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Quantitative reconstruction of Miocene climate patterns and evolution in Southern China based on plant fossils

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ABSTRACT

Southern China, especially Yunnan, has undergone high tectonic activity caused by the uplift of Himalayan Mountains during the Neogene, which led to a fast changing palaeogeography. Previous study shows that Southern China has been influenced by the Asian Monsoon since at least the Early Miocene. However, it is yet not well understood how intense the Miocene monsoon system was. In the present study, 63 fossil floras of 16 localities from Southern China are compiled and evaluated for obtaining available information concerning floristic composition, stratigraphic age, sedimentology, etc. Based on such reliable information, selected mega- and micro-floras have been analysed with the coexistence approach to obtain quantitative palaeoclimate data. Visualization of climate results in maps shows a distinct spatial differentiation in Southern China during the Miocene. Higher seasonalities of temperature and precipitation occur in the north and south parts of Southern China, respectively. During the Miocene, most regions of Southern China and Europe were both warm and humid. Central Eurasia was likely to be an arid center, which gradually spread westward and eastward. Our data provide information about Miocene climate patterns in Southern China and about the evolution of these patterns throughout the Miocene, and is also crucial to unravel and understand the climatic signals of global cooling and tectonic uplift.

1. Introduction

The Neogene climate system represents a transitional stage from the greenhouse climate of the Palaeogene to the icehouse climate of the Quaternary. It is during this phase that numerous climatic, tectonic and biotic key events occurred on the globe, such as the formation of the Antarctic ice sheet, enhancement of the Asian monsoon, acceleration of Tibetan Plateau uplift and expansion of C_4 grasses (e.g., Cerling et al., 1993, 1997; Quade and Cerling, 1995; An et al., 2001; Zachos et al., 2001; Zheng et al., 2004; Ségalen et al., 2007; Li et al., 2008). Therefore, this time interval is crucial to understand the long-term climatic changes in Eurasia, and globally (e.g., Mosbrugger et al., 2005).

During the Neogene, China, especially Southern China, has undergone outstanding environmental changes and large tectonic movements. Previous studies have shown that a broad belt of aridity stretched across China from west to east in the Palaeogene, but in the Neogene it was restricted to the Northwestern China, and most areas were warm and humid, as demonstrated by palaeobotanical (i.e. pollen, leaves, seeds, etc.) and lithological (i.e. gypsum, halite, coal, oil shale, etc.) evidence (Liu, 1997; Sun and Wang, 2005). Neogene tectonic movements led to the formation of many sedimentary basins and lignite deposits providing a possibility for the deposition and preservation of numerous Miocene fossil floras.

In China abundant Neogene fossil and modern floras exist, while only a few have been published regarding quantitative reconstructions of Neogene climate (Sun et al., 2002; Liang et al., 2003; Zhao et al., 2004; Kou et al., 2006; Yang et al., 2007; Xu et al., 2008; Xia et al., 2009). In order to better understand climate patterns and evolution in the first epoch of Neogene, i.e. Miocene, in China and to examine their response to the uplift of the Himalayas and Tibetan Plateau, it is necessary to conduct quantitative climate analyses systematically and extensively.

In this paper, we quantitatively reconstruct the Miocene climate of Southern China based on plant fossils using the coexistence approach (Mosbrugger and Utescher, 1997), and visualize results on georeferenced maps to illustrate the climate patterns and evolution in time and space. Moreover, a comparison between the present data and published data from Western and Central Eurasia is undertaken.

2. Environmental setting

China is geographically situated in East Asia covering a vast territory with an area of around 9.6 million km^2, and is bordered by the Tibetan Plateau and Himalayan Mountains in the southwest and the Pacific Ocean in the southeast. The topography of China is higher

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in the west and lower in the east with three main levels as follows: (i) Tibetan Plateau in West China with an average elevation of more than 4000 m above sea level (a. s. l.), (ii) Yungui Plateau, Loess Plateau, Inner Mongolian Plateau, Sichuan Basin, etc. in Central and Northern China (average elevation: 1000–2000 m a. s. l.), and (iii) plains and hills in East China (average elevation: less than 1000 m a. s. l.) (Sun and Wang, 2005).

Our study area, Southern China, covers the regions to the south of the Kunlunshan Mts, Qaidam Basin, Qinlingshan Mts, and the middle and lower reaches of the Yangtze River (Fig. 1). It has a complex terrain with a climate pattern influenced by monsoon systems. Three types of modern vegetation exist in Southern China, i.e., (i) Tibetan high elevation and cold vegetation dominated by grassland and meadow denoting a cold and dry climate, (ii) subtropical evergreen broad-leaved forest dominated by *Castanopsis*, *Cyclobalanopsis*, evergreen *Quercus*, Lauraceae and Theaceae indicative of hot and humid summers and dry winters, and (iii) tropical rainforest and seasonal rainforest dominated by species of families such as Moraceae, Meliaceae, Sapindaceae, Tiliaceae, Euphorbiaceae, Sapotaceae, Palmae and Dipterocarpaceae suggesting high humidity and temperature with mean annual temperature from 20 to 26.8 °C and annual precipitation above 1500 mm (Sun and Wang, 2005) (Fig. 1).

3. Materials and methods

For the quantitative climatic analyses of Southern China, 63 assemblages with 4 leaf, and 59 pollen floras from 16 fossil localities have been compiled from the literature, and were assigned to Early, Middle, and Late Miocene based on the correlation with the biostratigraphy and floristic comparison according to the references cited. The sequence stratigraphic framework of all fossil localities is based on outcrop and drilling data and allows a good correlation for this study. The leaf taxa are mostly identified by well-preserved venation and tooth morphology sometimes together with their seed and fruit impressions, which provides a reliable comparison with extant species. The pollen taxonomy is based on the palynological literature and monographs (e.g. Wang et al., 1995; Song, 1999), which permits a correlation with the nearest living relatives. All localities and samples are listed in Table 1 together with information on their stratigraphy and sedimentology, and with references concerning the fossil floras and geology. All the fossil taxa and their nearest living relatives are given in Table 2.

In the present study, the coexistence approach (CA, Mosbrugger and Utescher, 1997) is used for quantitative palaeoclimatic analyses for Southern China. This method can be applied for quantitative terrestrial climate reconstructions in the Cenozoic using plant fossils, including leaves, fruits and seeds, pollen and wood. Based on the assumption that the climatic requirements of fossil taxa are similar to those of their nearest living relatives (NLRs), the aim of the CA is to find the climatic ranges in which a maximum number of NLRs of a given fossil flora can coexist. The coexistence interval is taken as the best estimate of the palaeoclimatic conditions under which the fossil flora once lived. The application of the CA is facilitated by the computer program CLIMSTAT and the database PALAEOFLORA which contains NLRs of more than 4800 Cenozoic plant taxa together with climatic requirements of their nearest living relatives. In this study, seven climatic parameters have been considered for palaeoclimatic analysis, i.e. mean annual temperature (MAT), temperature of the coldest month (CMT), temperature of the warmest month (WMT), mean annual precipitation (MAP), wettest

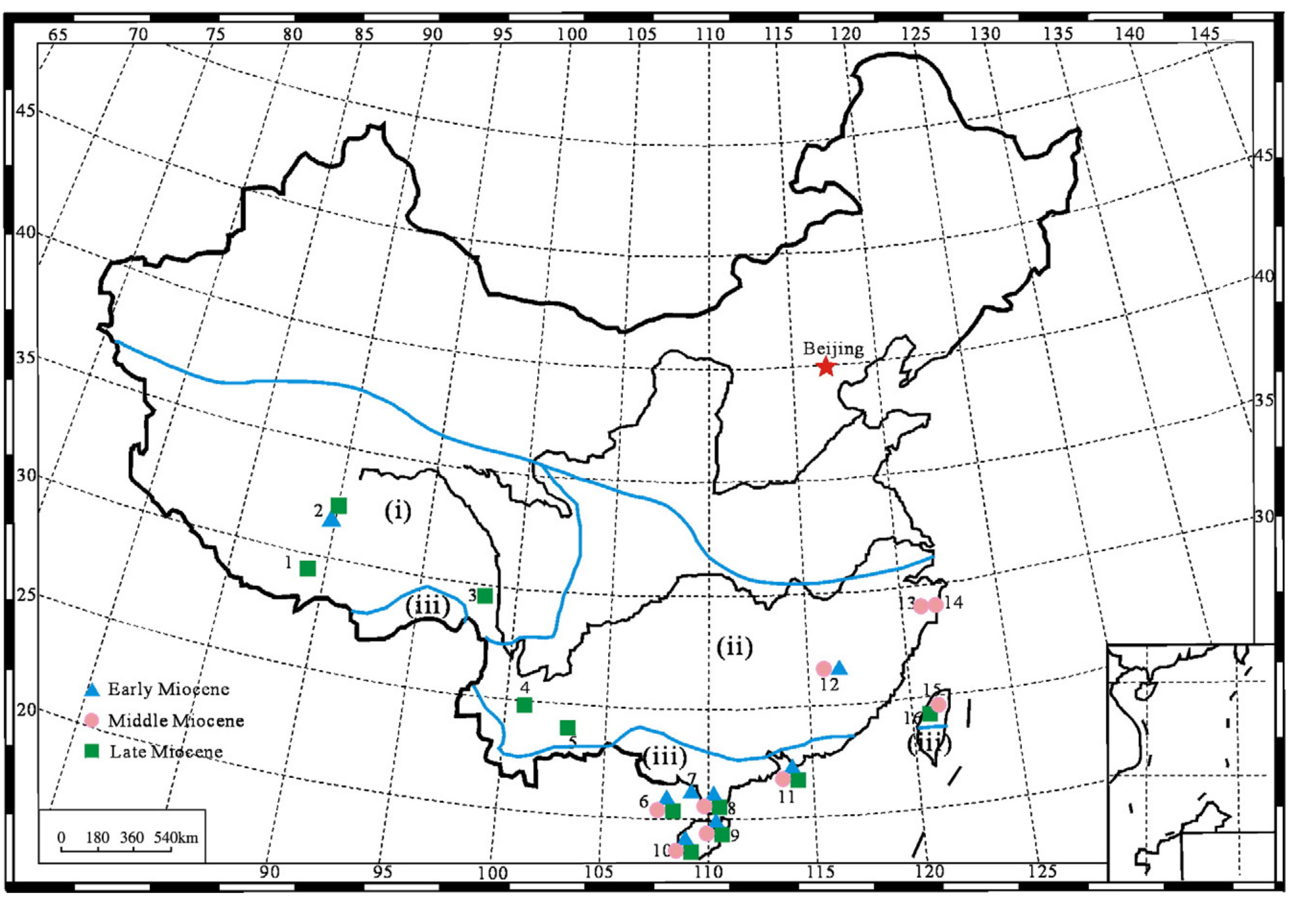

Fig. 1. Miocene fossil locations of Southern China along with the modern vegetation (modified from Wang 1992). 1. Namling. 2. Lunpola Basin. 3. Markam. 4. Lühe, Chuxiong. 5. Xiaolongtan, Kaiyuan. 6. Baibuwan Depression. 7. Weizhou Island. 8. Leizhou Peninsula. 9. Fushan Depression. 10. Yinggehai Basin. 11. Zhujiangkou Basin. 12. Toupo Basin, Guangchang. 13. Xianju. 14. Ninghai. 15. Shihti, Taibei. 16. Miaoli. Modern vegetation types: (i) Tibetan high elevation and cold vegetation, (ii) subtropical evergreen broad-leaved forest and (iii) tropical rainforest and seasonal rainforest.

