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Paleoclimatic estimation reveals a weak winter monsoon in southwestern China during the late Miocene: Evidence from plant macrofossils

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ABSTRACT

The late Miocene Xianfeng flora of Yunnan Province, southwestern China, was chosen to reconstruct the paleoclimate and the intensity of the Asian monsoon. Three available quantitative climate reconstruction methods from fossil plants, i.e. Leaf Margin Analysis (LMA), the Climate Leaf Analysis Multivariate Program (CLAMP), and the Coexistence Approach (CA) were used in this study. MATs (mean annual temperatures) resulting from these three approaches (i.e., LMA: 17.2 ± 2.38 °C; CLAMP: 15.43 ± 1.25 °C; CA: 17.2–21.7 °C) appear to have been higher than the present (14.9 °C), suggesting a much warmer climate in the late Miocene. Both the growing season precipitation (GSP) from CLAMP (1908.7 ± 217.7 mm) and mean annual precipitation (MAP) from CA (1206.0–1613.0 mm) estimates are higher than modern values (1003.2 mm (GSP) and 1038 mm (MAP) respectively) indicating a more humid climate during the late Miocene. By comparing these with climates reconstructed from neighboring late Miocene floras, we conclude that the general late Miocene climate appears warmer and more humid than present conditions in southwestern China. Furthermore, the evident differences in estimated monthly temperatures between the summer and winter, and precipitations between the humid and dry seasons indicate the existence of seasonality, though not as strong as that of today. Difference in precipitation of dry season indicates a marked strengthening in the winter monsoon since the late Miocene. A new monsoon intensity index has also been defined based on precipitation seasonality to investigate the intensity of the Asian monsoon.

1. Introduction

The late Miocene has been considered as an important geological epoch for the evolution of global climate (Quade et al., 1989; An, 2000; An et al., 2001; Zachos et al., 2001; Fortelius et al., 2002; Wang et al., 2003; Zheng et al., 2004; Bruch et al., 2007, 2011; Tang et al., 2011). Severe environmental changes occurred both on the continents and in the oceans during the late Miocene (Bruch et al., 2007). These changes, for example, include the development and spread of C4 grasses, the aridification of the interiors of continents and the expansion of open landscapes (Molnar, 2005). Also, the late Miocene witnessed the development and evolution of the East Asian monsoon climate, one of the most influential controlling forces shaping the paleoenvironment in East Asia during the Neogene (An, 2000; An et al., 2001; Guo et al., 2002; Liu and Yin, 2002; Dettman et al., 2003; Liu et al., 2011; Sun et al., 2011). Intensive studies have been carried out to reconstruct the history of the Asian monsoon system (e.g. Quade et al., 1989; An et al., 2001; Guo et al., 2002; Sun and Wang, 2005; Wan et al., 2007; Passey et al., 2009). However, the evolution and intensity of the Asian monsoon system through geological time have been highly debated (Sun and Wang, 2005; Wan et al., 2007; Tang et al., 2011; Yao et al., 2011). To date, several indices are used to investigate the development of monsoon intensity (Liu and Yin, 2002; Steinke et al., 2010). These indices are based on either climatic parameters (Chen et al., 1991; Parthasarathy et al., 1992; Liu and Yin, 2002; Zhao et al., 2009), loess-paleosol sequences and records from marine sediments, such as isotopic data (Quade et al., 1989; An et al., 2001; Dettman et al., 2001; Passey et al., 2009), atmospheric circulation system (Webster and Yang, 1992; Goswami et al., 1999; Wang and Fan, 1999), or a combination of wind and climatic parameters (Liu and Yin, 2002; Zhang and Wang, 2008). However, different monsoon indices usually give controversial results. For instance, using aeolian and marine proxies, An et al. (2001) divided the East Asian monsoon into three evolution stages of the Asian monsoon showing that the onset of

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the East Asian monsoon happened at about 9–8 Ma ago and the East Asian summer and winter monsoons intensified at about 3.6–2.6 Ma ago. However, by using Neogene pollen records, Jiang and Ding (2009) suggest that the East Asian summer monsoon was generally strong during the early to early middle Miocene and displayed a stepwise weakening since the late middle Miocene. Paleoclimatic reconstructions based on plant fossils provide opportunities to investigate the monsoon intensity quantitatively by using climatic variables. Several studies have tried to estimate the Asian monsoon intensity using temperature or precipitation parameters obtained from paleoclimatic reconstructions (Xia et al., 2009; Jacques et al., 2011a; Liu et al., 2011; Quan et al., 2011; Yao et al., 2011). Jacques et al. (2011a) investigated the Asian monsoon intensity in the late Miocene of southwestern China using the ratios of mean precipitation of the wettest and driest months to mean annual precipitation as indicators. However, the indices are based on two monthly means and not on mean values overall. Therefore, a new index is needed to accommodate the climatic parameters reconstructed based on paleoclimatic reconstructions.

