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Quantitative reconstruction of the Late Miocene monsoon climates of southwest China: A case study of the Lincang flora from Yunnan Province

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A B S T R A C T

The Miocene Lincang leaf assemblage is used in this paper as proxy data to reconstruct the palaeoclimate of southwestern Yunnan (SW China) and the evolution of monsoon intensity. Three quantitative methods were chosen for this reconstruction, i.e. Leaf Margin Analysis (LMA), Climate Leaf Analysis Multivariate Program (CLAMP), and the Coexistence Approach (CA). These methods, however, yield inconsistent results, particularly for the precipitation, as also shown in European and other East Asian Cenozoic floras. The wide range of the reconstructed climatic parameters includes the Mean Annual Temperature (MAT) of 18.5–24.7 °C and the Mean Annual Precipitation (MAP) of 1213–3711 mm. Compared with the modern Lincang climate (MAT, 17.3 °C; MAP, 1178.7 mm), the Miocene climate is slightly warmer, wetter and has a higher temperature seasonality. A detailed comparison on the palaeoclimatic variables with the coeval Late Miocene Xiaolongtan flora from the eastern part of Yunnan allows us to investigate the development and interactions of both South Asian and East Asian monsoons during the Late Miocene in southwest China, now under strong influence of these monsoon systems. Our results suggest that the monsoon climate has already been established in southwest Yunnan during the Late Miocene. Furthermore, our results support that both Southeast Asian and East Asian monsoons co-occurred in Yunnan during the Late Miocene.

1. Introduction

Knowledge about the past climates is crucial for our better understanding of the possible impacts of Global Change (Uhl et al., 2006). Quantitative palaeoclimatic data from the Chinese Neogene sites are still far from satisfactory, although the past decade has seen the large improvement on data accumulation from several individual Neogene floras throughout China. All this is particularly true for Yunnan Province, a province affected by both Southeast Asian and East Asian monsoons.

At present, the Chinese climates are mainly shaped by the Asian monsoon which produces two seasons with distinctly different weather patterns. In summer, the Asian monsoon is driven by two major convective heat sources: one developed over the Bay of Bengal–Indian Ocean–Arabian Sea, and the other over the South China Sea and the Philippines Sea (Wang and Fan, 1999). These two sources show poor interannual correlations (Wang and Fan, 1999). They are responsible for the so-called Southeast Asian summer monsoon and East Asian summer monsoon, respectively. These two monsoon systems result in a high precipitation over China in summer. On the other hand, in winter, high pressure over the Siberian–Mongolian regions and low pressure over the northwestern Pacific Ocean, Australasia, and the African continent produce strong northern winds known as the winter monsoon (Ding et al., 1995). These winter winds exert a strong impact on the South Chinese climates (Ding et al., 1995), causing low precipitation across the whole of Asia (Liu and Yin, 2002).

The Tibetan Plateau plays an important role in the Asian monsoon circulation patterns (Flohn, 1968; Liu and Yin, 2002). The onset of the Asian monsoon has been linked to the uplift of the Tibetan Plateau and the intensity of the monsoon linked to the height of the Tibetan Plateau. Previous studies showed that the East Asian monsoon was certainly established around 24 Ma (Guo et al., 2002; Garzione et al., 2005; Sun and Wang, 2005; Clift et al., 2008). Studying the mineralogical and sedimentological records from the northern part

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of South China Sea, Wan et al. (2007) found that the intensity of the East Asian monsoon underwent three profound shifts at ~15 Ma, ~8 Ma and 3 Ma, respectively. The continued uplift of the Tibetan Plateau may have played a significant role in strengthening the Asian monsoon at these times (An et al., 2001). The age of establishment of the South Asian monsoon is however controversial (Clift et al., 2008), but it is clear that both East and South Asian monsoon systems had been coupled since at least 17 Ma (Clift et al., 2008).

Parts of western, central and eastern China are under the influence of the East Asian monsoon, while western China is under the influence of the South Asian monsoon. Yunnan Province, located in southwestern China, is impacted by both monsoon systems. The Ailao Mountain, in central Yunnan, serves as the boundary between west and east of Yunnan (Yang, 1990). In general, eastern Yunnan is under the influence of East Asian monsoon, while the western part of the province is strongly affected by the South Asian monsoon (Li and Li, 1992). Fossil sites from Yunnan enable us to compare the evolution of both East Asian and South Asian monsoons using palaeoclimatic data. The Xiaolongtan Late Miocene fossil site, at present mainly under the influence of the East Asian monsoon (Li and Li, 1992), has already provided good palaeoclimatic data (Xia et al., 2009). The Lincang Late Miocene fossil site, at present mainly under the influence of the South Asian monsoon (Li and Li, 1992), has a rich palaeoflora (Guo, unpublished data, in preparation). These two coeval fossil assemblages give a good opportunity to compare the two monsoon systems in the Late Miocene. The palaeoclimate of the latter flora has not been reconstructed yet; this reconstruction will be the first goal of the present study.

Up to now, three main quantitative methods are available for reconstructing the palaeoclimate using fossil leaves: Leaf Margin Analysis (LMA (Bailey and Sinnott, 1915, 1916; Wolfe, 1979; Wing and Greenwood, 1993; Wilf, 1997; Greenwood, 2005, 2007)), Climate Leaf Analysis Multivariate Program (CLAMP (Wolfe, 1993; Wolfe and Spicer, 1999)), and the Coexistence Approach (CA [Mosbrugger and Utescher, 1997]). These methods do not always give consistent results (e.g., Liang et al., 2003; Yang et al., 2007): therefore, all of them should be applied to fossil leaf assemblages for cross-validation of the results (Uhl et al., 2006, 2007; Yang et al., 2007).

The aims of the present study are: one, to reconstruct the Lincang palaeoclimate using three quantitative methods; second, to compare it with the present-day Lincang climate; third, to discuss the Late Miocene monsoonal systems in southern Yunnan by comparing the Lincang and Xiaolongtan fossil sites.