Table 1
List of localities used for climate analyses (a) geography (longitude and latitude in decimal degree) and (b) stratigraphy and references.

a

Locality name	Sample name	Administrative district	Longitude	Latitude	Type of sample
Early Miocene					
Lunpola Basin	Dingqing 1	Tibet	90.00	32.30	Outcrop
Toupo Basin	Toupo 1	Guangchang, Jiangxi	116.19	26.50	Outcrop
Fushan Depression	Fushan 1	North continental shelf of South China Sea	109.56	19.50	Drilling
Leizhou Peninsula	Leizhou 1	North continental shelf of South China Sea	110.00	21.45	Drilling
Beibuwan Depression	Beibuwan 1	North continental shelf of South China Sea	108.30	20.30	Drilling
Yinggehai Depression	Yinggehai 1	North continental shelf of South China Sea	108.42	18.31	Drilling
Zhujiangkou Basin	Zhujiangkou 1	North continental shelf of South China Sea	113.45	22.25	Drilling
Weizhou Island	Weizhou 1	Beibu Gulf	109.03	21.02	Drilling
Middle Miocene					
Xianju	Zhangjiajing 1	Zhejiang	120.43	28.51	Outcrop
Ninghai	Tonglingzhu 1	Zhejiang	121.26	29.12	Outcrop
Toupo Basin	Toupo 2	Guangchang, Jiangxi	116.19	26.50	Outcrop
Shihti	Shihdi 1	Taipei, Taiwan	121.30	25.03	Outcrop
Fushan Depression	Fushan 2	North continental shelf of South China Sea	109.56	19.50	Drilling
Leizhou Peninsula	Leizhou 2	North continental shelf of South China Sea	110.00	21.45	Drilling
Beibuwan Depression	Beibuwan 2	North continental shelf of South China Sea	108.30	20.30	Drilling
Yinggehai Depression	Yinggehai 2	North continental shelf of South China Sea	108.42	18.31	Drilling
Zhujiangkou Basin	Zhujiangkou 2	North continental shelf of South China Sea	113.45	22.25	Drilling
Late Miocene					
Namling	Wulong 2	Tibet	89.00	29.43	Outcrop
Namling	Wulong a	Tibet	89.00	29.43	Outcrop
Namling	Wulong b	Tibet	89.00	29.43	Outcrop
Namling	Wulong c	Tibet	89.00	29.43	Outcrop
Namling	Wulong d	Tibet	89.00	29.43	Outcrop
Namling	Wulong e	Tibet	89.00	29.43	Outcrop
Markam	Lawula 1	Tibet	98.00	29.00	Outcrop
Markam	Lawula a	Tibet	98.00	29.00	Outcrop
Lunpola Basin	Dingqing 2	Tibet	90.00	32.30	Outcrop
Xiaolongtan	Xiaolongtan 1	Kaiyuan, Yunnan	103.11	23.48	Outcrop
Lühe	Lühe 1	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Lühe 2	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Lühe 5	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Lühe 8	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Lühe 10	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Lühe 12	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Lühe 13	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Lühe 16	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Lühe 18	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Lühe 21	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Lühe 22	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Lühe 23	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Lühe 26	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Lühe 29	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Lühe 30	Chuxiong, Yunnan	101.22	25.10	Outcrop
Miaoli	Miaoli 1	Taiwan	120.48	24.32	Outcrop
Fushan Depression	Fushan 3	North continental shelf of South China Sea	109.56	19.50	Drilling
Leizhou Peninsula	Leizhou 3	North continental shelf of South China Sea	110.00	21.45	Drilling
Beibuwan Depression	Beibuwan 3	North continental shelf of South China Sea	108.30	20.30	Drilling
Yinggehai Depression	Yinggehai 3	North continental shelf of South China Sea	108.42	18.31	Drilling
Zhujiangkou Basin	Zhujiangkou 3	North continental shelf of South China Sea	113.45	22.25	Drilling

b

Sample name	Type of flora	Sediments	Local stratigraphic unit	Correlation method	References
Early Miocene					
Dingqing 1	Pollen	Mudstone, shale	Lower part of Dingqing Fm.	Floristics	Wang et al., 1975
Toupo 1	Pollen	Sandstone, conglomerate	Middle part of Toupo Group	Floristics	Sun and He, 1987
Fushan 1	Pollen	Mudstone, conglomerate, sandstone	Xiayang Fm.	Floristics	Sun et al., 1981
Leizhou 1	Pollen	Mudstone, conglomerate, sandstone	Xiayang Fm.	Floristics	Sun et al., 1981
Beibuwan 1	Pollen	Mudstone, conglomerate, sandstone	Xiayang Fm.	Floristics	Sun et al., 1981
Yinggehai 1	Pollen	–	Meishan Fm.	Floristics	Sun et al., 1981
Zhujiangkou 1	Pollen	Conglomerate, sandstone, mudstone	Zhujiang Fm.	Floristics	Sun et al., 1981
Weizhou 1	Pollen	–	Weizhou Group	Floristics	Wu, 1980
Middle Miocene					
Zhangjiajing 1	Pollen	Coal	–	Floristics	Zheng, 1982
Tonglingzhu 1	Pollen	Mudstone	–	Floristics	Zheng, 1982
Toupo 2	Pollen	Siltstone, mudstone	Upper part of Toupo Group	Floristics	Sun and He, 1987
Shihdi 1	Leaves	Coal	Shihti mine between Taliao Fm. and Tsouho Fm.	Floristics, Geology	Chaney and Chuang, 1968

(continued on next page)

Table 1 (*continued*)

b

Sample name	Type of flora	Sediments	Local stratigraphic unit	Correlation method	References
Early Miocene					
Fushan 2	Pollen	Mudstone, sandstone	Jiaowei Fm.	Floristics	Sun et al., 1981
Leizhou 2	Pollen	Mudstone, sandstone	Jiaowei Fm.	Floristics	Sun et al., 1981
Beibuwan 2	Pollen	Mudstone, sandstone	Jiaowei Fm.	Floristics	Sun et al., 1981
Yinggehai 2	Pollen	–	Huangliu Fm.	Floristics	Sun et al., 1981
Zhujiangkou 2	Pollen	Sandstone, mudstone, shale	Lower part of Hanjiang Fm.	Floristics	Sun et al., 1981
Late Miocene					
Wulong 2	Leaves	Sandstone, conglomerate	Upper part of Wulong Fm.	Floristics, Geology	Li and Guo, 1976
Wulong a	Pollen	Sandstone, conglomerate	Upper part of Wulong Fm.	Floristics, Geology	Song and Liu, 1982
Wulong b	Pollen	Sandstone, conglomerate	Upper part of Wulong Fm.	Floristics, Geology	Song and Liu, 1982
Wulong c	Pollen	Sandstone, conglomerate	Upper part of Wulong Fm.	Floristics, Geology	Song and Liu, 1982
Wulong d	Pollen	Sandstone, conglomerate	Upper part of Wulong Fm.	Floristics, Geology	Song and Liu, 1982
Wulong e	Pollen	Sandstone, conglomerate	Upper part of Wulong Fm.	Floristics, Geology	Song and Liu, 1982
Lawula 1	Leaves	Sandstone	Lawula Fm.	Floristics	Tao and Du, 1987
Lawula a	Pollen	Sandstone	Lawula Fm.	Floristics	Tao and Du, 1987
Dingqing 2	Pollen	Shale	Upper part of Dingqing Fm.	Floristics	Wang et al., 1975
Xiaolongtan 1	Leaves	Marlite	Xiaolongtan Fm.	Floristics, Vertebrate fossil	Zhou, 1985
Lühe 1	Pollen	Mudstone	Xiaolongtan Fm.	Floristics, Geology	Xu et al., 2008
Lühe 2	Pollen	Mudstone	Xiaolongtan Fm.	Floristics, Geology	Xu et al., 2008
Lühe 5	Pollen	Coal	Xiaolongtan Fm.	Floristics, Geology	Xu et al., 2008
Lühe 8	Pollen	Sandstone	Xiaolongtan Fm.	Floristics, Geology	Xu et al., 2008
Lühe 10	Pollen	Sandstone	Xiaolongtan Fm.	Floristics, Geology	Xu et al., 2008
Lühe 12	Pollen	Mudstone	Xiaolongtan Fm.	Floristics, Geology	Xu et al., 2008
Lühe 13	Pollen	Mudstone	Xiaolongtan Fm.	Floristics, Geology	Xu et al., 2008
Lühe 16	Pollen	Mudstone	Xiaolongtan Fm.	Floristics, Geology	Xu et al., 2008
Lühe 18	Pollen	Mudstone	Xiaolongtan Fm.	Floristics, Geology	Xu et al., 2008
Lühe 21	Pollen	Mudstone	Xiaolongtan Fm.	Floristics, Geology	Xu et al., 2008
Lühe 22	Pollen	Mudstone	Xiaolongtan Fm.	Floristics, Geology	Xu et al., 2008
Lühe 23	Pollen	Mudstone	Xiaolongtan Fm.	Floristics, Geology	Xu et al., 2008
Lühe 26	Pollen	Mudstone	Xiaolongtan Fm.	Floristics, Geology	Xu et al., 2008
Lühe 29	Pollen	Mudstone	Xiaolongtan Fm.	Floristics, Geology	Xu et al., 2008
Lühe 30	Pollen	Sandstone	Xiaolongtan Fm.	Floristics, Geology	Xu et al., 2008
Miaoli 1	Pollen	Marine shales, siltstone, sandstone	Tungkong and Shangfuchi Fms.	Floristics, Geology	Canright, 1971
Fushan 3	Pollen	–	Dengloujiao Fm.	Floristics	Sun et al., 1981
Leizhou 3	Pollen	–	Dengloujiao Fm.	Floristics	Sun et al., 1981
Beibuwan 3	Pollen	–	Dengloujiao Fm.	Floristics	Sun et al., 1981
Yinggehai 3	Pollen	–	Lower part of Yinggehai Fm.	Floristics	Sun et al., 1981
Zhujiangkou 3	Pollen	Sandstone, mudstone, lignite	Upper part of Hanjiang Fm.	Floristics	Sun et al., 1981

month precipitation (HMP), driest month precipitation (LMP) and warmest month precipitation (WMP). In addition, the means annual ranges of temperature and precipitation are calculated as the difference between summer and winter temperatures (mean annual range of temperature: MART = WMT − CMT) and the difference between wettest and driest month precipitation (mean annual range of precipitation: MARP = HMP − LMP). Typically, resolution and reliability of the resulting coexistence intervals increase with the number of taxa included in the analysis and are relatively high for floras with ten or more taxa for which climate parameters are known. Thus, no climatic data are given here for floras with less than 10 taxa (see Mosbrugger and Utescher, 1997).