The uplift of the Tibetan Plateau and its adjacent areas has played an important role in the onset and enhancement of Asian monsoon systems (Kutzbach et al., 1989; Raymo and Ruddiman, 1992; An et al., 2001; Guo et al., 2002; Liu and Yin, 2002; Clift et al., 2008). The Yunnan-Guizhou Plateau, located adjacent to the southeast of the Tibetan Plateau, today has a complicated topography and diverse climates, as well as high plant diversity. The geological history of the Yunnan-Guizhou Plateau has strongly been affected by the uplift of the Tibetan Plateau during the Cenozoic (Tang and Shen, 1996; Sun et al., 2011). Quantitative paleoclimatic reconstructions of Neogene floras in this region are crucial to understand the environmental change and the evolution of the Asian monsoon system under the influence of the uplift of the Himalaya. More than 20 Neogene fossil floras have been reported in this region (Tao and Kong, 1973; Writing Group of Cenozoic Plants of China, 1978; Tao and Du, 1982; Tao and Chen, 1983; Zhou, 1985, 2000; Wang, 1996; Xu et al., 2000, 2004, 2008; Wang and Shu, 2004; Zhao et al., 2004; Kou et al., 2006; Sun et al., 2011). The last decade saw a great improvement in paleoclimatic reconstructions of Yunnan (Xu et al., 2000, 2004, 2008; Zhao et al., 2004; Kou et al., 2006; Xia et al., 2009; Jacques et al., 2011a; Sun et al., 2011; Yao et al., 2011). During the late Miocene, both the Lincang and the Xiaolongtan flora indicate a similar temperature to that of today but with a more humid climate (Xia et al., 2009; Jacques et al., 2011a). In the present work, we focus on the late Miocene Xianfeng flora from central Yunnan, which comprises more than 2000 plant fossils belonging to a total of 54 morphotypes (Xing, 2010), and therefore represents an excellent collection for paleoclimate studies.

Our study has three major objectives: (1) to quantitatively reconstruct the paleoclimate of the Xianfeng flora, (2) to propose a monsoon index applicable to paleoclimatic reconstruction, and (3) to reconstruct the monsoon intensity in the late Miocene of Yunnan.

2. Materials and methods

2.1. Fossil site and materials

The fossil site is situated in the Xianfeng Basin, 60 km north of Kunming, southwest China (Fig. 1; 25°25′ N, 102°51′ E, asl 1900 m). The Xianfeng Basin contains strata of the Xiaolongtan Formation, a formation well exposed in central Yunnan (Xing et al., 1999). The geological age of the Xiaolongtan Formation is considered to be late Miocene based on mammal fauna (Zhang, 1974; Dong, 2001), plant macrofossils, and pollen assemblages (Zhou, 1985, 2000; Wang, 1996).

The lithological sequence is composed of four members, named as N_1^1x to N_1^4x, respectively (Xing et al., 1999; Wu et al., 2006; Xing et al., 2010; Fig. 2). The third member is subdivided into two sub-members denoted as $N_1^3x^1$ and $N_1^3x^2$ in ascending order (Xing et al., 1999; Wu et al., 2006). More than 2000 plant fossils including leaves and fruits were collected from the $N_1^3x^2$ member (Xing, 2010; Xing et al., 2010).

Both Fagaceae and Lauraceae are the dominant families in this flora (Xing, 2010). 34 species belonging to 21 genera of nine families were preliminarily identified. They were used for the Coexistence Approach (CA) calculation (Appendix 2). In addition, 24 morphotypes remain unidentified at the moment. 54 leaf morphotypes (Appendix 1) were used to perform the Climate Leaf Analysis Multivariate Program (CLAMP) and Leaf Margin Analysis (LMA).

2.2. Methods

To date, there are two general approaches inferred from fossil leaf assemblages for assessing quantitative terrestrial paleoclimates: physiognomic techniques (i.e., morphologically based methodologies, such as Leaf Margin Analysis (LMA) and Climate Leaf Analysis Multivariate Program (CLAMP)) and nearest living relative techniques (taxonomy-based methodologies, such as the Coexistence Approach (CA)). Each method