2. Materials and methods

2.1. Fossil site

There are more than one hundred well exposed Neogene coal-bearing basins in Yunnan (Ge and Li, 1999; Xu et al., 2000), one of which is the Lincang Basin in southwest Yunnan (Fig. 1). The Lincang basin is well known for its important Ge (Germanium) deposit (Qi et al., 2004; Hu et al., 2009). The exploitation of the mineral yielded 43% of total Germanium production in China in 2007 (Hu et al., 2009). Therefore, it has received extensive attention in geological and geochemical researches (Ge and Li, 1999; Su et al., 1999; Li, 2000; Lu et al., 2000; Qi et al., 2004; Hu et al., 2009). The geology of the region consists of a Triassic granitoid batholith on which lies the Miocene Bangmai Formation (Qi et al., 2004; Hu et al., 2009). The Bangmai Formation is divided into three coal-bearing cycles (Qi et al., 2004; Hu et al., 2009). This formation is overlain by Quaternary deposits.

The fossil plants were found in the Bangmai Formation, Zhongzhai Village (23°54′N, 100°01′E), Lincang Municipality, Yunnan Province, South-West China (Fig. 1). A detailed stratigraphic column of the fossil site (Fig. 2) is drawn according to the stratigraphic description by Ge and Li (1999). The upper fossiliferous member is rich in diatoms, which indicates its correspondence to the unit N_{1b}^{5} described by Hu et al. (2009).

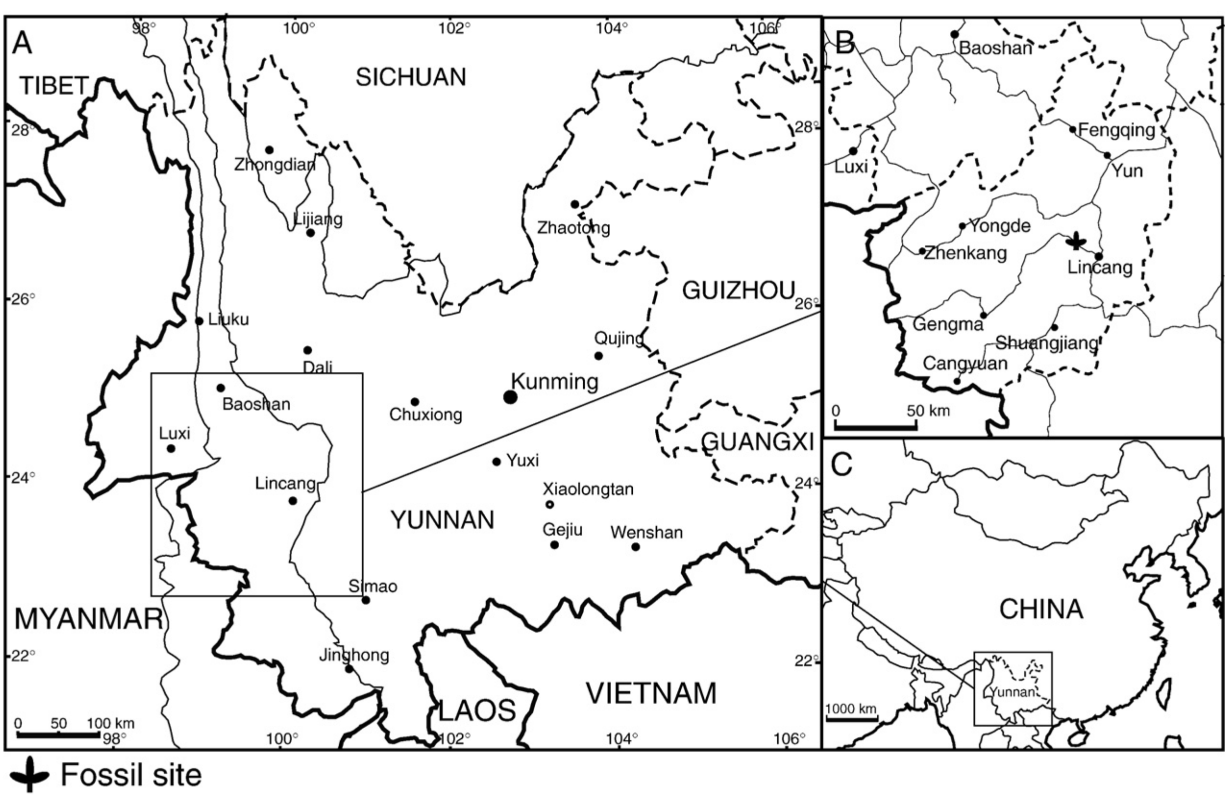

Fig. 1. Maps showing the fossil locality. A. Map of Yunnan. B. Map of Lincang Municipality with main roads. C. Map of China.