For the purpose of data visualization, mean values of the calculated coexistence intervals are used in Figs. 2–7. Results were processed with the GIS program ArcView 9.0 for visualizing the obtained palaeoclimate data in maps. Interpolations between data points were calculated using the *inverse distance weighted* method, which provides a relatively smooth gradient between the single data points, giving detailed patterns between closely situated localities and less detail between localities separated by greater distances. Moreover, this procedure smoothes out strong fluctuations between close localities thus reducing data noise. To avoid over-interpretation of the resulting maps, the underlying data points (i.e. localities) are clearly indicated and the interpolation is only visualized within a radius of 3° around the localities.

4. Results

All quantitative climate data for all floras comprising more than ten fossil taxa are given in Table 3 and are visualized in Figs. 2–7. The results are grouped as temperature parameters, precipitation parameters, MART and MARP.

4.1. Temperature parameters

All three maps for mean annual temperature (MAT, Fig. 2) in the Early, Middle, and Late Miocene show a distinct spatial differentiation mostly with a lower MAT in the north and higher MAT in the south, except the mid-latitude localities, e.g. Zhujiangkou Basin of Middle and Late Miocene. The maximum of MAT in the south can reach up to around 22–23 °C in the Early, Middle and Late Miocene. In addition, spatial differentiation also can be visible on the maps and the coastal area is warmer than the interior region. For example, in the Early Miocene, the interior locality Lupola Basin in Tibet records a MAT of 15 °C, whereas the coastal Fushan Depression is much warmer with MAT 22.2 °C.

The winter temperatures (CMT, Fig. 3) also display a spatial differentiation with relative high temperatures in the south and low ones in the north. In the Early Miocene, the temperature reaches around 5–7 °C in the north and up to 14–15 °C in the south with the interior area being colder than the coastal area due to the distance from the sea. In the Middle Miocene, all localities are near the sea but show a distinct difference for the CMT as a result of latitudinal influence. For example, it reaches 5–6 °C in the north and 14–15 °C in the south. In the Late Miocene, winter in the coastal area is still warmer than the interior area, but the central part of Southern China becomes colder than Tibet and the coastal area experienced a low temperature of 3–5 °C.

For summer temperatures (WMT, Fig. 3), spatial differentiation also can be clearly recognized from the maps. Within the three time

Table 2
The fossil taxa used by CA along with their nearest living relatives.

Taxon number	Fossil taxon	NLR
1	*Abies* sp.	*Abies* sp.
2	*Abiespollenites*	*Abies* sp.
3	*Abiespollenites* sp.	*Abies* sp.
4	*Abietineaepollenites*	*Pinus* sp.
5	*Abietineaepollenites microalatus* f. *minor*	*Pinus* sp.
6	*Abietineaepollenites* sp.	*Pinus* sp.
7	*Acer juanii*	*Acer* sp.
8	*Acer* sp.	*Acer* sp.
9	*Actinodaphne nipponica*	*Actinodaphne* sp.
10	*Adiantum* sp.	*Adiantum* sp.
11	*Alangium aequafolium*	*Alangium* sp.
12	*Alangium* sp.	*Alangium* sp.
13	*Albizzia bracteata*	*Albizia* sp.
14	*Albizzia miokalkora*	*Albizia* sp.
15	*Aleurites* sp.	*Aleurites* sp.
16	*Alisma* sp.	Alismataceae
17	*Alnipollenites quadrapollenites*	*Alnus* sp.
18	*Alnipollenites* sp.	*Alnus* sp.
19	*Alnipollenites verus*	*Alnus* sp.
20	*Alnus protomaximowizii*	*Alnus* sp.
21	*Alnus schmahausenii*	*Alnus serrulata*
22	*Alnus* sp.	*Alnus* sp.
23	*Alnus* spp.	*Alnus* sp.
24	Amaranthaceae	Amaranthaceae
25	Anacardiaceae	Anacardiaceae
26	*Anodendron* sp.	Apocynaceae
27	Apocynaceae	Apocynaceae
28	Araliaceae	Araliaceae
29	*Araucaria* sp.	*Araucaria* sp.
30	*Araucariacites* sp.	*Araucaria* sp.
31	*Ardisia* sp.	*Ardisia* sp.
32	*Artemisia* sp.	*Artemisia* sp.
33	*Asplenium* sp.	*Asplenium* sp.
34	*Baeckea* sp.	Myrtaceae
35	*Bambusa* sp.	*Bambusa* sp.
36	*Berberis* sp.	*Berberis* sp.
37	*Berchemia miofloribungda*	*Berchemia* sp.
38	*Betula* cf. *utilis*	*Betula* sp.
39	*Betula* cf. *vera*	*Betula* sp.
40	*Betula mankongensis*	*Betula* sp.
41	*Betula* sp.	*Betula* sp.
42	Betulaceae	Betulaceae
43	Bombacaceae	Bombacaceae
44	*Bombacacidites* sp.	*Bombax* sp.
45	Boraginaceae	Borraginaceae
46	*Broussonetia* sp.	*Broussonetia* sp.
47	*Buxapollis* sp.	*Buxus* sp.
48	*Caesalpinia* sp.	*Caesalpinia* sp.
49	Campanulaceae	Campanulaceae
50	Caprifoliaceae	Caprifoliaceae
51	*Caprifoliipites*	*Viburnum* sp.
52	*Carpinipites* sp.	*Carpinus* sp.
53	*Carpinus* cf. *fargesiana*	*Carpinus* sp.
54	*Carpinus grandis*	*Carpinus betulus*
55	*Carpinus* sp.	*Carpinus* sp.
56	*Carya cathayensis*	*Carya* sp.
57	*Carya* sp.	*Carya* sp.
58	*Carya* spp.	*Carya* sp.
59	*Caryapollenites simplex*	*Carya cordiformis*
60	*Caryapollenites* sp.	*Carya* sp.
61	*Cassia oblonga*	*Cassia* sp.
62	*Cassia suffruticosa*	*Cassia* sp.
63	*Castanea miomollissima*	*Castanea* sp.
64	*Castanea* sp.	*Castanea* sp.
65	*Castanea* spp.	*Castanea* sp.
66	Castaneoideae	Fagaceae
67	*Castanopsis miocuspidata*	*Castanopsis chrysophylla*
68	*Casuarinidites cainozoicus*	Casuarinaceae
69	*Cedripites* sp.	*Cedrus* sp.
70	*Cedrus* sp.	*Cedrus* sp.
71	Celastraceae	Celastraceae
72	*Celastrus* sp.	*Celastrus* sp.
73	*Celtis* sp.	*Celtis* sp.
74	*Celtis* spp.	*Celtis* sp.
75	*Ceratopteris* spp.	Pteridaceae
76	*Phelline* spp.	*Phelline* sp.
77	Chenopodiaceae	Chenopodiaceae
78	*Chenopodipollis microporatus*	Chenopodiaceae
79	*Chenopodipollis multiplex*	Chenopodiaceae
80	*Chenopodipollis multiporatus*	Chenopodiaceae
81	*Chenopodipollis* sp.	Chenopodiaceae
82	*Chenopodium* sp.	Chenopodiaceae
83	*Cibotium* sp.	Dicksoniaceae
84	*Cibotiumspora* sp.	Dicksoniaceae
85	*Cinnamomum* sp.	*Cinnamomum* sp.
86	*Cinnamomum* sp. 1	*Cinnamomum* sp.
87	*Cinnamomum* sp. 2	*Cinnamomum* sp.
88	*Cinnamonum oguniense*	*Cinnamomum* sp.
89	*Cleyera* sp.	*Cleyera* sp.
90	Compositae	Asteroideae
91	*Coniogramme devolii*	*Polypodium* sp.
92	*Coniogramme* sp.	*Polypodium* sp.
93	*Convolvulus* sp.	*Convolvulus* sp.
94	Cornaceae	Cornaceae
95	*Cornus* sp.	*Cornus* sp.
96	*Corylopsis princeps*	*Corylopsis* sp.
97	*Corylopsis* spp.	*Corylopsis* sp.
98	*Corylus maequarii*	*Corylus* sp.
99	*Corylus* sp.	*Corylus* sp.
100	*Crassoretitriletes nanhaiensis*	*Lygodium* sp.
101	*Crassoretitriletes* sp.	*Lygodium* sp.
102	*Crassoretitriletes vanraadshooveni*	*Lygodium* sp.
103	Cruciferae	Brassicaceae
104	*Cupuliferoipollenites*	Cupuliferae
105	*Cupuliferoipollenites oviformis*	Cupuliferae
106	*Cupuliferoipollenites pusillus*	Cupuliferae
107	*Cupuliferoipollenites* sp.	Cupuliferae
108	*Cyathea* sp.	Cyatheaceae
109	*Cyathidites minor*	Cyatheaceae
110	*Cyclobalanopsis mandraliscae*	Fagaceae
111	*Cyclobalanopsis praegilva*	Fagaceae
112	*Cyclobalanopsis* sp.	Fagaceae
113	Cyperaceae	Cyperaceae
114	*Cyperacites* sp.	Cyperaceae
115	*Cyrillaceaepollenites megaexactus*	Cyrillaceae
116	*Dacrydiumidites*	Podocarpaceae
117	*Dacrydiumites florinii*	Podocarpaceae
118	*Dalbergia lucida*	*Dalbergia* sp.
119	*Daphne* sp.	*Daphne* sp.
120	*Davallia* sp.	*Davallia* sp.
121	Dennstaedtiaceae	*Dennstaedtia* sp.
122	*Desmodium pulchellum*	Leguminosae
123	*Desmos kaiyunanensis*	Anonaceae
124	*Dicksonia* sp.	Leguminosae
125	*Dicolpopollis kockelii*	Palmae
126	*Diospyros* sp.	*Diospyros* sp.
127	*Dodonaea japonica*	*Dodonaea* sp.
128	*Echinatisporis*	Selaginellaceae
129	*Elaeagnus* sp.	*Elaeagnus* sp.
130	*Engelhardtia* spp.	*Engelhardtia* sp.
131	*Engelhardtioidites levis*	*Engelhardtia* sp.
132	*Engelhardtioidites* sp.	*Engelhardtia* sp.
133	*Ephedripites* sp.	*Ephedra* sp.
134	*Equisetum* sp.	*Equisetum* sp.
135	Ericaceae	Ericaceae
136	*Ericaceoipollenites* sp.	Ericaceae
137	*Ericipites*	Ericaceae
138	*Erythrophleum ovatifolium*	Fabaceae
139	Euphorbiaceae	Euphorbiaceae
140	*Extrapunctatosporis megapunctos*	Polypodiaceae
141	*Extrapunctatosporites* sp.	Polypodiaceae
142	*Fagara* sp.	*Zanthoxylum* sp.
143	*Fagopyrum* sp.	*Fagopyrum* sp.
144	*Fagus* sp.	*Fagus* sp.
145	*Ficus* sp.	*Ficus* sp.
146	*Florschuetzia* cf. *levipoli*	Sonneratiaceae
147	*Florschuetzia levipoli*	Sonneratiaceae
148	*Florschuetzia semilobata*	Sonneratiaceae
149	*Florschuetzia* sp.	Sonneratiaceae
150	*Florschuetzia trilobata*	Sonneratiaceae
151	*Fraxinoipollenites* sp.	*Fraxinus* sp.