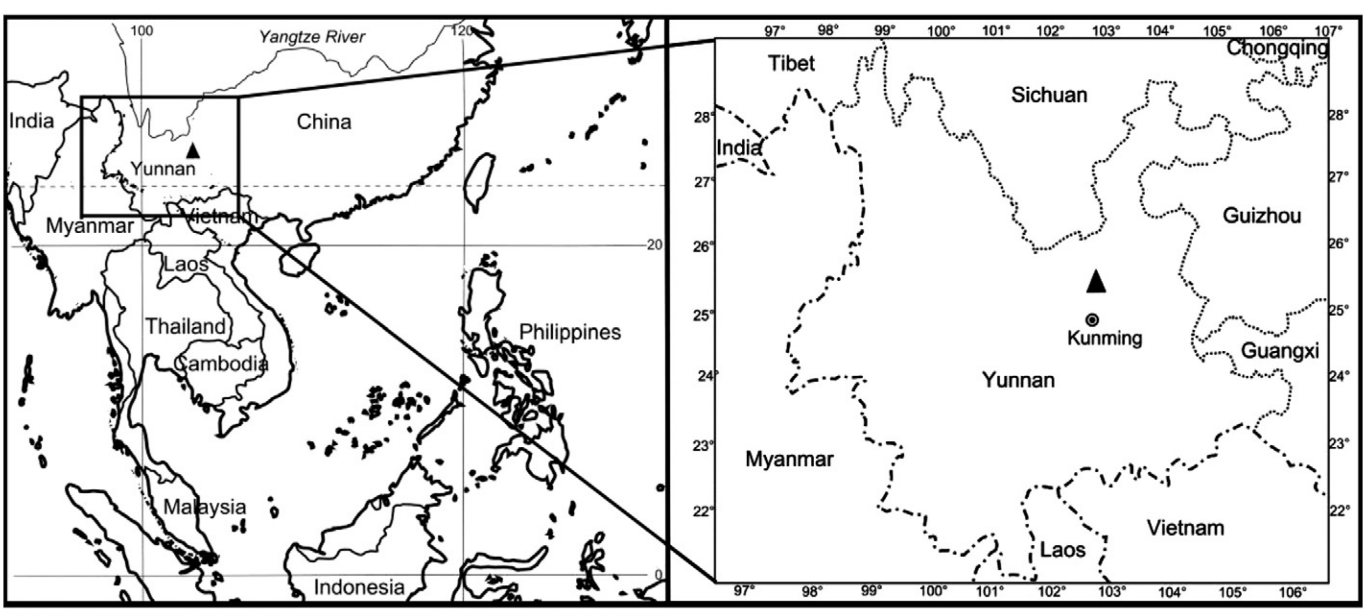

Fig. 1. Map showing the fossil locality (black triangle).
Adapted from Xing et al. (2010).