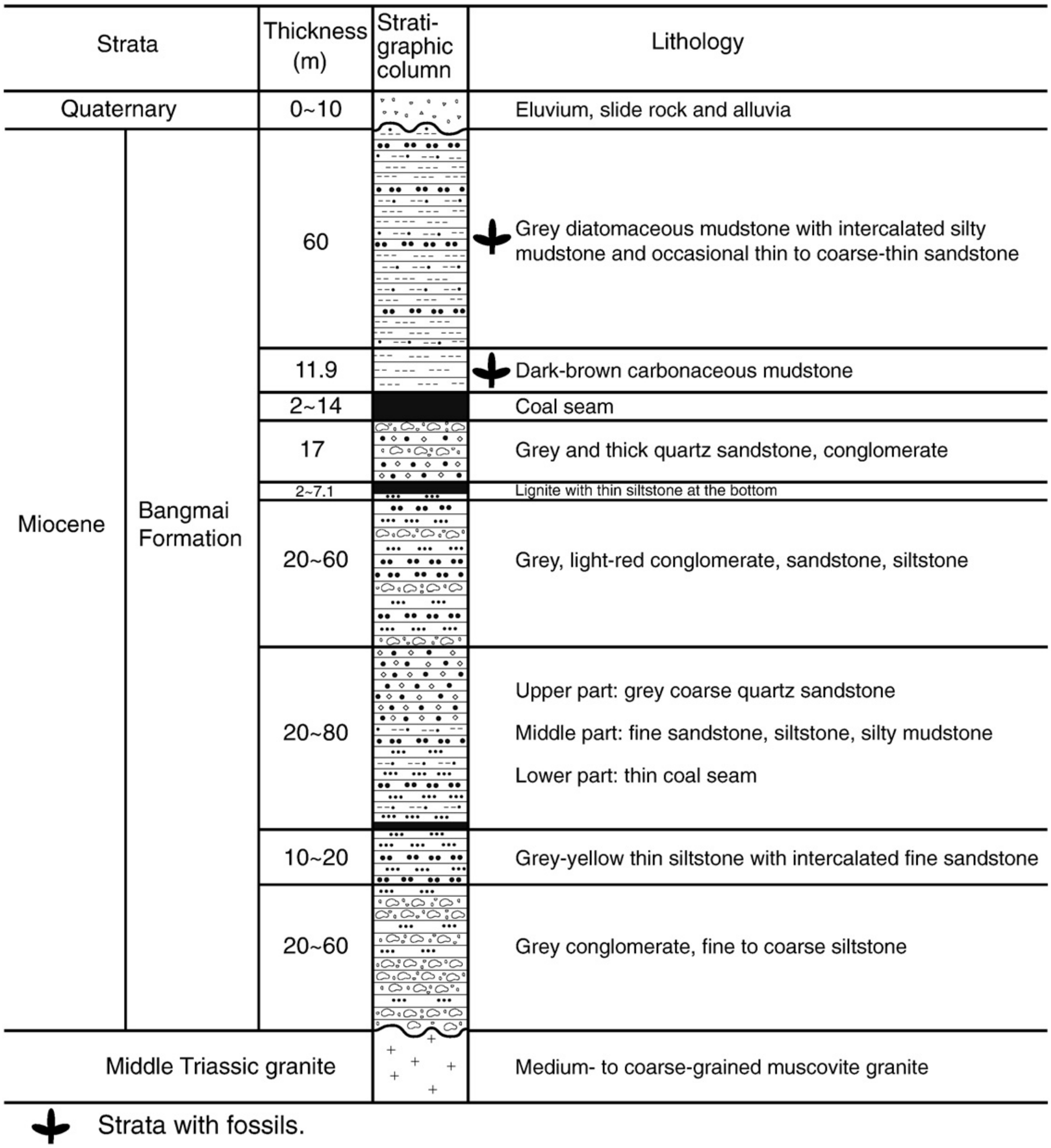

Fig. 2. Stratigraphy of the fossil site.

Based on stratigraphy, Ge and Li (1999) indicate that the Bangmai Formation underlies the Mangbang Formation in Tengchong Basin (Southwest Yunnan), and therefore the Bangmai Formation is assigned to the Late Miocene. Tengchong represents a volcanic basin, where a series of volcanic rocks can be sampled for K–Ar datings of the Mangbang Formation. The K–Ar datings of the Mangbang Formation yielded the age of 3.8–3.2 Ma (Li et al., 2000). The geological age of the Bangmai Formation in the Tengchong Basin should thus be older than 3.8 Ma. From a biostratigraphical point of view, the Bangmai palaeoflora from Lincang is dominated by several evergreen genera, such as *Cyclobalanopsis*, *Castanopsis*, and *Cinnamomum*. This assemblage is comparable with several other Late Miocene floras in Yunnan, such as the Xiaolongtan palaeoflora in southeast Yunnan (Zhou, 1985; Xia et al., 2009), the Nanlin palaeoflora in west Yunnan (Ge and Li, 1999) and the Shuanghe palaeoflora in northwest Yunnan (WGCPC, 1978). The floristic aspects of these Late Miocene floras are totally different from those of the Pliocene Sanying (Tao and Kong, 1973) and Lanping (Tao, 1986) palaeofloras, with *Quercus* sect. *Heterobalanus* as the dominant taxon. In summary, we consider the Lincang flora from the Bangmai Formation to be of Late Miocene age, i.e. younger than 11.6 Ma and older than 3.8 Ma.

2.2. Fossil samples

The plant fossils uncovered from Lincang mainly represent leaves, but some fruit specimens occur occasionally. Most fossils are preserved as impressions. Tao and Chen (1983) reported some fossils (16 species) from Bangmai, Zhongzhai. Other specimens (73 species) have been identified by Guo (unpublished data, in preparation). To avoid problems due to floral mixing (Mosbrugger and Utescher, 1997), here we only worked on the fossils identified by Guo (unpublished data, in preparation) as all of these fossils come from the same locality and fossil layer. A total of 73 species belonging to 51 genera and 35 families are included in the present study (Table 1).

2.3. Climatic parameters

Abbreviations of climatic parameters used in the text are as following: 3-DRY, three consecutive driest months' precipitation; 3-WET, three consecutive wettest months' precipitation; CMT, coldest month (mean) temperature; GRS, length of growing season; GSP, growing season precipitation; MAP, Mean Annual Precipitation; MAT, Mean Annual

Table 1
List of fossil species in Lincang.