(continued on next page)

Table 2 (*continued*)

Taxon number	Fossil taxon	NLR
152	Gentianaceae	Gentianaceae
153	*Gleditsia integra*	*Gleditsia* sp.
154	*Gleicheniidites* sp.	*Gleichenia* sp.
155	*Glyptosrobus* sp.	*Glyptostrobus lineat*
156	*Gothanipollis bassensis*	Loranthaceae
157	Gramineae	Gramineae
158	*Graminidites media*	Gramineae
159	*Graminidites*	Gramineae
160	Hamamelidaceae	Hamamelidaceae
161	*Hamamelis* sp.	*Hamamelis* sp.
162	*Hemiptelea* sp.	*Hemiptelea davidii*
163	*Hicriopteris* sp.	Pteridaceae
164	*Homalium* sp.	*Homalium* sp.
165	*Humulus* sp.	*Humulus* sp.
166	*Hydrocharis* sp.	*Hydrocharis* sp.
167	*Hydrosporites levis*	Salviniaceae
168	*Hydrosporites* sp.	Salviniaceae
169	*Ilex* sp.	*Ilex* sp.
170	*Ilexpollenites longipolliniata*	*Ilex* sp.
171	*Ilexpollenites margaritatus*	*Ilex* sp.
172	*Ilexpollenites membranous*	*Ilex* sp.
173	*Inaperturopollenites*	Taxodiaceae
174	*Indigofera praesuffruticosa*	Fabaceae
175	*Jasminum paralanceolarium*	*Jasminum* sp.
176	Juglandaceae	Juglandaceae
177	*Juglans japonica*	*Juglans* sp.
178	*Juglans regia*	*Juglans* sp.
179	*Juglans* sp.	*Juglans* sp.
180	*Juglanspollenites verus*	*Juglans* sp.
181	*Ketelaeria* sp.	*Keteleeria* sp.
182	Labiatae	Labiatae
183	*Laevigatosporites* sp.	Polypodiaceae
184	*Laricoidites*	*Larix* sp.
185	*Laricoidites magnus*	*Larix* sp.
186	Lauraceae	Lauraceae
187	*Laurus obovalis*	*Laurus* sp.
188	Leguminosae	Leguminosae
189	*Leiotriletes adriennis*	Schizaeaceae
190	*Leiotriletes* sp.	*Lygodium* sp.
191	*Lespedeza* sp.	*Lespedeza* sp.
192	Liliaceae	Liliaceae
193	*Liliacidites* sp.	Liliaceae
194	*Liquidambar*	*Liquidambar* sp.
195	*Liquidambar brandonensis*	*Liquidambar* sp.
196	*Liquidambar mangelsdefianus*	*Liquidambar* sp.
197	*Liquidambarpollenites minutus*	*Liquidambar* sp.
198	*Liquidambarpollenites stigmosus*	*Liquidambar* sp.
199	*Lithocarpus* sp.	Fagaceae
200	*Litsea grabaui*	*Litsea* sp.
201	*Lonicera* sp.	*Lonicera* sp.
202	*Lonicerapollis gallwitzii*	*Lonicera* sp.
203	Lycopodiaceae	Lycopodiaceae
204	*Lycopodium* sp.	*Lycopodium* sp.
205	*Lythrum* sp.	Lythraceae
206	*Macaranga* spp.	Euphorbiaceae
207	*Machilus americana*	Lauraceae
208	*Machilus* sp.	Lauraceae
209	*Machilus ugoana*	Lauraceae
210	*Magnolia miocenica*	*Magnolia* sp.
211	*Magnolia* sp.	*Magnolia* sp.
212	*Magnolipollis elongatus*	*Magnolia* sp.
213	*Mallotus* sp.	*Mallotus* sp.
214	*Margcolporites* sp.	*Caesalpinia* sp.
215	*Margocolporites vanwijhei*	*Caesalpinia* sp.
216	Meliaceae	Meliaceae
217	*Metasequoia* sp.	*Metasequoia* sp.
218	*Microlepia* sp.	*Microlepia* sp.
219	*Momipites coryloides*	*Engelhardtia* sp.
220	*Monocolpopollenites*	Palmae
221	*Monosulcites* sp.	Palmae
222	Moraceae	Moraceae
223	*Myrica elliptica*	*Myrica* sp.
224	*Myrica longifolia*	*Myrica* sp.
225	*Myrica* sp.	*Myrica* sp.
226	*Myriophyllum* sp.	*Myriophyllum vertici*
227	Myrtaceae	Myrtaceae
228	*Myrtaceidites parvus*	Myrtaceae

Table 2 (*continued*)

Taxon number	Fossil taxon	NLR
229	*Myrtaceidites* sp.	Myrtaceae
230	*Neolitsea* sp.	*Neolitsea* sp.
231	*Nothaphoebe precavaleriei*	Lauraceae
232	*Nuphar* sp.	*Nuphar* sp.
233	Nymphaeaceae	Nymphaeaceae
234	Nyssaceae	Nyssaceae
235	*Nyssapollenites*	*Nyssa* sp.
236	*Oenanthe* sp.	*Oenanthe* sp.
237	Oleaceae	Olacaceae
238	Onagraceae	Onagraceae
239	*Ophioglossum* sp.	*Ophioglossum* sp.
240	*Ormosia xiaolongtanensis*	Fabaceae
241	*Osmunda* sp.	*Osmunda* sp.
242	*Osmundacidites primarius*	*Osmunda* sp.
243	*Osmundacidites wellmanii*	*Osmunda* sp.
244	*Ostrya* sp.	*Ostrya* sp.
245	*Ostryoipollenites* cf. *rhenanus*	Betulaceae
246	Palmae	Palmae
247	*Passiflora* sp.	*Passiflora* sp.
248	*Peltandripites* sp.	*Peltandra* sp.
249	*Perinomonoletes* sp.	Polypodiaceae
250	*Phoebe pseudolanceolata*	*Phoebe* sp.
251	*Photinia* sp.	*Photinia* sp.
252	*Phragmites* sp.	*Phragmites* sp.
253	*Phyllanthus* sp.	*Phyllanthus* sp.
254	*Phyllostachys* sp.	Poaceae
255	*Picea* sp.	*Picea* sp.
256	Pinaceae	Pinaceae
257	*Pinus* sp.	*Pinus* sp.
258	*Pinuspollenites minutus*	*Pinus* sp.
259	*Pinuspollenites pristinipollinia*	*Pinus* sp.
260	*Pinuspollenites strobipites*	*Pinus* sp.
261	*Pithecellobium lucidum*	Fabaceae
262	Plantaginaceae	Plantaginaceae
263	*Platanus* sp.	*Platanus* sp.
264	*Platycarya* sp.	*Platycarya* sp.
265	*Platycaryapollenites shandongensis*	*Platycarya* sp.
266	*Podocarpidites*	*Podocarpus* sp.
267	*Podogonium oehningense*	*Gleditsia* sp.
268	*Podogonium* sp.	*Gleditsia* sp.
269	Polygonaceae	Polygonaceae
270	*Polygonum* sp.	*Polygonum* sp.
271	Polypodiaceae	Polypodiaceae
272	Polypodiaceaesporites gracilis	Polypodiaceae
273	*Polypodiaceaesporites haardti*	Polypodiaceae
274	*Polypodiaceaesporites megahaardti*	Polypodiaceae
275	*Polypodiaceaesporites ovatus*	Polypodiaceae
276	*Polypodiaceaesporites wanglougangensis*	Polypodiaceae
277	*Polypodiaceaesporties gracilis*	Polypodiaceae
278	*Polypodiaceoisporites*	*Pteris* sp.
279	*Polypodiisporites*	*Polypodium* sp.
280	*Polypodiisporites* cf. *perverrucatus*	*Polypodium* sp.
281	*Polypodiisporites favus*	*Polypodium* sp.
282	*Polypodiisporites usmensis*	*Polypodium* sp.
283	*Polypodium* sp.	*Polypodium* sp.
284	*Potamogeton* sp.	*Potamogeton* sp.
285	*Proteacidites* cf. *mollis*	Proteaceae
286	*Psophosphaera* sp.	Pinaceae
287	Pteridaceae	Pteridaceae
288	*Pteridium* sp.	*Pteridium* sp.
289	*Pteris* sp.	*Pteris* sp.
290	*Pterium* sp.	*Pteridium* sp.
291	*Pterocarya* sp.	*Pterocarya* sp.
292	*Pterocaryapollenites stellatus*	*Pterocarya* sp.
293	*Punica* sp.	*Punica* sp.
294	*Quercus* spp.	*Quercus* sp.
295	*Quercoidites*	*Quercus* sp.
296	*Quercoidites asper*	*Quercus* sp.
297	*Quercoidites henrici*	*Quercus* sp.
298	*Quercoidites microhenrici*	*Quercus* sp.
299	*Quercoidites minor*	*Quercus* sp.
300	*Quercus lantenoisii*	*Quercus* sp.
301	*Quercus namlingensis*	*Quercus* sp.
302	*Quercus prespathulata*	*Quercus* sp.
303	*Quercus sinomiocenica*	*Quercus* sp.
304	*Quercus wulongensis*	*Quercus* sp.
305	Ranunculaceae	Ranunculaceae

Table 2 (*continued*)

Taxon number	Fossil taxon	NLR
306	*Rhamnaceidites* sp.	*Rhamnus* sp.
307	*Rhapis* sp.	Palmae
308	*Rhododendron namlingense*	*Rhododendron* sp.
309	*Rhododendron sanzugawaense*	*Rhododendron* sp.
310	*Ricinus* spp.	*Ricinus* sp.
311	*Robinia nipponica*	*Robinia* sp.
312	*Rosa* sp.	*Rosa* sp.
313	Rubiaceae	Rubiaceae
314	*Rumex* sp.	*Rumex* sp.
315	Rutaceae	Rutaceae
316	*Sagittaria* sp.	*Saggitaria* sp.
317	*Salix miosinica*	*Salix* sp.
318	*Salixipollenites discoloripites*	*Salix* sp.
319	*Salixipollenites hiatus*	*Salix* sp.
320	*Salix* sp.	*Salix* sp.
321	*Salvinia* spp.	*Salvinia* sp.
322	Sapindaceae	Sapindaceae
323	*Sapodaceoidaepollenites kirchheimeri*	Sapotaceae
324	Sapotaceae	Sapotaceae
325	*Schizaeoisporites* sp.	Schizaeaceae
326	Scrophulariaceae	Schizaeaceae
327	*Selaginella* sp.	*Selaginella* sp.
328	*Sequiapollenites* sp.	Taxodiaceae
329	*Smilax* sp.	*Smilax* sp.
330	*Sophora miojaponica*	*Sophora* sp.
331	*Sophora paraflavescens*	*Sophora* sp.
332	*Sorbus* cf. *wilsoniana*	*Sorbus* sp.
333	Sparganiaceae	Sparganiaceae
334	*Sphagnumsporites* sp.	*Sphagnum* sp.
335	*Sterculia* sp.	*Sterculia* sp.
336	Sterculiaceae	Sterculiaceae
337	*Stereisporites* sp.	Sphagnaceae
338	*Symplocoipollenites*	*Symplocos* sp.
339	*Talisiipites*	Sapindaceae
340	Taxodiaceae	Taxodiaceae
341	*Taxodiaceaepollenites hiasus*	Taxodiaceae
342	*Thalictrum*	*Thalictrum* sp.
343	*Thermopsis prebarbata*	Fabaceae
344	*Tilia* sp.	*Tilia* sp.
345	*Tiliaepollenites instructus*	Tiliaceae
346	*Trapa* sp.	*Trapa* sp.
347	*Triporopollenites* sp.	Betulaceae
348	*Tsuga* sp.	*Tsuga* sp.
349	*Tsugaepollenites igniculus*	*Tsuga* sp.
350	*Tsugaepollenites maximus*	*Tsuga* sp.
351	*Tsugaepollenites neogenicus*	*Tsuga* sp.
352	*Tsugaepollenites veridifluminipites*	*Tsuga* sp.
353	*Typha lesquereuxii*	*Typha* sp.
354	*Typha* sp.	*Typha* sp.
355	Ulmaceae	Ulmaceae
356	*Ulmus* sp.	*Ulmus* sp.
357	*Ulmipollenites granopollenites*	Ulmaceae
358	*Ulmipollenites undulosus*	Ulmaceae
359	Umbelliferae	Umbelliferae
360	*Utricularia* sp.	*Utricularia* sp.
361	*Verrucatosporites* sp.	Polypodiaceae
362	*Xanthium* sp.	Compositae
363	*Zelkova* sp.	*Zelkova* sp.
364	*Zonocostites* cf. *ramonae*	Rhizophoraceae