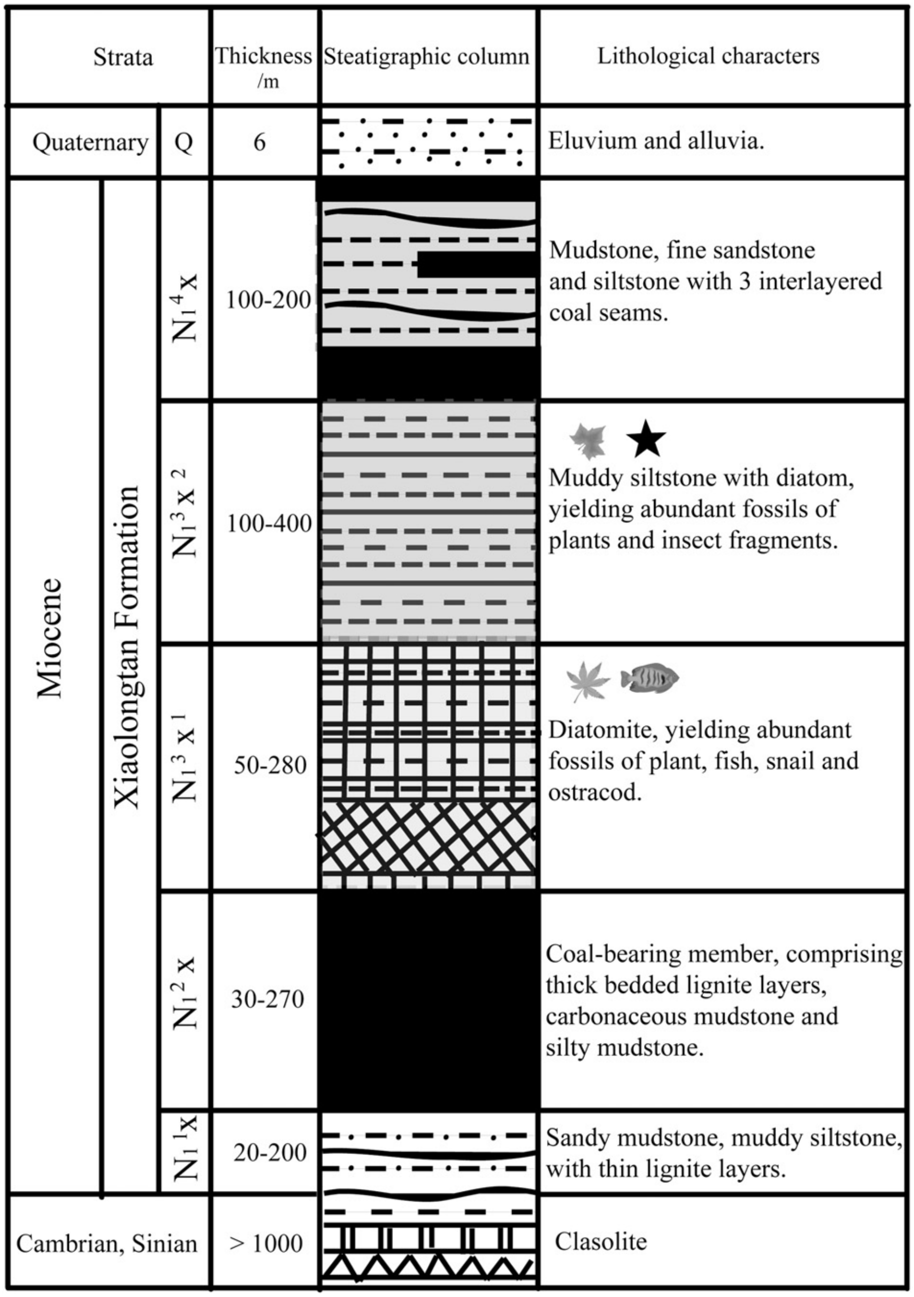

Fig. 2. The sketch strata table of the Xianfeng coalmine. The member where the fossils cones were collected is marked as pentagram.
Adapted from Xing et al. (2010); simplified after the data of Xing et al. (1999) and Wu et al. (2006).

has specific advantages and disadvantages. Therefore, different methods are preferable to cross-validate the results (Uhl et al., 2006, 2007; Yang et al., 2007; Xia et al., 2009; Jacques et al., 2011a).

In this study, we use Leaf Margin Analysis (LMA), Climate Leaf Analysis Multivariate Program (CLAMP) and Coexistence Approach (CA) to reconstruct the paleoclimate of the late Miocene Xianfeng flora.

2.2.1. Climatic parameters

Abbreviations of climatic parameters used in the text are as follows: mean annual temperature (MAT), mean temperature of the warmest month (WMT), mean temperature of the coldest month (CMT), length of the growing season (LGS), growing season precipitation (GSP), mean monthly growing season precipitation (MMGSP), precipitation during the three consecutive wettest months (MP3WET), precipitation during the three consecutive driest months (MP3DRY), relative humidity (RH), specific humidity (SH), enthalpy, mean annual precipitation (MAP), mean precipitation of the driest month (MPDRY), mean precipitation of the warmest month (MPWAR), mean precipitation of the wettest month (MPWET), and monsoon intensity index (MSI).

2.2.2. Leaf Margin Analysis

In order to compare different models, we use both the East Asia model (Wolfe, 1979; Wing and Greenwood, 1993) and the Chinese model (Su et al., 2010) to estimate the MAT of the Xianfeng flora.

The East Asian model: $MAT = 1.141 + 30.6 \times p$.
The Chinese model: $MAT = 1.038 + 27.6 \times p$.

The standard error (SE) is calculated by (Miller et al., 2006):

$$SE = b \times \sqrt{[1 + \varphi(n-1)p(1-p)] \times \frac{p(1-p)}{n}}$$

Table 1
Results of LMA and CLAMP analyses compared with the modern values. The modern data except enthalpy are from the China meteorological data sharing service system (www.cdc.cma.gov.cn). The modern enthalpy of Xianfeng is calculated by the following formula: Enthalpy = 1.006 ∗ MAT(K) + SH(kg/kg) ∗ (1.84 ∗ T(K) + 2502).

Climatic parameters	LMA-East Asian model	LMA-Chinese model	CLAMP-PhysgAsia1	Modern value
MAT (°C)	19.1 ± 2.22	17.32 ± 2.46	15.43 ± 1.25	14.9
WMT (°C)			26.78 ± 1.51	19.7
CMT (°C)			6.23 ± 2.57	7.6
GRS (months)			7.63 ± 0.74	9
GSP (mm)			1908.7 ± 217.7	1003.2
MMGSP (mm)			237.4 ± 25.3	162.0
MP3WET (mm)			794.7 ± 139.0	584.5
MP3DRY (mm)			248.0 ± 41.2	38.2
Relative humidity (%)			76.82 ± 6.04	72
Specific humidity (g/kg)			9.67 ± 1.18	9.57
Enthalpy (kJ/kg)			327.0 ± 5.4	318.29

where p is the proportion of woody dicotyledons with entire leaf margins in an investigated flora; b is the slope in the LMA equation; φ is the overdispersion factor, we assume to have a value of 0.052 based on Miller et al. (2006); and n is the total number of woody dicotyledon leaves in the assemblage.

2.2.3. Climate Leaf Analysis Multivariate Program (CLAMP)

The statistical methodology underlying CLAMP is Canonical Correspondence Analysis (CCA), a multivariate method that relates attributes (in ecology species, but in CLAMP leaf architecture) to environmental gradients (Wolfe, 1993; Wolfe and Spicer, 1999). Four calibration datasets are currently available on the CLAMP website: Physg3arc/brcAZ (Wolfe, 1993; Wolfe and Spicer, 1999; Spicer, 2009), PhysgAsia1 (Jacques et al., 2011c) and PhysgIndia1 (Srivastava et al., 2012). As the PhysgAsia1 calibration yields more accurate results in monsoonal areas (Jacques et al., 2011c) and the Xianfeng flora is located in southwestern China, we use the PhysgAsia1 dataset.