Fossil species	Family	Included in LMA and CLAMP	Included in CoA
Glyptostrobus europaeus (Brongn.) Heer	Taxodiaceae		×
Calocedrus lantenoisi (Laurent) Tao	Cupressaceae		×
Schisandra sp.1	Schisandraceae	×	×
Piper sp.1	Piperaceae	×	×
Cinnamomum naitoanum Huzioka et Takahashi	Lauraceae	×	×
Cinnamomum scheuchzeri Heer	Lauraceae	×	×
Cinnamomum sp.1	Lauraceae	×	×
Litsea grabaui Hu et Chaney	Lauraceae	×	×
Neocinnamomum sp.1	Lauraceae	×	×
Smilax grandifolia (Unger) Heer	Smilacaceae		×
Cyperacites sp.	Cyperaceae		
Lumnitzera sp.1	Combretaceae	×	×
Terminalia sp.1	Combretaceae	×	×
Trapa sp.	Lythraceae		
Syzygium sp.1	Myrtaceae	×	×
Syzygium sp.2	Myrtaceae	×	×
Albizia sp.1	Fabaceae	×	×
Gleditsia miosinensis Hu et Chaney	Fabaceae	×	×
Dalbergia prehupeana Tao	Fabaceae	×	×
Desmodium sp.1	Fabaceae	×	×
Maackia sp.	Fabaceae	×	×
Milletia sp.	Fabaceae	×	×
Mucuna sp.1	Fabaceae	×	×
Ormosia sp.	Fabaceae	×	×
Shuteria sp.	Fabaceae	×	×
Sophora miojaponica Hu et Chaney	Fabaceae	×	
Photinia sp.	Rosaceae	×	×
Sorbus sp.	Rosaceae	×	×
Stranvaesia sp.1	Rosaceae	×	×
Berchemia sp.1	Rhamnaceae	×	×
Celtis miobungeana Hu et Chaney	Cannabaceae	×	×
Ficus sp.1	Moraceae	×	×
Castanopsis sp.1	Fagaceae	×	×
Castanopsis sp.2	Fagaceae	×	×
Cyclobalanopsis mandraliscae (Gaudin) Tanai	Fagaceae	×	×
Cyclobalanopsis sp.1	Fagaceae	×	×
Cyclobalanopsis sp.2	Fagaceae	×	×
Lithocarpus reniifolius Tao	Fagaceae	×	×
Lithocarpus sp.1	Fagaceae	×	×
Lithocarpus sp.2	Fagaceae	×	×
Lithocarpus sp.3	Fagaceae	×	×
Lithocarpus sp.	Fagaceae	×	×
Quercus latifolia Li	Fagaceae	×	×
Quercus simulata Knowlton	Fagaceae	×	×
Quercus sp.1	Fagaceae	×	×
Quercus sp.	Fagaceae		×
Engelhardia sp.1	Juglandaceae	×	×
Betula mioluminifera Hu et Chaney	Betulaceae	×	×
Populus glandulifera Heer	Salicaceae	×	×
Capparis sp.1	Capparaceae	×	×
Rhus sp.1	Anacardiaceae	×	×
Pistacia miochinensis Hu et Chaney	Anacardiaceae	×	×
Toxicodendron sp.1	Anacardiaceae	×	×
Toxicodendron sp.2	Anacardiaceae	×	×
Koelreuteria sp.1	Sapindaceae		×
Toona bienensis (Hu et Chaney) Tao	Meliaceae	×	×
Aphanamixis sp.	Meliaceae	×	×
Murraya sp.	Rutaceae	×	×
Zanthoxylum sp.1	Rutaceae	×	×
Helicteres sp.1	Malvaceae	×	×
Reevesia sp.	Malvaceae	×	×
Loranthus palaeoeuropaeus Kutuzk.	Loranthaceae		×
Schoepfia sp.1	Schoepfiaceae	×	×
Tetragonia sp.1	Aizoaceae		×
Hydrangea lanceolimba Hu et Chaney	Hydrangeaceae	×	×
Ternstroemia maekawai Matsuo	Ternstroemiaceae	×	×
Bumelia pseudolycioides Berry	Sapotaceae	×	×
Chrysophyllum sp.1	Sapotaceae	×	×
Styrax sp.1	Styracaceae	×	×
Ilex sp.1	Aquifoliaceae	×	×
Viburnum sp.	Adoxaceae	×	×
Pittosporum sp.1	Pittosporaceae	×	×

Temperature; MMGSP, mean monthly growing season precipitation; MPDRY, mean precipitation of the driest month; MPWARM, mean precipitation of the warmest month; MPWET, mean precipitation of the wettest month; RH, relative humidity; SH, specific humidity; and WMT, warmest month (mean) temperature.

2.4. Leaf Margin Analysis (LMA)

Leaf Margin Analysis is a univariate method based on the relationship between the proportion of woody dicotyledons with entire leaf margins and Mean Annual Temperature (MAT) (Wing and Greenwood, 1993). Previous work has indicated that LMA shows regional constraints (Gregory-Wodzicki, 2000; Kowalski, 2002; Greenwood et al., 2004). We apply LMA equations which are based on datasets from East Asia (Wolfe, 1979; Wing and Greenwood, 1993) and China (Su et al., 2010), respectively:

$$MAT = 1.141 + 30.6 \times p \quad \text{(Wolfe, 1979; Wing and Greenwood, 1993)}$$

$$China: \; MAT = 1.038 + 27.6 \times p \quad \text{(Su et al., 2010)}$$

where p is the proportion of woody dicotyledons with entire leaf margins in an investigated flora. A species gets a score of 1 if it has only entire leaves, a score of 0.5 if both entire and toothed leaves are represented, and a score of 0 if only toothed leaves are presented. LMP is the total score divided by species number.

The standard error (SE) is calculated by:

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

where 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); p is the percentage of woody dicotyledons with entire leaves; and n is the total number of woody dicotyledon leaves in the assemblage. This estimation of the standard error is better than the one proposed by Wilf (1997) because it accounts for the over-dispersed character of the binary data (Miller et al., 2006).

The model of Su et al. (2010) has been recently developed based on 50 humid to mesic Chinese forests for which long-term meteorological records are available. This model is statistically different from other previously developed LMA models, and gives statistically better results for estimation of modern temperature of Chinese sites. This new model is thus believed to give better results for Chinese palaeoflora; therefore, we decided to include it in the present analysis besides a more traditional model.

Sixty-three woody dicotyledonous morphotypes were scored for calculation (Table 1).

2.5. Climate Leaf Analysis Multivariate Program (CLAMP)

CLAMP is a multivariate program for quantitative reconstruction of palaeoclimates developed from a dataset of Central American, North American and Japanese sites (Wolfe, 1993). The main idea of CLAMP is the application of the Canonical Correspondence Analysis (CCA), a multivariate method to relate species to environmental gradients. There are two CLAMP databases; CLAMP3A, including 173 samples, and CLAMP3B with 144 sites. We use the CLAMP3B dataset as it excludes the alpine nest not suitable for warmer climates: the alpine nest groups cold sites with a slightly different physiognomic signature and should be excluded for analysis of warm site (Wolfe, 1993; Wolfe and Spicer, 1999). We operated CLAMP by following the CLAMP official website (http://www.open.ac.uk/earth-research/spicer/CLAMP/Clampset1.html). The scoring sheet is available as Supplementary data 1.

Eleven climate parameters could be calculated as following, MAT, WMT, CMT, GRS, GSP, MMGSP, 3-WET, 3-DRY, RH, SH, and enthalpy.

For meteorological calibration of the dataset, two kinds of data are available: the gridded and ungridded meteorological data (Spicer et al., 2009). The ungridded meteorological data were used. As in LMA, 63 woody dicotyledonous morphotypes were scored (Table 1).

2.6. Coexistence Approach (CA)

The aim of the Coexistence Approach is to find for a given fossil flora and a given climate parameter the climatic interval in which all nearest living relatives known for a fossil can coexist (Mosbrugger and Utescher, 1997). As the climatic requirements of a fossil species are not known, the requirements of the nearest living relative (NLR) are used. To limit the uncertainty in the determination of the NLR, we decided to work at the generic level (Yang et al., 2007).