intervals, the maximum and minimum WMT lies around 28–29 °C and 24–25 °C, respectively. The interior area shows higher temperatures compared with the coastal area.

4.2. Precipitation parameters

For mean annual precipitation (MAP, Fig. 4), maps for the Early and Middle Miocene show a humid climate with the mean annual rainfall exceeding 1000 mm, and in the coastal area, the value reaches up to 1300 to 1500 mm. However, in the Late Miocene, in the middle part of Southern China, it is less humid than in other places. For instance, the precipitation in Lühe and Markam attains 500–600 mm and 700–800 mm, respectively.

For precipitation of the wettest month (HMP, Fig. 5), most of the coastal areas have a high value of precipitation above 200 mm. Even in the Middle and Late Miocene, it reaches up to 280–300 mm. Most interior areas, although the values are lower than that of the coastal area, also experience a considerably abundant rainfall of around 160–180 mm.

Precipitation of the driest month (LMP, Fig. 5) does not show an obvious spatial differentiation during the three stages. Most of the coastal and interior areas have the similar value around 20 to 40 mm, but the interior is a bit drier than the coastal area.

Precipitation of the warmest month (WMP, Fig. 6) shows a spatial differentiation with around 100 mm in the north and 140 to 160 mm in the south during the Early, Middle and Late Miocene. One exception is the flora from Lühe, Yunnan Province in the Late Miocene, based on which less than 100 mm of summer rainfall is calculated by the CA method.

4.3. MART

The mean annual range of temperature (MART, Fig. 2), calculated as the difference between WMT and CMT, displays a lower seasonality in the south (MART about 12 °C) with warmer summers and winters, while revealing a higher seasonality in the north (MART about 20 °C) with warmer summers and colder winters. Lowest seasonalities of temperature occur in the coastal area of Southern China. The interior region shows a higher seasonality than the coastal area, which is maybe due to the influence of the continental climate.

4.4. MARP

The mean annual range of precipitation (MARP, Fig. 4), defined as the difference between the precipitation of wettest month (HMP) and driest month (LMP), shows a higher seasonality in the south (MARP about 220 mm, with abundant summer rainfall and less winter rainfall) and a lower seasonality in the north (MARP about 100 mm, with less rainfall in summers and winters). Highest seasonalities of precipitation occur in the coastal region within our study area, i.e. Beibuwan Depression, Leizhou Peninsula and Zhujiangkou Basin, which coincides with the pattern observed in HMP.

5. Discussion

5.1. Comparison with Western and Central Eurasian Miocene climatic data

Since the establishment of the international research network NECLIME—*Neogene Climate Evolution in Eurasia* in 2000, numerous Western Eurasian Miocene climatic estimates have been calculated (Ivanov et al., 2002, 2008; Bruch et al., 2004, 2006, 2007; Mosbrugger et al., 2005; Akgün et al., 2007; Böhme et al., 2007; Erdei et al., 2007; Martinetto et al., 2007; Syabryaj et al., 2007; Utescher et al., 2000; 2007a,b; Kvacek et al., 2008). As well, some Central Eurasian localities in Kazakhstan (Bruch and Zhilin, 2007) have also been investigated for Miocene climatic analyses.

These data provide a good basis for comparison with our Chinese data. For revealing similarities and differences of Miocene climate patterns and evolution in Eurasia, our present data together with the published data of Western and Central Eurasia have been visualized for MAT and MAP in the Early, Middle and Late Miocene (Fig. 7).

In the Early Miocene, the data from Southern China fit very well with the European data showing a warm climate, but the MAT of Southern China shows a distinct latitudinal differentiation, while in Europe latitudinal differentiation is weak. Central Eurasia is less warm than Europe and Southern China, but fits pretty well with the western part of Southern China, having a similar temperature around 15 °C. MAP in the Early Miocene shows Southern China and Europe are humid with precipitation above 1000 mm, while Central Eurasia is less humid than Southern China and Europe. In the Middle Miocene,

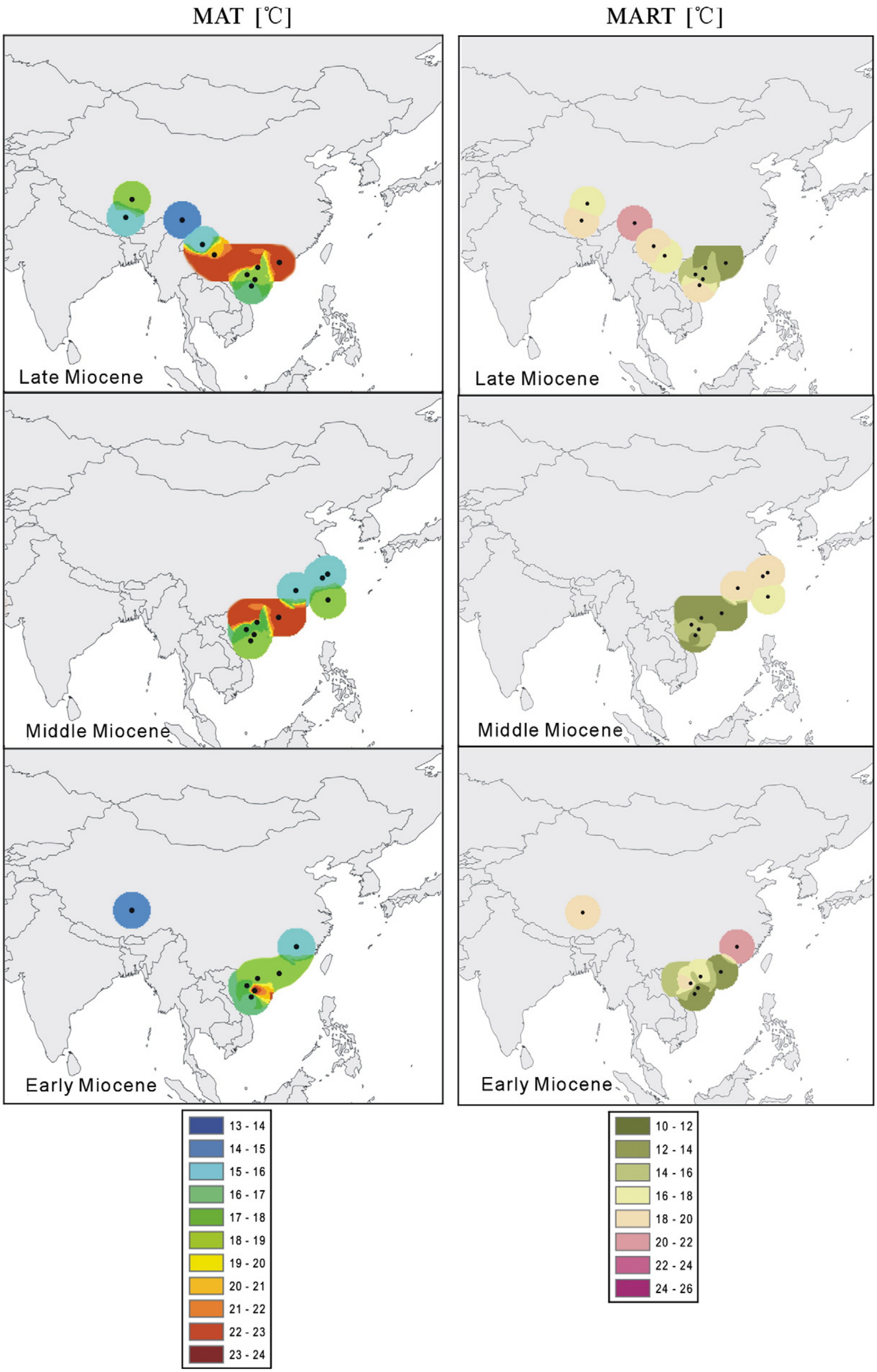

Fig. 2. Visualization of climate results in maps for mean annual temperature (MAT) and mean annual range of temperature (MART) in Southern China.