2.2.4. Coexistence Approach (CA)

The aim of the Coexistence Approach is to find the climatic interval for a given fossil flora in which all known nearest living relatives (NLRs) of the fossil taxa can coexist (Mosbrugger and Utescher, 1997). To reduce uncertainties related to the determination of the NLR, we use the generic level for most taxa (Xia et al., 2009). As the NLRs of fagaceous and two pinaceous species were assigned by detailed architectural comparisons with extant species, we decided to use the specific level for these species (Jones, 1986; Zhou et al., 1995; Luo and Zhou, 2002; Xing, 2010). For taxa not available in the Paleoflora database (Utescher and Mosbrugger, 2012), we follow the procedures stated in Xia et al. (2009) and Jacques et al. (2011a) to supplement the database. 34 taxa were used in this study (Appendix 2). Climatic intervals were calculated using the ClimStat program (Heinemann, 1998–1999).

2.3. Seasonality and monsoon intensity indices

The contrasts of summer (wet season) and winter (dry season) temperatures and precipitation are important characters of a monsoon climate (Liu and Yin, 2002). Therefore, the seasonalities of temperature and precipitation are important indices to describe the intensity of the Asian monsoon system. Liu and Yin (2002) defined a monsoon intensity index as the product of temperature and precipitation seasonalities. However, in some cases, the temperature and precipitation seasonalities are sometimes uncoupled (e.g. Xia et al., 2009; Jacques et al., 2011a). Therefore, the product of temperature and precipitation seasonality might not be a good index. As monsoon influence on vegetation is mainly expressed as precipitation (Sun and Wang, 2005), precipitation rates in different seasons are essential meteorological variables describing a monsoon climate (Wang and Ho, 2002). van Dam (2006) defined precipitation seasonality as the difference between precipitations during the wettest and the driest month. This index shows a higher correlation with precipitation in the wettest month than with precipitation in the driest month (van Dam, 2006), which means that a region with high precipitation in the wettest month usually has a higher seasonality. Because of this, it is difficult to compare regions with different annual precipitations. In this study, we use the difference between WMT and CMT to illustrate seasonality in temperature. To investigate seasonality in precipitation, we use the ratio of MP3WET and MP3DRY to GSP as indicators and we define the difference between these two parameters as the monsoon intensity index (MSI = (MP3WET − MP3DRY) ∗ 100 / GSP). These results will be compared to the indicators defined by Jacques et al. (2011a) based on CA analysis and the index defined by Liu and Yin (2002).

3. Results

3.1. LMA

MATs obtained by the East Asian regression model and the Chinese model are 19.1 ± 2.22 °C and 17.32 ± 2.46 °C respectively (Table 1).

3.2. CLAMP

54 leaf morphotypes were used in CLAMP calculations. The leaf scores are listed in Appendix 1. The results are shown in Table 1. MATs are calculated to be 15.43 ± 1.25 °C which suggests a slightly warmer climate than the present day (14.9 °C). WMT (26.78 ± 1.51 °C) is much higher (19.7 °C), while CMT (6.23 ± 2.57 °C) is similar to the modern value (7.6 °C). The difference between WMT and CMT indicates a clearly seasonal climate. GSP is calculated as 1908.7 ± 217.7 mm, which is much higher than the present (1003.2 mm). MP3WET is calculated to be 794.7 ± 139.0 mm, also higher than the present. It is worth noting that MP3DRY (248.0 ± 41.2 mm) is much higher than the present (34.9 mm). Enthalpy (321.3 ± 4.9 kJ/kg) is higher than the present (318.29 kJ/kg).

3.3. CA

The results of the CA are given in Table 2 and the delimiting species of the coexistence intervals are also listed, as well as the outliers. The climatic parameter ranges of the NLR taxa used in the analysis are listed in Appendix 2. In this analysis, one species at a maximum is not included in the coexistence intervals indicating that overall reliable

Table 2
Results of the CA compared with modern values. The modern data are from the China meteorological data sharing service system (www.cdc.cma.gov.cn).

Climatic variables	Coexistence intervals	Modern values	Minimal border	Maximal border	Outliers
MAT (°C)	17.2–21.7	14.9	*Pinus prekesiya*	*Quercus* aff. *guyavaefolia*	None
WMT (°C)	23.4–26.1	19.7	*Cyclobalanopsis* aff. *gilva*	*Nothaphoebe* sp.	None
CMT (°C)	10.7–13.0	7.6	*Pinus prekesiya*	*Castanopsis* aff. *delavayi*	*Quercus* aff. sect. *Heterobalanus*
MAP (mm)	1206.0–1613.0	1011.3	*Cyclobalanopsis* aff. *gilva*	*Rhus* sp.	None
MPWET (mm)	224.0–236.0	205.9	*Nothaphoebe* sp.	*Alangium* aff. *chinensis*	*Rhus* sp.
MPDRY (mm)	19.0–24.6	11.5	*Machilus* sp.	*Castanopsis* aff. *calathiformis*	*Cyclobalanopsis* aff. *gilva*
MPWAR	137.6–178.0	204.8	*Lithocarpus lancifolius*	*Pistacia* sp.	None

Table 3
The precipitation seasonality of three late Miocene floras in Yunnan. The precipitation values of Xiaolongtan and Lincang are based on Xia et al. (2009), Jacques et al. (2011a,b) and the values of the Lühe flora are from Xu et al. (2008).