We excluded cosmopolitan genera from the analysis, as they provide no specific information regarding the climatic requirements (Xia et al., 2009). Other excluded genera include aquatic plants, as they are less dependent on climatic conditions (Xia et al., 2009). Sixty-nine species were retained for the analysis (Table 1).

The climatic tolerances of each NRL genus were taken from the Palaeoflora database (Mosbrugger and Utescher, 1997) and complemented from the Xiaolongtan palaeoclimatic reconstruction (Xia et al., 2009). When the climatic data from the two sources were inconsistent, the broader intervals were applied. For genera not included in both datasets, the standard method of Mosbrugger and Utescher (1997) was followed. We first determined the distribution range of the genus using various monographs and manuals of regional floras (e.g. Flora of China, Flora Yunnanica, Flora Neotropica, Flora of North America). Then at least ten (or as many as possible) climatic stations were chosen in order to reflect the climatic range of the genus. The data of the climatic stations were retrieved from Mueller (1996). Their combination represents the climatic tolerance of the genus. Seven climatic parameters were selected: MAT, WMT, CMT, MAP, MPWET, MPDRY, and MPWARM. The details of the climatic data for each genus are given in Supplementary data 2.

The coexistence interval for each climatic parameter was calculated using the software ClimStat version 1.02 (Heinemann, 1998–1999).

2.7. Monsoon intensity

Wang and Fan (1999) defined a monsoon index; however, as it is based on climatic data unavailable from the Lincang and Xiaolongtan fossil sites (the difference of 850-hPa westerlies between a southern region and a northern region), we cannot use it here. Liu and Yin (2002) defined another monsoon index based on mean winter and summer temperatures and precipitations. As the quantitative methods used only gave the CMT and WMT but not a seasonal mean, we could not calculate this index either. Therefore, we used the ratio of MPWET on MAP and MPDRY on MAP as indicators of monsoon strength. These ratios have been calculated based on CA results only, for Lincang and Xiaolongtan Late Miocene and modern climates.

3. Results

3.1. LMA

When the East Asian regression model was used, MAT was calculated as 24.4 ± 2.07 °C. When the Chinese model was used, MAT was calculated as 22.0 ± 1.87 °C. Both values indicate a warm climate.

3.2. CLAMP

The position of Lincang site in the physiognomic ordination space is indicated in Fig. 3. It is positioned away from all other sites of the calibration dataset (Axis 2 versus Axis 3). The results of CLAMP are shown in Table 2. MAT was calculated to be 20.6 ± 1.2 °C; GSP as 3711 ± 336 mm. It is necessary to mention that GRS was reconstructed as 11.6 ± 0.7 months. Therefore, the whole year can be considered as the growing season. The reconstructed climate is clearly warmer than today in Lincang, especially in the warmest month (WMT) (Table 2). CLAMP also indicates a very wet climate in Lincang during the Late Miocene, with annual precipitation rates as high as in present-day islands or more equatorial regions (e.g., Borneo, New Guinea, French Guiana, and southern Cameroon). The dry season precipitation (3-DRY) represents one fourth of the annual precipitation. CLAMP results thus suggest a weak seasonality of precipitation; however, the seasonality of temperature appeared pronounced (WMT = 29.0 °C compared to CMT = 11.4 °C).

3.3. CA

Results of CA are given in Table 3, where the species that represent the limit of the coexistence intervals are also listed, as well as the outlier species. MAT was calculated to be 18.5–19.0 °C and MAP as 1213–1394 mm, which indicate a wet climate, although not as wet as indicated by CLAMP. Of 69 species included in the analysis, no more than one is excluded in the coexistence intervals, i.e. 98 to 100% are included in these intervals. This is indicative of a significant coexistence interval. CA indicates a warmer climate than at present, especially during the warmest month (WMT). The driest month precipitation (MPDRY) represents 5.9 to 9.7% of the wettest month precipitation (MPWET), indicating a strong seasonality in precipitation unlike the CLAMP results. The seasonality in temperature is also pronounced (WMT = 27.3–27.8 °C compared to CMT = 9.6–12.5 °C).

3.4. Monsoon intensity

In Lincang, our results (Table 5) show that the wettest month precipitation (MPWET) represents 15.5 to 25.0% of annual precipitation rates (compared to 21% at present day), whereas the driest month precipitation (MPDRY) represents 1.3 to 1.7% of MAP (compared to 0.9% at present day).

4. Discussion

The results from CLAMP, LMA and CA are generally consistent (Tables 2 and 3). There are, however, two inconsistencies: the MAT given by the Eastern Asian model of LMA (24.4 ± 2.07 °C) is clearly higher than other estimates of MAT (18.5–19.0 °C from CA, 20.6 ± 1.2 °C from CLAMP); the MAP of CA (1213–1394 mm) and GSP of CLAMP (3711 ± 336 mm) are clearly different.

4.1. Estimation of MAT with LMA

The linear relationship between MAT and leaf margin percentage is regionally constrained (Gregory-Wodzicki, 2000; Kowalski, 2002; Greenwood et al., 2004).

Here, we give the results of LMA for two Asian models: the Eastern Asian model (Wolfe, 1979; Wing and Greenwood, 1993) and the newly developed Chinese model (Su et al., 2010). Su et al. (2010) demonstrate that previous models for LMA do not totally fit modern Chinese flora, and propose a new model. For our study, the Chinese model also gives a lower value than the Eastern Asian model. In the present analysis, the value from the Chinese model is clearly more consistent with CLAMP and CA values, confirming that this model is more appropriate for Chinese Neogene floras.