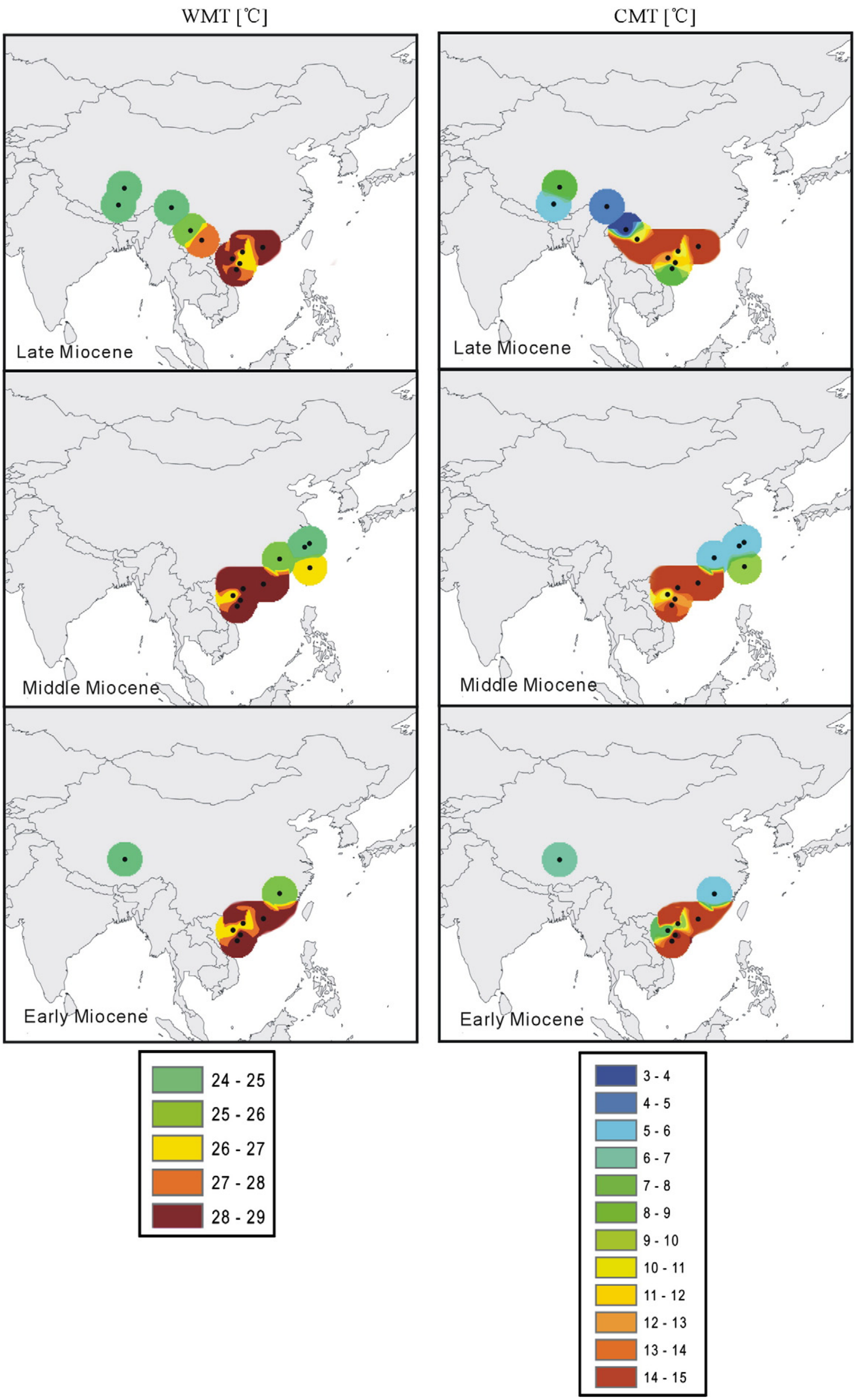

Fig. 3. Visualization of climate results in maps for temperature of the warmest month (WMT) and temperature of the coldest month (CMT) in Southern China.

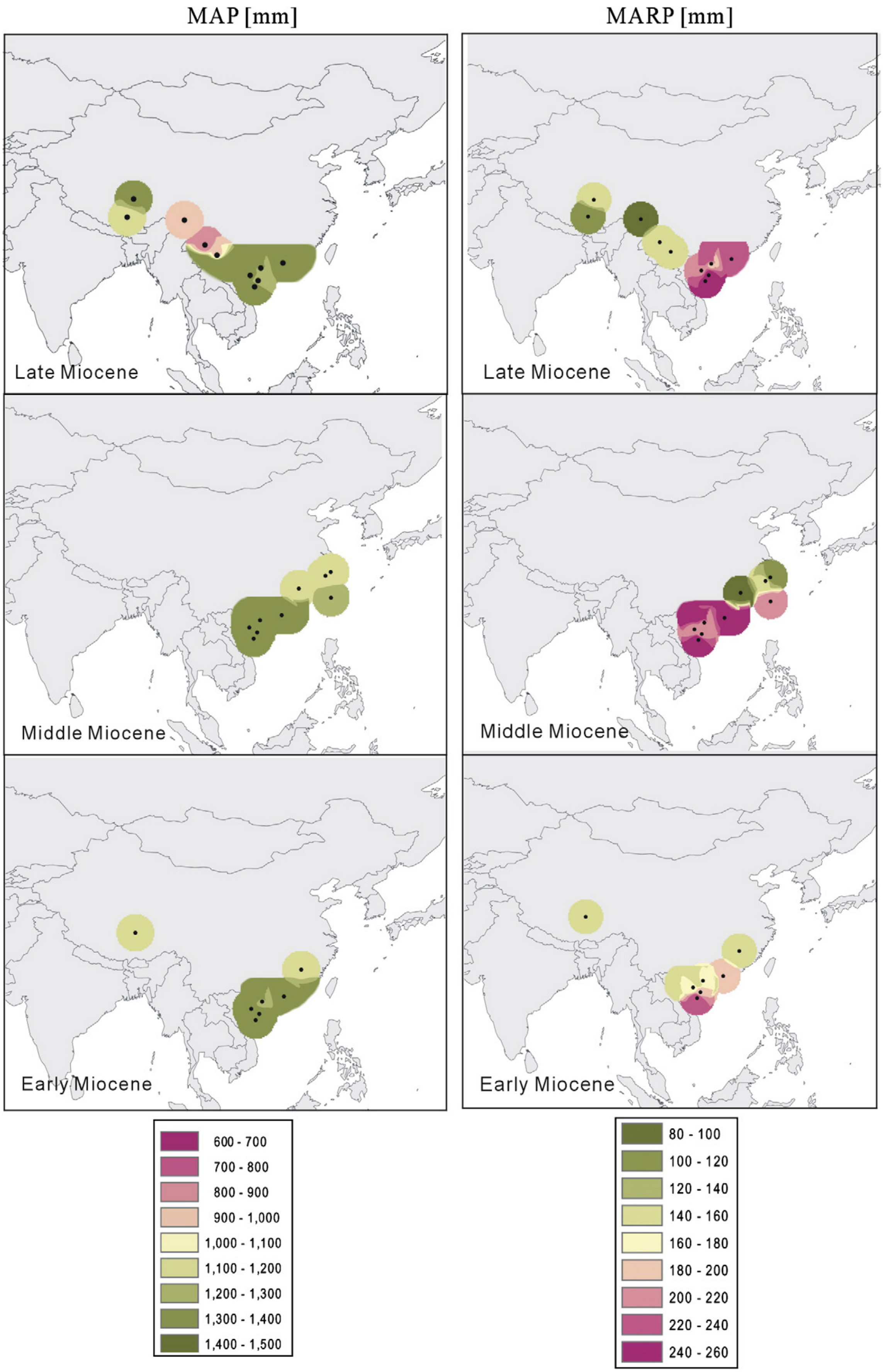

Fig. 4. Visualization of climate results in maps for mean annual precipitation (MAP) and mean annual range of precipitation (MARP) in Southern China.

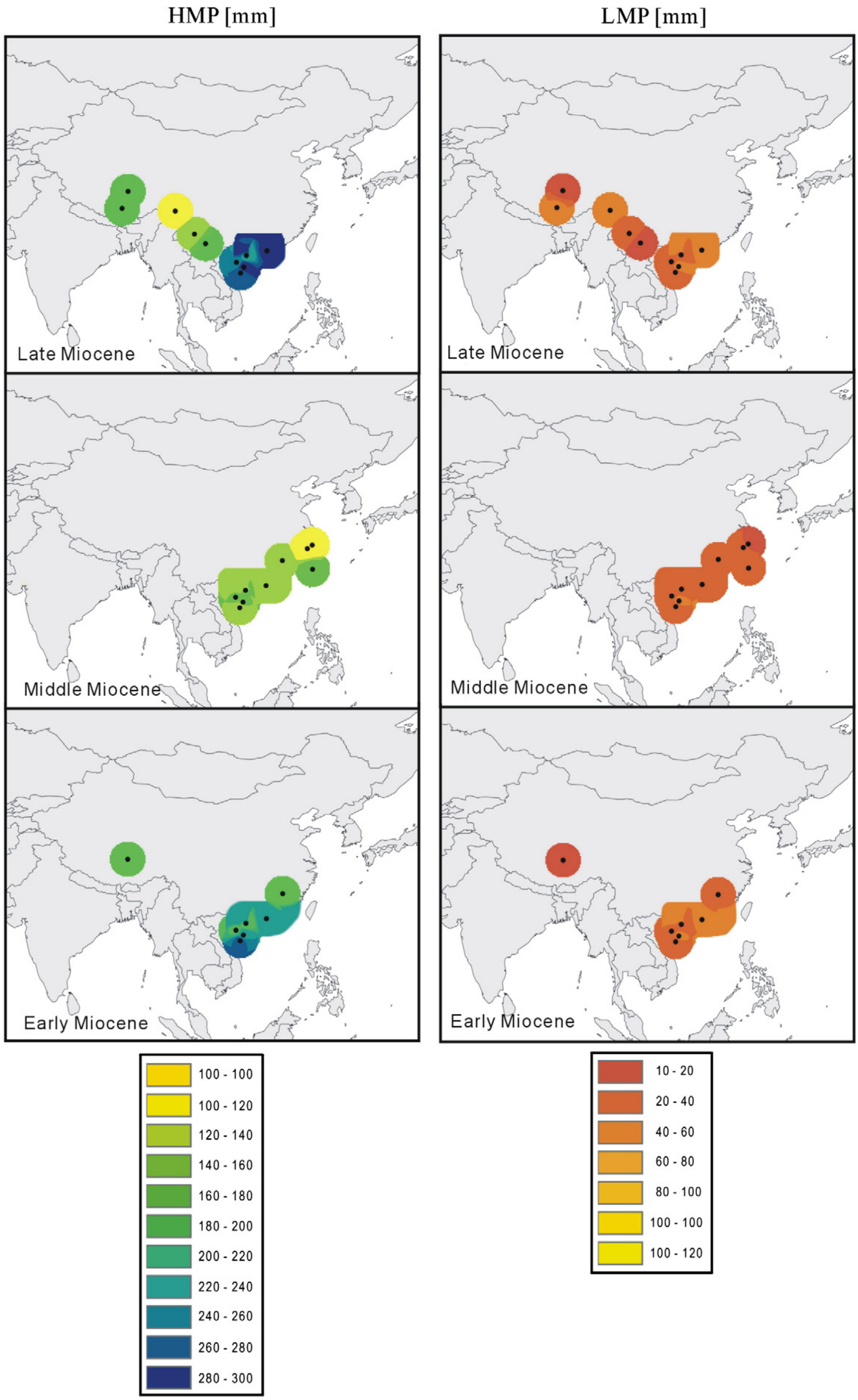

Fig. 5. Visualization of climate results in maps for wettest month precipitation (HMP) and driest month precipitation (LMP) in Southern China.