Fossil sites	MPWET/MAP∗100		MPDRY/MAP∗100		MP3WET/GSP∗100		MP3DRY/GSP∗100		MSI: (MP3WET − MP3DRY)/GSP∗100		(WMT − CMT)(MP3WET − MP3DRY)	
	Miocene	Modern	Miocene	Modern	Miocene	Modern	Miocene	Modern	Miocene	Modern	Miocene	Modern
Xianfeng	13.9–19.6	20.4	1.2–2.0	1.1	41.6	58.2	13.0	3.8	28.6	54.4	11,243.7	6874.0
Xiaolongtan	13.7–20.4	18.7	1.2–2.0	1.4	42	53.5	10.7	5.1	31.3	48.4	8768.5	4565.5
Lincang	15.5–25.0	21.0	1.3–1.7	0.9	40.7	57	9.7	3.5	31.0	53.5	11,331.2	6704.3
Lühe	14.3–31.6	22.1	0.8–2.3	0.9	–	–	–	–	–	–		

coexistence intervals are obtained. For MAT 17.2–21.7 °C, WMT 23.4–26.1 °C, and CMT 10.7–13.0 °C are obtained. For MAP 1206.0–1613.0 mm, MPWET 224.0–236.0 mm, MPDRY 19.0–24.6 mm, and MPWAR 137.6–178.0 mm are obtained.

3.4. Seasonality and monsoon intensity

CLAMP suggests the difference between WMT and CMT (ca. 20 °C) than the present (12.1 °C), whereas CA (ca. 13 °C) suggests a similar temperature seasonality to today.

The indices for precipitation seasonality and monsoon intensity of four late Miocene floras are listed in Table 3. In Xianfeng, Xiaolongtan and Lincang, MP3WETs represent 40.7–42% of GSPs (compared to 53.5–58.2% at present day), whereas MP3DRYs represent 9.7–13% of GSPs (compared to 3.5–5.1% at present day). Compared to CLAMP, MPWETs of CA are similar or slightly lower than the present. The ratios of MPDRY to MAP of Xianfeng and Lincang are higher, whereas Xiaolongtan and Lühe have similar values to the present day. MSIs of Xianfeng, Xiaolongtan and Lincang vary from 28.6 to 31.3 which are much lower than the modern values (48.4–54.4) (Table 3). In contrast, results based on the index defined by Liu and Yin (2002) are much higher than the present.

4. Discussion

4.1. Comparison of different methods

MATs obtained from different methods vary from 15.43 to 21.7 °C (Tables 1 and 2). The Chinese LMA calibration gives a lower MAT than the East Asia calibration. This trend was also found in previous studies (Su et al., 2010; Jacques et al., 2011a). Both MATs estimated by LMA fall in the range of the coexistence interval. The lowest value is obtained from CLAMP. Also in previous studies it was shown that CLAMP tends to produce lower values when compared with CA and LMA (Sun et al., 2002; Liang et al., 2003; Kvaček, 2007; Uhl et al., 2007).

CLAMP gives lower CMT than CA (Tables 1 and 2). For WMT, CLAMP gives slightly higher values than, or values at the upper limit of, the coexistence interval (Tables 1 and 2). So, the results from CLAMP indicate a higher seasonality in temperature than those from CA. GSP estimated by CLAMP is much higher than MAP derived from CA (Tables 1 and 2). The most significant difference is the precipitation in the dry months. MP3DRY is over twenty times that of MPDRY from CA. However, it is difficult to state which method provides a more plausible solution. There are various possibilities that could explain the contradictory results. It could be assumed that only one month of the dry season was rather dry and both other months were considerably more humid. A possible source of error in the CA application could be the NLR concept used in the present study. However, reconstructions of both methods consistently indicate that MP3DRY and MPDRY were both considerably higher than at present and suggest a relatively humid dry season.

4.2. Paleoclimate of the late Miocene Xianfeng flora

MATs estimated from the three methods are all higher than the present value (14.9 °C) (Table 1). However, the difference between the past and modern values is not equally distributed throughout the year. WMTs from CLAMP (26.78 ± 1.51 °C) and CA (23.4–26.1 °C) are significantly higher than the present-day value (19.7 °C), whereas CMT obtained from CLAMP (6.23 ± 2.57 °C) is close to the modern value (6.8 °C), while the CA result (10.7–13.0 °C) is significantly higher (Table 1). These results indicate a warmer climate, especially a warmer summer, in Xianfeng during the late Miocene.