Even using the Chinese model, the LMA yielded the highest MAT. A similar trend was found in the study of another Miocene site in Yunnan (Xia et al., 2009), but differs from other studies on European data, where the CA often gave the highest temperature (Mosbrugger and Utescher, 1997; Sun et al., 2002; Liang et al., 2003; Uhl et al., 2007). Several authors (Burnham et al., 2001; Uhl et al., 2003)

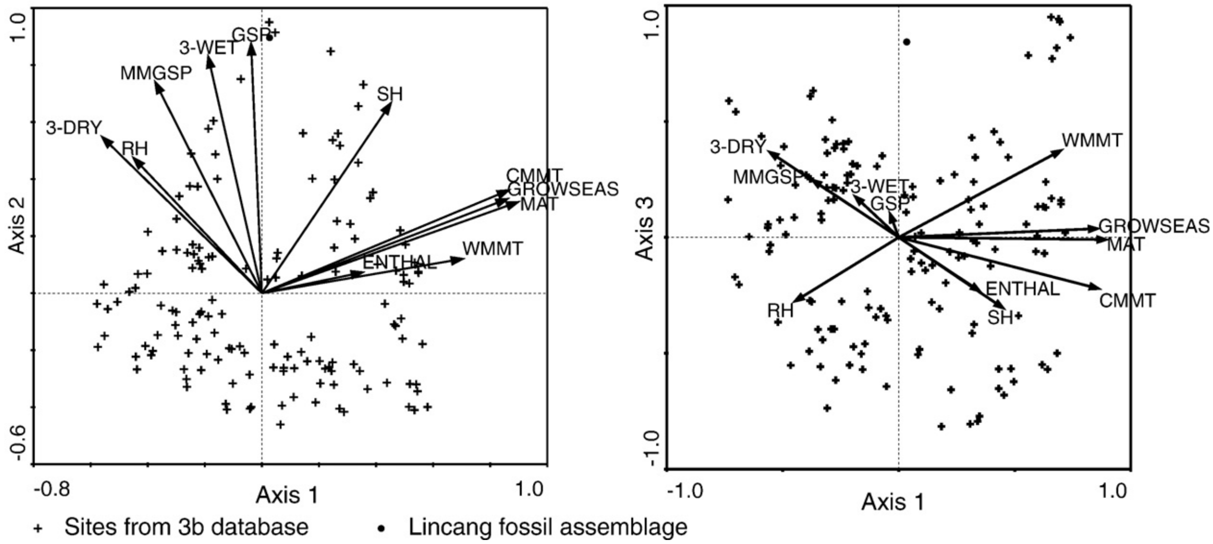

Fig. 3. Position of the calibration sites and the Lincang fossil site in physiognomic space. Lincang is outside the calibration data cloud (see on the right).

suggested that LMA may underestimate the MAT due to taphonomic bias. For low latitudes in China, only Xia et al. (2009) gave temperature calculated by different quantitative methods. Our analyses confirm their hypothesis of an overestimation of MAT by LMA at low latitudes in contrast to underestimation of MAT by LMA in higher latitudes.

4.2. Differences of precipitation between CA and CLAMP

The main differences between the CA and CLAMP results lie in the precipitation results. As the growing season is calculated at about 12 months (Table 2), we can reasonably consider GSP as an estimation of MAP. CLAMP gives a MAP of 3711 ± 336 mm, while CA gives a MAP of 1213–1394 mm. We therefore looked at these values in more details.

The CA results are close to modern precipitation rates in Yunnan (Table 3; Yunnan Meteorological Bureau, 1984). We also checked the intervals for all the taxa present in the Lincang flora: four taxa have a nearest living relative with a precipitation range not exceeding 1700 mm (*Photinia* sp., *Shuteria* sp., *Rhus* sp.1, and *Populus glandulifera*), and 23 taxa do not exceed 2000 mm. The CA is certainly not free of errors, particularly if one of the following problems occurs: misidentification of the nearest living relative, differences of climatic requirements between a fossil and its assigned nearest living relative, and errors from the estimation of climatic requirements of the nearest living relative (Mosbrugger and Utescher, 1997; Kvacek, 2007). The CA may be governed too much by the present environmental conditions, as it deals with NLRs. The distribution of a plant is not only constrained by the climate but also by the presence of pollinators and seed dispersal agents for example. To reduce the possibility of misidentification, we have worked at the generic level. As a result, the NLR distribution in most cases is not restricted to a small geographic area. Besides, in the present study, we scored over twenty taxa for the CA, which appear not to favour a high annual precipitation rate (MAP > 2000 mm); therefore, we think that CA clearly rejects the high MAP hypothesis suggested by CLAMP results.

Table 2
Result of CLAMP analysis compared with the modern values. The modern data are from the Yunnan Meteorological Bureau (1984).

Climatic variable	CLAMP results	Modern values
MAT (°C)	20.6 ± 1.2	17.3
WMT (°C)	29.0 ± 1.6	21.3
CMT (°C)	11.4 ± 1.9	10.8
GRS (month)	11.6 ± 0.7	12
GSP (mm)	3711 ± 336	1178.7
MMGSP (mm)	396 ± 37	98.2
3-WET (mm)	1595 ± 1403	680.2
3-DRY (mm)	976 ± 93	41.7
RH (%)	74.2 ± 7.4	74
SH (g/kg)	10.2 ± 0.9	10.9
Enthalpy (kJ/kg)	318.9 ± 3.2	325.3

The estimation of MAP from CLAMP, 3711 ± 336 mm, is quite high; such high values are not encountered in any of the 135 meteorological stations dispersed throughout Yunnan Province (Yunnan Meteorological Bureau, 1984). In Lincang County, the highest rainfalls ever recorded so far was in the year of 1983, with an annual precipitation rate of 3151 mm (Wang, 2006). In general the county has MAP under 2000 mm, with one site with MAP as high as 2542 mm (Wang, 2006). The fairly high precipitation of the Lincang flora, based on CLAMP results, is more similar to that found in the equatorial regions or some islands like New Guinea, the Philippines, Borneo, Madagascar, Ecuador, or French Guiana (Mueller, 1996). The reconstruction of precipitation using multivariate methods is less accurate than that for temperatures (Traiser et al., 2005). Besides, CLAMP tends to overpredict the precipitation of the warmer/moister sites (Gregory-Wodzicki, 2000), so CLAMP estimates for precipitation are not robust (Kennedy et al., 2002; Yang et al., 2007). The Lincang fossil site clearly falls in this category of warmer/moister sites (Tables 2 and 3). To see how well CLAMP can estimate the GSP for our site, we looked at the CLAMP 3B data set in more detail. Lincang site plots away from all 3B sites in the physiognomic space (Fig. 3). This might be due to the fact that there is no monsoonal site in the calibration dataset. The 3B dataset is therefore maybe not appropriate to reconstruct monsoon climates. We also plotted the vector scores of CLAMP 3B sites for GSP against GSP (Fig. 4). The Lincang has quite a high score for this vector (3.27); in the CLAMP 3B dataset, GSP varied from 1600 to 4290 mm. The lowest value (1600 mm) is more similar to the value of CA (1213–1394 mm). Therefore, we agree with previous authors, who warned against CLAMP use for climatic regimes poorly represented in the CLAMP dataset, especially tropical regimes (Kowalski, 2002; Spicer et al., 2004). The inclusion of more sites with high rainfalls in the future may improve the resolution of CLAMP for high GSP. However, several authors (e.g., Wolfe, 1995; Mosbrugger and Utescher, 1997) underlined the difficulty of reconstructing precipitation from proxy data. Furthermore, Wolfe (1995) explained that the three Asian samples (from Japan) included in the CLAMP dataset were unlike the samples from similar climates in North America; it may be that Chinese climates also have a different physiognomic signature. In spite of the very high GSP given by

Table 3
Results of CoA compared with modern values. The modern data are from the Yunnan Meteorological Bureau (1984).