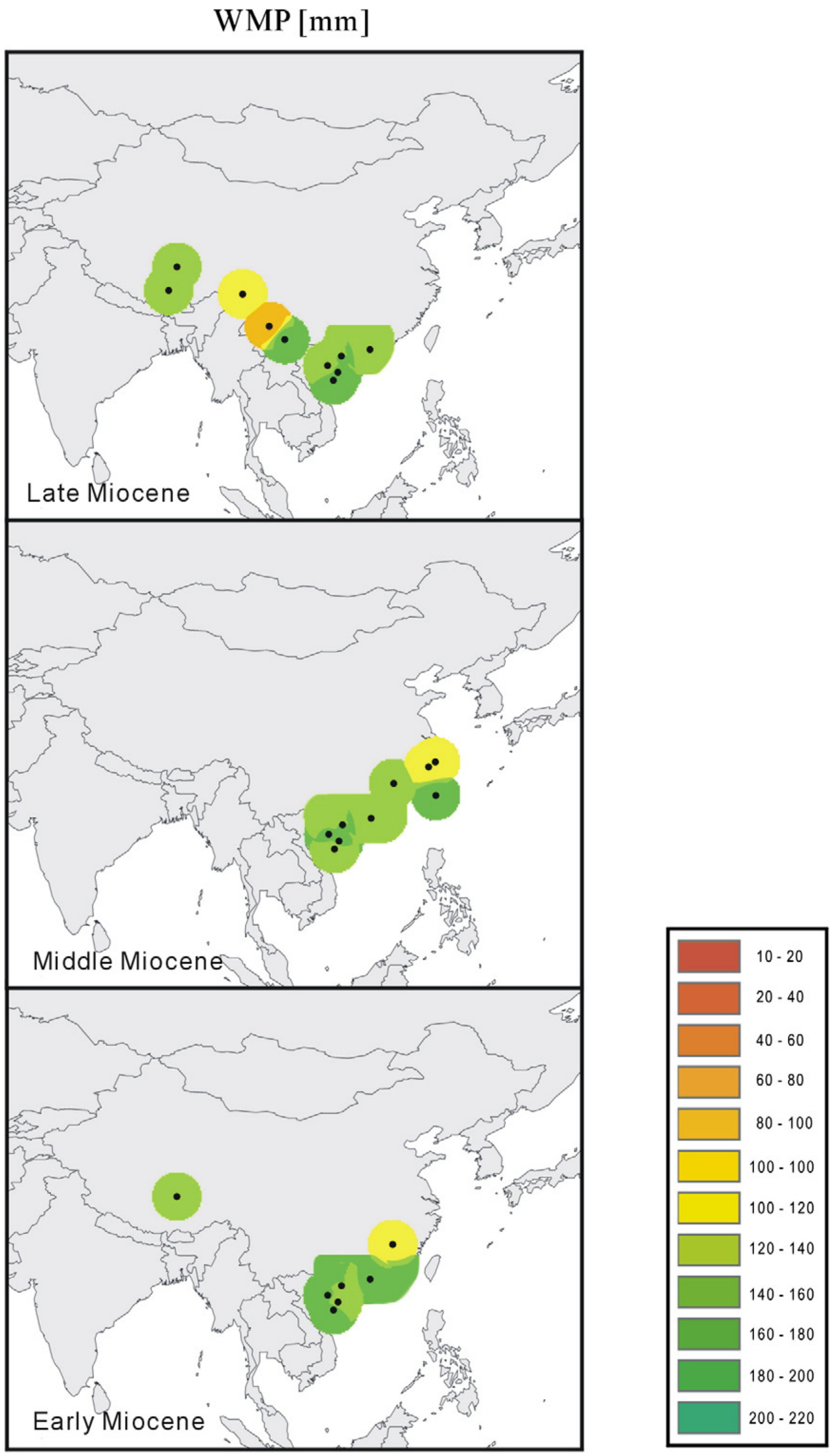

Fig. 6. Visualization of climate results in maps for warmest month precipitation (WMP) in Southern China.

MAT of Southern China displays an obvious latitudinal differentiation with a range from 15 to 23 °C, while in Europe latitudinal differentiation is still weak and the gradient is not so distinct. During this period, Southern China and Europe are still humid, but in some regions in Europe precipitation decreases. In the Late Miocene, Southern China and Europe show the same trend with the climate in the north being less warm than in the south. In the north of Europe and middle of Southern China, temperature has decreased and less humid areas begin to expand during this time interval compared with the Middle Miocene situation.

5.2. Possible casual influences on Miocene climate evolution in Southern China

As mentioned above, MAT and MAP of Lunpola Basin in Tibet during the Early Miocene are recorded as 15 °C and 1113 mm, respectively. Additionally, MAT and MAP of this locality together with other two localities in Tibet, Namling and Markam, in the Late Miocene are also above 15 °C and over 1000 mm, while at present the Lunpola Basin has an elevation of more than 4600 m a. s. l. with MAT −1.2 °C and MAP 308.3 mm (IDBMC, 1984). Although the

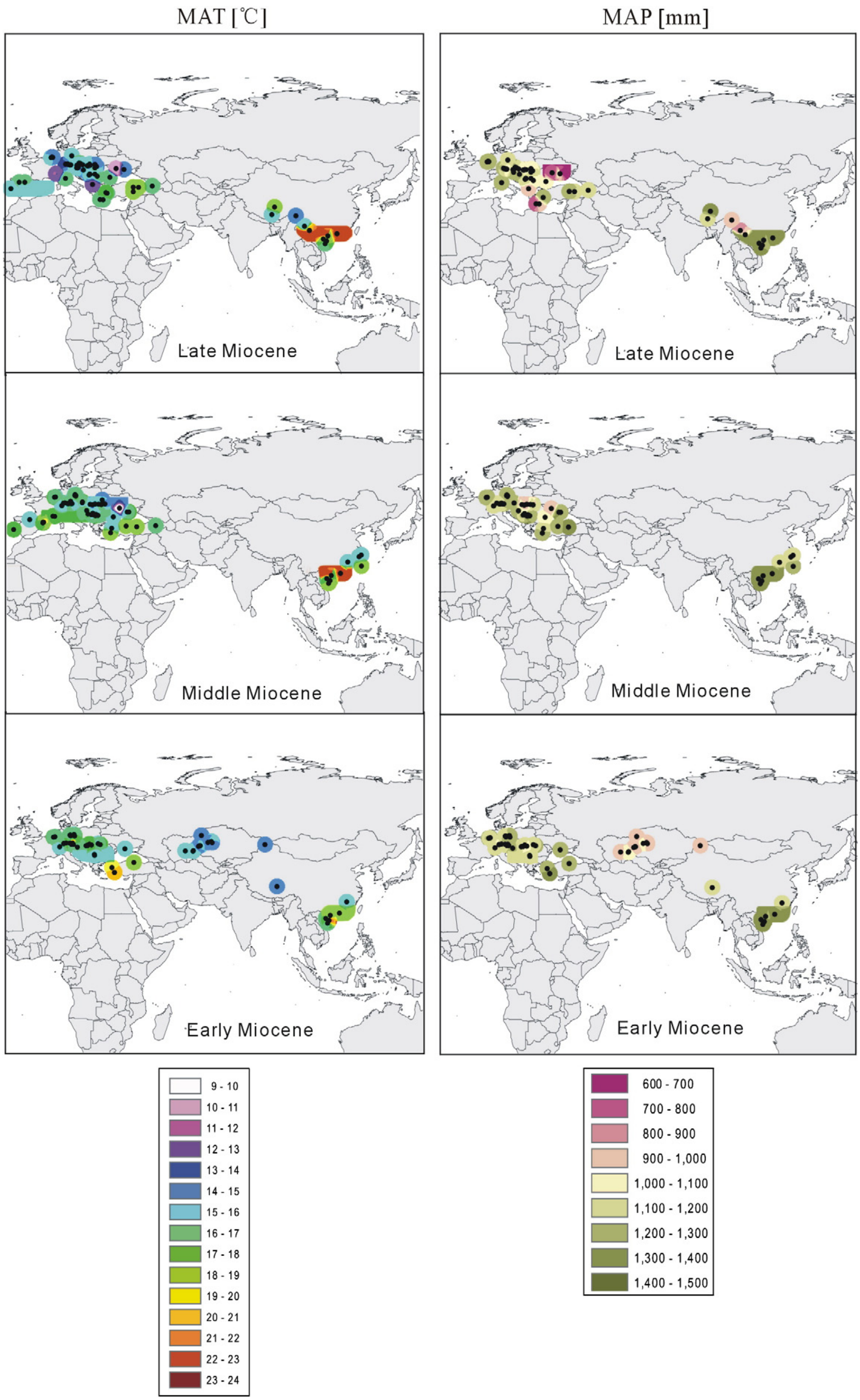

Fig. 7. Visualization of climate results in maps for comparison of mean annual temperature (MAT) and mean annual precipitation (MAP) in Europe.

Table 3
Results of climate analysis with the coexistence approach border and center values of the coexistence intervals for (a) temperature and (b) precipitation parameters; l.b.: lower borders of coexistence intervals, u.b.: upper borders of coexistence intervals.