This trend with slightly higher or similar MAT, clearly higher WMT, and similar or lower CMT can also be seen from previous works on the late Miocene Lincang and Xiaolongtan floras in this region (Xia et al., 2009; Jacques et al., 2011a,c). The results also match

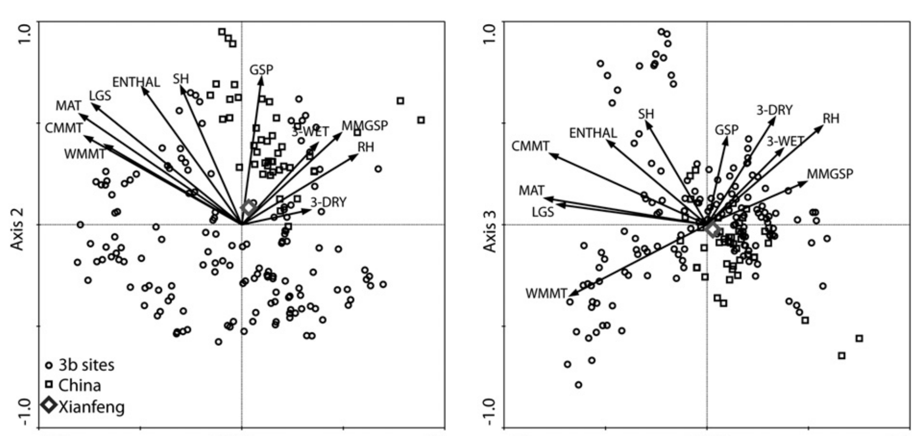

Fig. 3. Two-dimensional views of physiognomic space of the PhysgAsia1 calibration in Axis 1/2 space and Axis 1/3 space.

well with data obtained from various quantitative paleoclimatic reconstructions of the Miocene (Mosbrugger et al., 2005; Bruch et al., 2011; Liu et al., 2011; Utescher et al., 2011), which suggest a warmer temperature in a global average in late Miocene. The difference between the WMT and CMT indicates a stronger seasonality of temperature in Xianfeng during the late Miocene than at present day.

All the precipitation parameters estimated by CLAMP and CA are higher than those of the present (Tables 1, 2). These results indicate a more humid climate in the Xianfeng flora. The wetter climate in central Europe and China during the Miocene has been demonstrated by many other studies (Mosbrugger et al., 2005; Yang et al., 2007; Xu et al., 2008; Utescher et al., 2009, 2011; Xia et al., 2009; Bruch et al., 2011; Jacques et al., 2011a,b; Yao et al., 2011) and the global climate was warmer than today (Zachos et al., 2001; Utescher et al., 2007, 2009, 2011), which may explain higher precipitation.

Among the precipitation parameters, MP3WET from CLAMP and the MPWET from CA are similar to the present value, while MP3DRY and MPDRY are obviously higher. The difference between precipitation in wet month(s) and dry month(s) indicates clear precipitation seasonality during the late Miocene. In CLAMP physiognomic space Xianfeng clearly plots within the Chinese sites (Fig. 3), which suggests a seasonal climate. MP3WET from CLAMP represents about four times that of MP3DRY and MPWET from CA represents 9 to 12 times that of MPDRY; these compared with the ratio today which is about 18 times. These results indicate that precipitation seasonality was lower in Xianfeng during the late Miocene than at present. This trend also agrees with other paleoclimatic reconstructions (Jacques et al., 2011a,b; Yao et al., 2011). To summarize, our results indicate a monsoonal warm temperate climate in Xianfeng during the late Miocene.

4.3. The late Miocene climate of Yunnan

In previous works, three late Miocene floras from Yunnan were used to reconstruct paleoclimates, i.e. Lühe flora from western Yunnan (Xu et al., 2008), Xiaolongtan flora of southeastern Yunnan (Xia et al., 2009), and Lincang flora from southwestern Yunnan (Jacques et al., 2011a,c). By comparing the climates of Xianfeng with the results from these published studies, we have a better understanding of the late Miocene climate of Yunnan (Table 4).

The paleoclimatic ranges of Lühe are relatively wide compared to the other floras. Most modern climatic parameters are within the range of the coexistence intervals obtained for the Lühe flora. However, WMT and MPDRY are higher than the present, suggesting a warm summer and more humid winter for the late Miocene Lühe flora. For the other three sites, their MATs are higher than those of the present, with WMTs being significantly higher in the case of Xianfeng and Lincang while for Xialongtan the values are about the same level. On the other hand, CMTs obtained from CA and CLAMP are generally lower than those of the present except the CA result for Xianfeng. For all these three sites, there is a stronger seasonality in temperature during the Miocene than at present.

Compared to modern precipitation parameters, all these three sites had a more humid climate during the late Miocene in Yunnan. It is significant that precipitation in the dry season is much higher in the late Miocene. The results indicate a relatively weaker seasonality in precipitation during the Miocene than at present (Tables 3, 4).

In conclusion, Yunnan had a warm, humid and seasonal climate during the late Miocene.