Climatic variable	Coexistence interval	Modern value	Minimal border	Maximal border	Outliers	Percentage of species included in coexistence interval
MAT (°C)	18.5–19.0	17.3	*Terminalia* sp.1	*Sorbus* sp.	*Chrysophyllum* sp.1	98.5%
WMT (°C)	27.3–27.8	21.3	*Terminalia* sp.1	*Calocedrus lantenoisi*		100%
CMT (°C)	9.6–12.5	10.8	*Shuteria* sp.	*Sorbus* sp.	*Chrysophyllum* sp.1	98.5%
MAP (mm)	1213–1394	1178.7	*Murraya* sp.	*Shuteria* sp.		100%
MPWET (mm)	216–304	247	*Mucuna* sp.1	*Photinia* sp.	*Rhus* sp.1	98.5%
MPDRY (mm)	18.0–21.0	10.9	*Rhus* sp.1	*Calocedrus lantenoisi*		100%
MPWARM (mm)	118–172	220.8	*Reevesia* sp.	*Betula mioluminifera*	*Calocedrus lantenoisi*	98.5%

CLAMP, the RH and SH values (Table 4) it gives for the fossil site are very similar to the modern ones.

4.3. Miocene climate in Lincang

Compared to the present day (Tables 2 and 3), the Miocene climate of Lincang appears to be a little warmer; winter temperatures are similar, but summer temperatures are higher. Concerning the precipitation, we only apply the results from the CA, as CLAMP results display high uncertainties. The Lincang region during the Miocene was under a slightly wetter climate than the present, with the reconstructed precipitations for both the driest and wettest months in Lincang somewhat higher than those of today. As a conclusion, the Miocene climate of Lincang can be considered similar to the modern one: a subtropical climate (Wang, 2006).

Steppuhn et al. (2007) made several simulations of the Tortonian climate. For the Lincang region, their model yielded the following results: MAT 20–25 °C, summer temperatures 25–30 °C, winter temperature 20 °C, and MAP 1000–1500 mm (approximations from their map). Our results (Tables 2 and 3) corroborate the results except for the winter temperature. However, we calculated the mean temperature of the coldest month, whereas Steppuhn et al. (2007) gave the mean temperature for the three winter months (i.e. December, January and February). Apart from a real discrepancy between the model and our results, this may suggest a short cold period that does not last for three months. In fact, the mean winter temperature in Lincang today is 11.7 °C, whereas the CMT is 10.8 °C. During the Miocene, the cold season might have been even shorter than at present.

The main climatic difference between the Miocene and the present day in Lincang concerns the WMT (Tables 2 and 3): the warmest month was clearly warmer during the Miocene than at present. This decrease of summer temperatures may be a side effect of the Tibetan Plateau uplift. Lincang lies now at an altitude of about 1500 m above sea level. It is therefore possible that an increased elevation in the region triggered this summer cooling. Analysis of Lincang granitoid batholith cooling has been interpreted to demonstrate that the region underwent an uplift of 672–1263 m since the Pliocene, and especially since 3 Myr (Shi et al., 2006). Such uplift may lead to temperature decrease of 4.0–7.5 °C, based on an altitudinal gradient of 0.594 °C/100 m as established for this region (Wang, 2006). This difference is consistent for the difference between WMT, but not for differences between MAT and CMT.

4.4. Neogene climates in Yunnan

The close comparison of Yunnan Neogene palaeoclimates is a difficult task for several reasons: the poor regional stratigraphy which hinders the stratigraphical correlations between different depositional basins, and the important distance between two sites. Slight differences between sites may be due to spatial or temporal distances. Therefore, we will focus our comparison on Lincang and Xiaolongtan palaeofloras in order to understand the Miocene climates in both eastern and western Yunnan (Table 5). Both palaeofloras indicate a warm and wet climate with seasonality in temperature and precipitation. Their precipitations, as indicated by CA, were similar. The main difference is registered in the

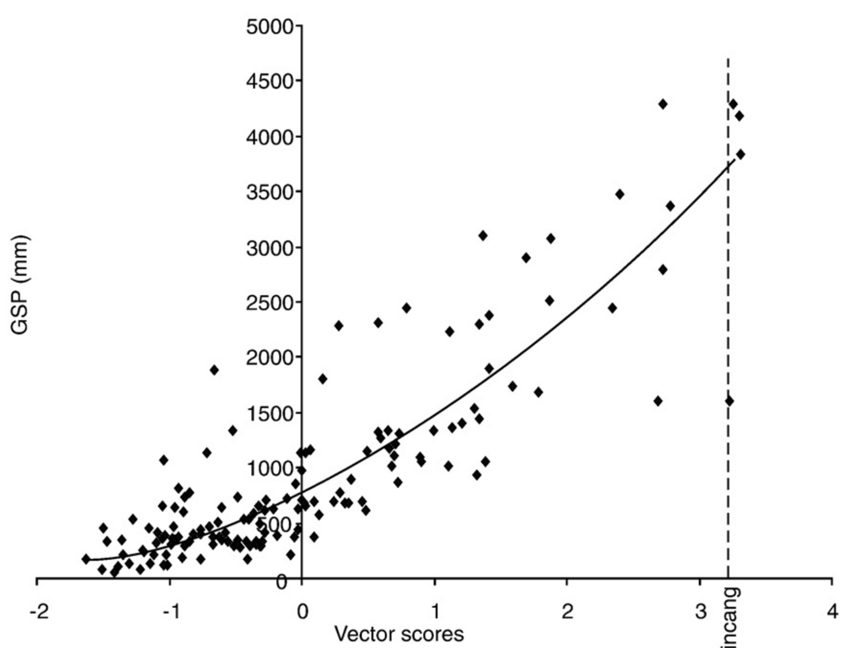

Fig. 4. Diagram showing GSP against the vector scores for each site of CLAMP 3B dataset. The vector scores are given by the classical CLAMP analysis.