a

Locality name	Sample name	Taxa total	Taxa analysed	l.b.	MAT (°C)	u.b.	l.b.	CMT (°C)	u.b.	l.b.	WMT (°C)	u.b.
Early Miocene												
Lunpola Basin	Dingqing 1	21	14	11.60	15.00	18.40	−0.30	6.10	12.50	21.60	24.85	28.10
Toupo Basin	Toupo 1	109	59	15.70	15.90	16.10	5.00	5.25	5.50	25.40	25.50	25.60
Fushan Depression	Fushan 1	26	14	22.20	22.20	22.20	13.60	15.10	16.60	28.10	28.20	28.30
Leizhou Peninsula	Leizhou 1	40	21	15.60	18.45	21.30	6.60	9.55	12.50	24.70	26.40	28.10
Beibuwan Depression	Beibuwan 1	47	29	15.60	17.00	18.40	6.60	7.35	8.10	24.70	26.40	28.10
Yinggehai Depression	Yinggehai 1	30	16	14.80	16.60	18.40	13.60	14.20	14.80	28.10	28.10	28.10
Zhujiangkou Basin	Zhujiangkou 1	55	35	15.60	18.80	22.00	14.30	14.55	14.80	28.10	28.10	28.10
Weizhou Island	Weizhou 1	117	64	15.70	17.05	18.40	6.60	9.55	12.50	25.00	25.00	25.00
Middle Miocene												
Xianju	Zhangjiajing 1	28	20	15.70	15.90	16.10	3.80	5.80	7.80	23.60	24.60	25.60
Ninghai	Tonglingzhu 1	21	17	15.70	15.90	16.10	3.80	5.80	7.80	23.60	24.60	25.60
Toupo Basin	Toupo 2	104	54	15.70	15.90	16.10	5.00	5.25	5.50	24.90	25.25	25.60
Shihti	Shihdi 1	19	12	15.70	18.95	22.20	2.50	9.55	16.60	25.00	26.55	28.10
Fushan Depression	Fushan 2	23	13	14.80	18.05	21.30	9.60	12.20	14.80	28.10	28.10	28.10
Leizhou Peninsula	Leizhou 2	65	40	15.60	17.00	18.40	9.60	12.20	14.80	28.10	28.10	28.10
Beibuwan Depression	Beibuwan 2	54	34	15.60	17.00	18.40	6.60	7.35	8.10	24.70	26.40	28.10
Yinggehai Depression	Yinggehai 2	33	18	14.80	18.50	22.20	13.60	14.20	14.80	28.10	28.10	28.10
Zhujiangkou Basin	Zhujiangkou 2	40	25	22.20	22.20	22.20	14.30	14.55	14.80	28.10	28.10	28.10
Late Miocene												
Namling	Wulong 2	9	Not enough taxa									
Namling	Wulong a	19	10	13.30	14.70	16.10	1.70	4.75	7.80	22.80	24.20	25.60
Namling	Wulong b	21	11	15.70	15.90	16.10	3.80	5.80	7.80	22.80	24.20	25.60
Namling	Wulong c	23	14	13.30	17.05	20.80	1.70	7.50	13.30	22.80	25.45	28.10
Namling	Wulong d	17	Not enough taxa									
Namling	Wulong e	13	Not enough taxa									
Markam	Lawula 1	14	12	11.20	15.10	19.00	−1.60	5.45	12.50	24.00	26.15	28.30
Markam	Lawula a	16	10	13.30	14.70	16.10	1.70	4.75	7.80	22.80	24.20	25.60
Lunpola Basin	Dingqing 2	21	18	15.70	18.50	21.30	3.80	8.55	13.30	21.70	24.90	28.10
Xiaolongtan	Xiaolongtan 1	48	35	20.60	20.70	20.80	5.60	10.20	14.80	27.20	27.65	28.10
Lühe	Lühe 1	16	11	13.30	17.60	21.90	−0.10	7.75	15.60	22.80	25.45	28.10
Lühe	Lühe 2	20	16	13.30	15.40	17.50	−0.10	3.80	7.70	23.00	25.45	27.90
Lühe	Lühe 5	18	12	9.10	15.40	21.70	−2.70	6.45	15.60	19.30	23.70	28.10
Lühe	Lühe 8	10	Not enough taxa									
Lühe	Lühe 10	14	12	11.50	16.60	21.70	−1.00	7.30	15.60	23.00	25.65	28.30
Lühe	Lühe 12	9	Not enough taxa									
Lühe	Lühe 13	9	Not enough taxa									
Lühe	Lühe 16	16	12	11.50	16.60	21.70	−1.00	7.30	15.60	23.00	25.55	28.10
Lühe	Lühe 18	25	15	11.60	15.00	18.40	−0.30	6.10	12.50	23.00	25.45	27.90
Lühe	Lühe 21	14	Not enough taxa									
Lühe	Lühe 22	20	12	13.30	17.50	21.70	−0.10	7.75	15.60	22.80	25.45	28.10
Lühe	Lühe 23	16	11	11.50	16.60	21.70	−1.00	7.30	15.60	23.00	25.65	28.30
Lühe	Lühe 26	7	Not enough taxa									
Lühe	Lühe 29	8	Not enough taxa									
Lühe	Lühe 30	9	Not enough taxa									
Miaoli	Miaoli 1	11	Not enough taxa									
Fushan Depression	Fushan 3	19	10	15.60	18.45	21.30	9.60	11.45	13.30	24.70	26.40	28.10
Leizhou Peninsula	Leizhou 3	56	33	15.60	18.45	21.30	6.60	10.70	14.80	24.70	26.40	28.10
Beibuwan Depression	Beibuwan 3	50	31	15.60	18.45	21.30	9.60	12.20	14.80	28.10	28.10	28.10
Yinggehai Depression	Yinggehai 3	32	16	14.80	16.60	18.40	1.70	8.25	14.80	28.10	28.10	28.10
Zhujiangkou Basin	Zhujiangkou 3	44	28	22.00	22.00	22.00	14.30	14.55	14.80	28.10	28.10	18.10

b

Locality name	Sample name	l.b.	MAP (mm)	u.b.	l.b.	HMP (mm)	u.b.	l.b.	LMP (mm)	u.b.	l.b.	WMP (mm)	u.b.
Early Miocene													
Lunpola Basin	Dingqing 1	705	1113	1520	102	174	245	8	16	24	82	127	172
Toupo Basin	Toupo 1	1183	1195	1206	109	172.5	236	18	28	37	108	110	112
Fushan Depression	Fushan 1	1183	1352	1520	225	235	245	19	43	67	85	124	163
Leizhou Peninsula	Leizhou 1	1035	1278	1520	134	189.5	245	12	27	41	93	128	163
Beibuwan Depression	Beibuwan 1	1122	1321	1520	148	196.5	245	19	30	41	120	142	163
Yinggehai Depression	Yinggehai 1	1183	1373	1562	225	265	304	19	30	41	120	148	175
Zhujiangkou Basin	Zhujiangkou 1	1183	1352	1520	225	235	245	19	43	67	120	142	163
Weizhou Island	Weizhou 1	1096	1151	1206	175	178	180	17	27	37	108	125.5	143
Middle Miocene													
Xianju	Zhangjiajing 1	1096	1151	1206	109	173	237	11	27	43	72	108	143
Ninghai	Tonglingzhu 1	1096	1151	1206	109	126	143	11	18	24	72	108	143
Toupo Basin	Toupo 2	1096	1151	1206	109	126	143	18	30	41	108	126	143

Table 3 (*continued*)

b

Locality name	Sample name	l.b.	MAP (mm)	u.b.	l.b.	HMP (mm)	u.b.	l.b.	LMP (mm)	u.b.	l.b.	WMP (mm)	u.b.
Middle Miocene													
Shihti	Shihdi 1	979	1288	1597	164	230	295	5	22	38	108	147	185
Fushan Depression	Fushan 2	1183	1398	1613	150	254	358	16	46	75	120	142	163
Leizhou Peninsula	Leizhou 2	1183	1352	1520	225	235	245	16	27	37	120	142	163
Beibuwan Depression	Beibuwan 2	1183	1352	1520	225	235	245	19	30	41	120	142	163
Yinggehai Depression	Yinggehai 2	1183	1380	1577	225	283	340	6	24	41	85	130	175
Zhujiangkou Basin	Zhujiangkou 2	1183	1398	1613	225	283	340	8	40	72	85	124	163
Late Miocene													
Namling	Wulong 2												
Namling	Wulong a	705	956	1206	84	114	143	16	42	67	82	113	143
Namling	Wulong b	1096	1151	1206	84	164.5	245	16	42	67	82	131	180.0
Namling	Wulong c	705	1113	1520	85	161	236	16	42	67	82	131	180
Namling	Wulong d												
Namling	Wulong e												
Markam	Lawula 1	879	1117	1355	106	151	195	43	49	55	49	111	172
Markam	Lawula a	705	956	1206	84	114	143	16	42	67	82	113	143
Lunpola Basin	Dingqing 2	1096	1308	1520	84	164.5	245	8	16	24	82	123	163
Xiaolongtan	Xiaolongtan 1	961	990	1018	160	162	164	11	18	24	108	144	180
Lühe	Lühe 1	529	1106	1682	91	182	272	5	31	56	47	110	172
Lühe	Lühe 2	619	883	1146	109	124	139	9	23	37	73	84	95
Lühe	Lühe 5	581	1051	1520	92	169	245	8	23	37	73	127	180
Lühe	Lühe 8												
Lühe	Lühe 10	619	1151	1682	109	191	272	8	32	56	47	110	172
Lühe	Lühe 12												
Lühe	Lühe 13												
Lühe	Lühe 16	619	1151	1682	109	191	272	8	32	56	47	110	172
Lühe	Lühe 18	619	1070	1520	109	145	180	8	23	37	73	118	163
Lühe	Lühe 21												
Lühe	Lühe 22	529	1106	1682	92	182	272	8	23	37	73	123	172
Lühe	Lühe 23	619	1151	1682	109	191	272	8	23	37	73	123	172
Lühe	Lühe 26												
Lühe	Lühe 29												
Lühe	Lühe 30												
Miaoli	Miaoli 1												
Fushan Depression	Fushan 3	823	1218	1613	204	297	389	8	51	93	120	142	163
Leizhou Peninsula	Leizhou 3	1035	1278	1520	204	225	245	12	28	43	120	142	163
Beibuwan Depression	Beibuwan 3	1183	1380	1577	225	244	262	19	30	41	85	124	163
Yinggehai Depression	Yinggehai 3	1183	1373	1562	225	265	304	7	24	41	120	148	175
Zhujiangkou Basin	Zhujiangkou 3	1183	1398	1613	225	283	340	19	43	67	85	124	163

elevation history of the Tibetan Plateau is still controversial (Molnar, 2005; Harris, 2006; Passey et al., 2009), our results suggest the Tibetan Plateau did not uplift to an elevation of above 3000 m before the Early Miocene, so the moist air masses from the Indian Ocean could penetrate into the plateau and transport humidity over a long distance. Consequently, the Tibetan Plateau also experienced a warm and humid climate during the Miocene, which is quite different from the dry, cold climate condition of the present.

As well-known, the modern climate of China is dominated by the monsoon systems. In the summer, warm and moist air masses from the Pacific and Indian Oceans carry abundant rainfall to the inland of China except for Northwest China and the Tibetan Plateau. In winter, Siberian dry and cold continental air masses prevail, resulting in dry, cold climate conditions. Though there is much debate concerning the timing of onset, and the subsequent history of the East Asian monsoon (Passey et al., 2009), more and more evidence indicates that the onset of the East Asian monsoon can be traced back to the Late Oligocene/Early Miocene (Sun and Wang, 2005; Li et al., 2008). Afterwards a global intensification of orogenic movements considerably influenced the climate system; especially the rapid uplift of the Himalayas and Tibetan Plateau since the Late Miocene seems to have caused a stronger East Asian monsoon which triggered the upwelling systems of the Indian Ocean (An et al., 2001).

In our present study, the spatial patterns of HMP (summer rainfall), MAP and MARP may suggest that the East Asian monsoon had an impact on the climate evolution during the Miocene in Southern China. In the Early Miocene, the summer rainfall experienced a transition from over 230 mm in the coastal areas, Yinggehai Depression, Zhujiangkou Basin and Fushan Depression, to 174 mm in the interior area (Lunpola Basin). In the Late Miocene, the summer rainfall in the coastal areas increased, reaching 297 mm at a maximum in the Fushan Depression. Moreover, MAP displays a distinct spatial differentiation and abundant rainfall in Southern China with a gradient from ca. 1400 mm in the coastal area to ca. 1000 mm in the interior area during the Early, Middle, and Late Miocene. MARP shows few localities have a higher seasonality (MARP about 220 mm, i.e. abundant summer rainfall and less winter rainfall) in the Early Miocene, and the area with high MARP increases in the Middle and Late Miocene. All this evidence implies that the East Asian monsoon linked with the uplift of the Himalayas and Tibetan Plateau could have played an important role in the climate evolution in Southern China during at least the Middle and Late Miocene, and the monsoon tends to intensify from Early to Late Miocene, causing warm and humid climate conditions in the coastal areas and most interior regions of Southern China.

6. Conclusions

On the basis of above studies, the following conclusions can be drawn:

(i) The climatic data shows a distinct spatial differentiation in Southern China during the Early, Middle and Late Miocene.

(ii) Most regions of Southern China and Europe were warm and humid during the Miocene. Central Eurasia was likely to be an arid center, which gradually spreading westward and eastward.
(iii) The Asian monsoon linked with the uplift of the Himalayas and Tibetan Plateau could be the possible factors causing heavy rainfall and warm temperature in the climate evolution of Southern China during the Miocene.

However, this is only a first attempt to reconstruct the Miocene climate in China. More evidence is necessary from the whole territory especially from Northwestern China to support our conclusions and to better understand the intensification of aridity in the interior of Asia.

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