Asian monsoon system in Yunnan nowadays and the late Pliocene floras in western Yunnan. 1. Longmen, Yongping; 2. Longling; 3. Liantie, Eryuan; 4. Yangyi, Baoshan; 5. Tuantian, Tengchong. Detailed information on each flora is in the Supplement Table 1.





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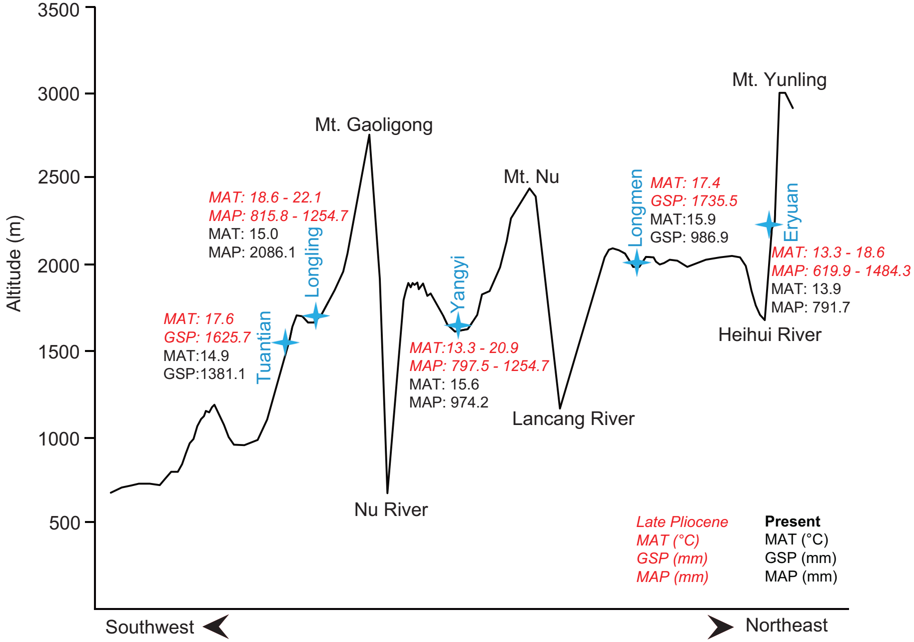


**Fig. 3.** Spatial comparison on temperature and precipitation between the late Pliocene and nowadays in western Yunnan (modified from Kou et al., 2006). Climatic data correspond to Supplement Table 1.





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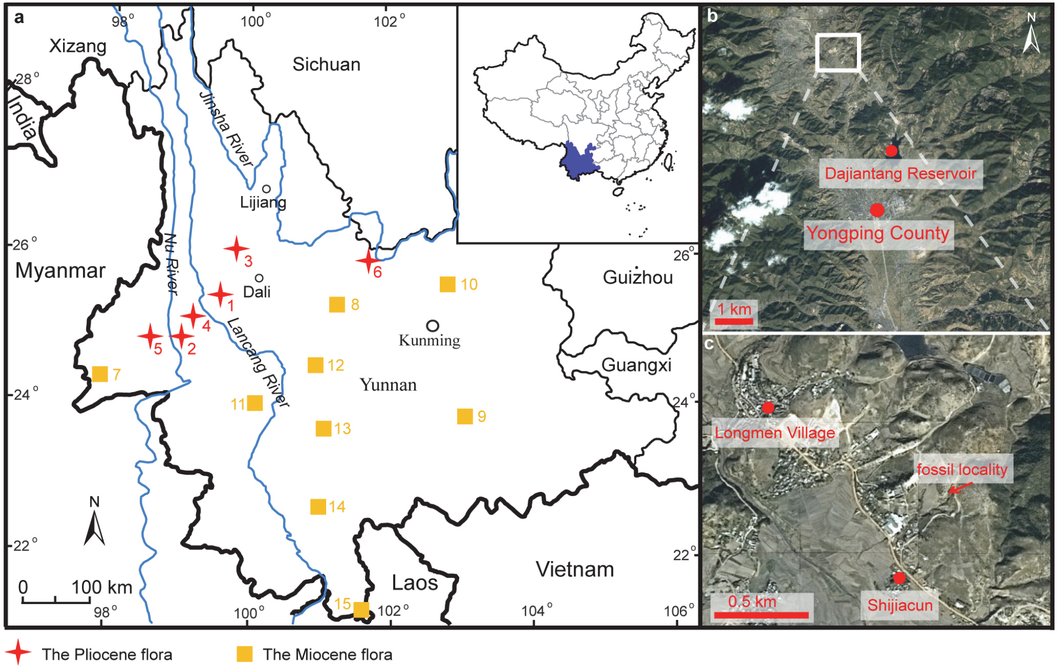