Table 4
Relative contribution of wettest month and driest month to annual precipitation rates. All values are in percentage.

	Lincang		Xiaolongtan	
	Modern	Miocene	Modern	Miocene
Wettest month	21.0	15.5–25.0	18.7	13.7–20.4
Driest month	0.9	1.3–1.7	1.4	1.2–2.0

temperatures: the Lincang palaeoclimate was warmer than the Xiaolongtan one, though at present the climate at Xiaolongtan is warmer than at Lincang. Along with uncertainties in the methods and taphonomic biases, a small climatic change which may have occurred between the depositions of the two sites could be the explanation.

The Miocene climate of Lincang was also very similar to the modern one (Tables 2 and 3) except for WMT, just as the Mangdan Miocene climate was similar to the modern one (Zhao et al., 2004).

On a broader scale, the Lühe palynoflora (Xu et al., 2008), the Mangdan carpoflora (Zhao et al., 2004), and the Eryuan palynoflora (Kou et al., 2006), from northwestern and western Yunnan also indicate a Mio-Pliocene climate with warmer summers than at present and a clear seasonality in temperature and precipitation. The palaeoprecipitation was either similar to the modern ones or slightly higher. Because of a lack of spatial and temporal resolution in this region, small Neogene climatic variations known in other parts of the globe, particularly Europe (Utescher et al., 2009), cannot be ascertained.

In the Miocene, the proxy data (Bruch et al., 2006) and the simulations (Steppuhn et al., 2006, 2007) indicate a weaker meridional temperature gradient. The polar regions, during the Miocene, were warmer than at present (Wolfe, 1994; White et al., 1997; Steppuhn et al., 2006, 2007). On the other hand, the equatorial temperatures have remained much the same since the Cretaceous (Skelton et al., 2003). The Neogene cooling may have been more pronounced in the high latitudes than at the low latitudes (Bruch et al., 2006). Lincang is located at a relatively low latitude; therefore, the similarity of its Miocene and modern climates is not surprising.

4.5. The development of the Asian Monsoon

To discuss the Miocene monsoon in the region of Lincang, we only used the results derived from the CA, as CLAMP calibration is at present inappropriate to estimate precipitation under a monsoonal climate (Fig. 3). As discussed above, the higher past WMT coupled with a similar CMT indicates a higher seasonality during the Miocene than at present. Furthermore, the pronounced seasonality in the Miocene was also marked by precipitation, MPDRY as 18–21 mm and MPWET as 224–304 mm, but in the same range as the modern one in Lincang (Yunnan Meteorological Bureau, 1984). Wang (2006) pointed out that the precipitation seasonality in Yunnan is largely linked with the Asian monsoon systems. The high reconstructed precipitation of the warmest month in Lincang (MPWARM = 118–172 mm) confirms the occurrence of monsoon in this region during the Miocene.

Table 5
Comparison of Neogene climate results from quantitative analyses in Yunnan. The Xiaolongtan data are from Xia et al. (2009).

Age	Lincang		Xiaolongtan	
	CoA	CLAMP	CoA	CLAMP
	Late Miocene		Late Miocene	
MAT (°C)	18.5–19.0	20.6 ± 1.2	16.7–19.2	18.1 ± 1.2
WMT (°C)	27.3–27.8	29.0 ± 1.6	25.4–26.0	25.9 ± 1.6
CMT (°C)	9.6–12.5	11.4 ± 1.9	7.7–8.7	10.8 ± 1.9
MAP (mm)	1213–1394	3711 ± 336	1215–1639	1964 ± 336
MPWET (mm)	216–304		224–248	
MPDRY (mm)	18–21		19–24	

The relative strength of the Asian palaeomonsoons is still under debate, with conflicting values from proxy data (Wu et al., 1998; Xia et al., 2009) and simulation data (Steppuhn et al., 2007). Our results (Table 4) suggest that the Miocene summer monsoon in Lincang could be similar to that at present, but the Miocene winter monsoon was weaker than that at present day (i.e., higher proportion of winter precipitation than at present). Today Lincang, located in southwest Yunnan, is mainly under the influence of the South Asian monsoon, whereas Xiaolongtan, situated in east Yunnan, is mainly under the influence of the East Asian monsoon. In the Miocene (Table 4), the monsoons experienced by these two sites were of comparable strength, suggesting that the South and East Asian monsoon strengths were similar at that time.

The monsoon is a complex climatic phenomenon; the presence of the Tibetan Plateau is a cause of this (Raymo and Ruddiman, 1992; An et al., 2001). The uplift of the Tibetan Plateau increased the intensity of the Asian monsoons (Prell and Kutzbach, 1992; Fluteau et al., 1999; An et al., 2001; Steppuhn et al., 2006; Micheels et al., 2007), particularly the winter monsoon (Liu and Yin, 2002). For Prell and Kutzbach (1992), high elevations of the Tibetan Plateau, at least half of the modern one, are a prerequisite for strong monsoon. The summer monsoon reconstructed in this study is in favour of a Tibetan Plateau that reached half of its present elevation in Late Miocene. The lower intensity of the winter monsoon during the Late Miocene in Yunnan suggests a lower altitude for the Tibetan Plateau at that time. However, other parameters influence the strength of the monsoon: orbital parameters, extension of polar ice, and carbon dioxide (Prell and Kutzbach, 1992). More glacial conditions strengthen the winter monsoon and dampen the summer monsoon (Prell and Kutzbach, 1992; An et al., 2001). A warmer global climate during the Late Miocene can also explain a strong summer monsoon associated with a weaker winter monsoon. Several models have been suggested for the uplift of the Tibetan Plateau, from a gradual uplift since the Oligocene (Chung et al., 1998) to a recent and abrupt uplift (Sun and Liu, 2000). Other studies suggest a diachronic uplift of different parts of the Plateau (Harris, 2006; Wang et al., 2008). More reconstructions of the Yunnan palaeomonsoon are needed to gain a better insight into the development of the monsoon climatic regime, and its link to the uplift of the Tibetan Plateau.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.palaeo.2010.04.014.

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