4.4. The intensity of the Asian monsoon during the late Miocene in Yunnan

The results of the intensity of the Asian monsoon based on precipitation indicators are listed in Table 3. Based on Liu and Yin's index, the monsoon was much stronger during the late Miocene. As the index is the product of the temperature and precipitation

Table 4
Paleoclimatic comparison of four late Miocene floras in Yunnan. The Lincang, Xiaolongtan and Lühe data are from Jacques et al. (2011a,b), Xia et al. (2009) and Xu et al. (2008) respectively. The modern values are from the Yunnan Meteorological Bureau (1984) and the China meteorological data sharing service system (www.cdc.cma.gov.cn).

Climatic			Xianfeng			Lincang				Xiaolongtan			Lühe	
Parameters	LMA	CLAMP	CA	Modern	LMA	CLAMP	CA	Modern	LMA	CLAMP	CA	Modern	CA	Modern
MAT (°C)	17.32 ± 2.46	15.43 ± 1.25	17.2–21.7	14.9	22.0 ± 1.9	19.8 ± 1.25	18.5–19.0	17.3	22.3 ± 2.3	19.9 ± 1.25	16.7–19.2	19.7	13.3–20.9	16.0
WMT (°C)		26.78 ± 1.51	23.4–26.1	19.7		27.3 ± 1.51	27.3–27.8	21.3		26.7 ± 1.51	25.4–26.0	24.3	22.5–27.5	21.4
CMT (°C)		6.23 ± 2.71	10.7–13.0	7.6		11.2 ± 2.57	9.6–12.5	10.8		12.5 ± 2.57	7.7–8.7	12.8	2.5–12.6	8.7
MAP (mm)		–	1206.0–1631	1011.3		–	1213–1394	1178.7			1215–1639	820.5	803.6–1254.7	862.9
MPWET		–	224.0–236.0	205.9		–	216–304	247		–	224–248	153.5	179.4–249.6	190.7
MPDRY		–	19.0–24.6	11.5		–	18–21	10.9		–	19–24	11.4	10.2–18.5	8.2
GSP		1908.7 ± 217.7		1003.2		2269.7 ± 217.7	–	1178.7		1970.3 ± 217.7		820.5		
MP3WET (mm)		794.7 ± 139.0	–	603		924.4 ± 139.0	–	680.2		827.8 ± 139.0		439.4		
MP3DRY (mm)		248.0 ± 41.2	–	34.9		220.6 ± 41.2	–	41.7		210.3 ± 41.2		42.2		

seasonality, it is highly correlated with high temperature in the warm month and high precipitation in wet season which means that a region with high temperature in the warmest month and high precipitation in the wettest month usually has a higher seasonality. Because of this, it is difficult to compare regions with different annual temperatures and precipitations. Therefore, this index might not be a good one to estimate the monsoon intensity. In contrast, for the studied Yunnan sites, based on our index, the monsoon was weaker during the late Miocene than at the present (Table 3). Because the strength of the monsoon is the result of the alternation of humid winds in the summer and dry winds in the winter, we need to have a closer look to understand what causes the weakness of the late Miocene monsoon in Yunnan. MP3WETs of the three floras represent about 40.7–46% of annual precipitation rates, which is less than the present values (Table 3). MP3DRYs in the late Miocene represent 10–13% of the GSPs, while MP3DRYs only represent 3.5–5.1% of the GSPs at present (Table 3). This trend also matches the results of MPDRY and MPWET from CA (Table 3). The MPWETs of late Miocene sites are similar or a little lower than the present values and the MPDRYs or the mean values are higher than the present values. The large differences of dry season (winter) precipitation between the late Miocene and present day point towards a weaker winter monsoon during the late Miocene. This corresponds to a time of wetter conditions in southwestern China (Jacques et al., 2011a,b; Sun et al., 2011; Yao et al., 2011). Considering the similarity in summer precipitation, the late Miocene and present day summer monsoon may have been of similar intensity.

Our results confirm that the evolution of the winter and the summer monsoon was not coupled (Wang et al., 2005). The winter monsoon is the result of high pressure over the Siberian–Mongolian region compared to low pressure over the ocean (Ding et al., 1995). In the late Miocene world, where the global climate was warmer and the latitudinal temperature gradient was weaker than today (Utescher et al., 2011), the winter temperature of the Siberian–Mongolian region might not have been as cold and the atmospheric pressure during the winter not as high. In other words, the strength of the winter winds might have been weaker than at present. The weaker winter monsoon in the late Miocene was also suggested by other proxies (e.g. Jia et al., 2003; Wan et al., 2007).

5. Conclusion

Three methods were used to reconstruct the paleoclimate of the late Miocene Xianfeng flora. The results indicate that the Xianfeng flora experienced a monsoonal warm temperate climate. By comparing it with other neighboring late Miocene floras, we conclude that Yunnan had a warmer, humid and seasonal climate. The precipitation seasonality was weaker and, based on our monsoon intensity index, a weaker winter monsoon was suggested.

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