**Fig. A1.** Maps showing fossil localities of this study and floras with quantitative paleoclimate reconstructions. Information on fossil localities and reconstructed climates are detailed in Supplement Table 1. **(a)** 1. Longmen, Yongping (this study); 2. Longling (Xu et al., 2004; Kou et al., 2006); 3. Liantie, Eryuan (Kou et al., 2006); 4. Yangyi, Baoshan (Kou et al., 2006); 5. Tuantian, Tengchong (Xie et al., 2012); 6. Yuanmou (Yao et al., 2012); 7. Longchuan (Zhao et al., 2004); 8. Lühe, Chuxiong (Xu et al., 2008); 9. Xiaolongtan, Kaiyuan (Xia et al., 2009; Jacques et al., 2011a); 10. Xianfeng, Xundian (Xing et al., 2012); 11. Bangmai, Lincang (Jacques et al., 2011a, b); 12. Jingdong (Zhang et al., 2012); 13. Zhenyuan (Zhang et al., 2012); 14. Jinghong (Zhang et al., 2012); 15. Mengla (Zhang et al., 2012). **(b)** and **(c)** Fossil locality of this study.





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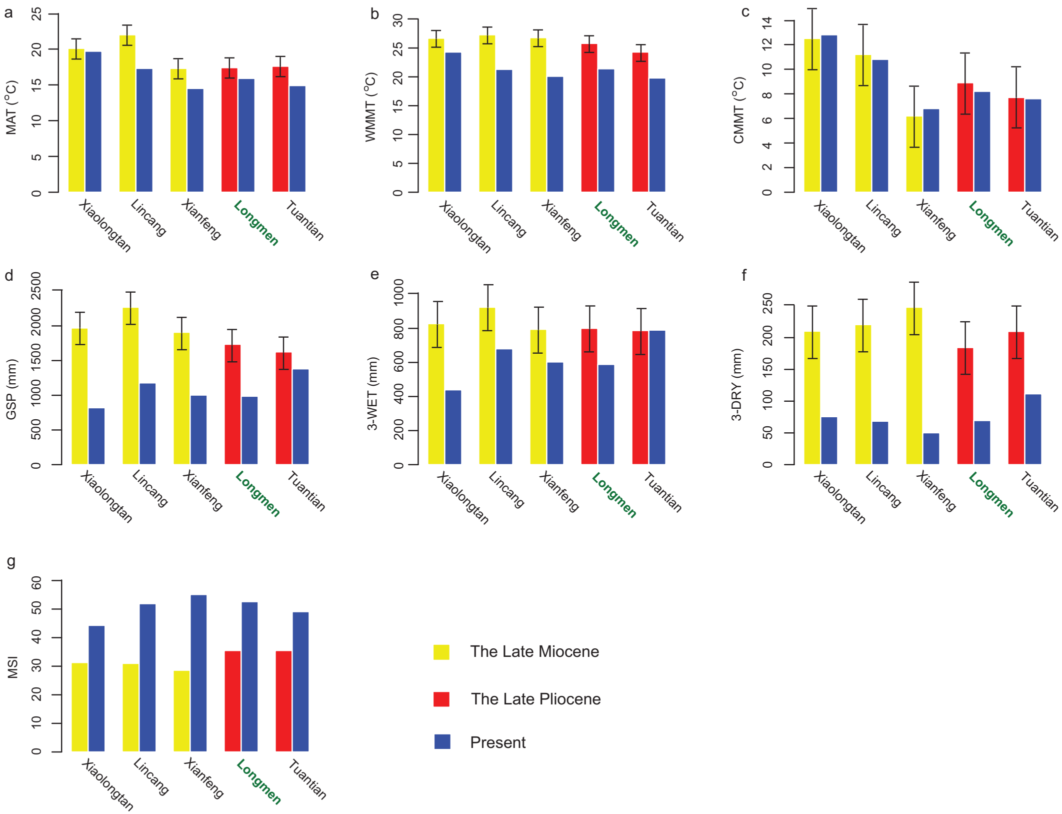


**Fig. A2.** Comparisons on climatic parameters among the late Miocene, the late Pliocene and the present day in Yunnan. Climatic data of the late Miocene and the late Pliocene are from the calibrated CLAMP dataset (PhysgAsia1) (see more details in Supplement Table 1). Climatic data of the present day are from Yunnan Meteorological Bureau (1984).





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