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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, and is also crucial to unravel and understand the climatic signals of global cooling and tectonic uplift.

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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 C₄ 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 km², 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 bio-

stratigraphy 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
E sulo Missono			0		
Early Miocene	D'annin 1	TT1 t	00.00	22.20	O. tana
Lunpola Basin	Diligqilig I	Tibet	90.00	32.30	Outcrop
Toupo Basin	Toupo I	Guangchang, Jiangxi	100.50	26.50	Outcrop
Fushan Depression	FUSIIdii I	North continental shelf of South China Sea	110.00	19.50	Drilling
Leiznou Peninsula	Leiznou I	North continental shelf of South China Sea	100.00	21.45	Drilling
Beibuwan Depression	Beibuwan I	North continental shelf of South China Sea	108.30	20.30	Drilling
Yinggehai Depression	Yinggehai I	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	Dingging 2	Tibet	90.00	32.30	Outcrop
Xiaolongtan	Xiaolongtan 1	Kaivuan, 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
Lübe	Lübe 12	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Lühe 13	Chuxiong Vunnan	101.22	25.10	Outcrop
Lübe	Lübe 16	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lübe	Lübe 18	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lübo	Lübo 21	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Luite 21 Lübo 22	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Luite 22	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Luite 25	Chuxiong, Yunnan	101.22	25.10	Outcrop
Luite	Luile 20	Chuxiong, Yunnan	101.22	25.10	Outcrop
Lühe	Luite 29	Chuxiong, Yunnan	101.22	25.10	Outcrop
Luite	Luite 50 Misseli 1	Chuxiong, Fuinian	101.22	23.10	Outcrop
WildOll Fusher Derression	IviidUli I	IdiWdii North continental shalf of Couth China Coo	120.46	24.32	Drilling
Fushan Depression	Fusilali 3	North continental shell of South China Sea	110.00	19.50	Drilling
Leizhoù Peninsula	Leizhou 3	North continental shell of South China Sea	100.00	21.45	Drilling
Belbuwan Depression	Belbuwan 3	North continental shelf of South China Sea	108.30	20.30	Drilling
Yinggenal Depression	Yinggenai 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
	51				
Early Miocene	D-11-	Madata and all all		Planistica	Weeks 1, 1077
Dingqing 1	Pollen	wudstone, shale	Lower part of Dingqing Fm.	FIORISTICS	wang et al., 1975
Toupo 1	Pollen	Sandstone, conglomerate	Middle part of Toupo Group	FIORISTICS	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	Floristics Geology	Chaney and Chuang 1968

and Tsouho Fm.

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.

	, 0		I dX011 1101
Taxon number	Fossil taxon	NLR	76
1	Abies sp.	Abies sp.	77
2	Abiespollenites	Abies sp.	78
3	Abiespollenites sp.	Abies sp.	79
4	Abietineaepollenites	Pinus sp.	81
5	Abietineaepollenites microalatus I. minor	Pinus sp.	82
7	Acer inanii	Acer sp.	83
8	Acer sp.	Acer sp.	84
9	Actinodaphne nipponica	Actinodaphne sp.	85
10	Adiantum sp.	Adiantum sp.	86
11	Alangium aequafolium	Alangium sp.	88
12	Alangium sp.	Alangium sp.	89
13	Albizzia miokalkora	Albizia sp.	90
15	Aleurites sp	Aleurites sp	91
16	Alisma sp.	Alismataceae	92
17	Alnipollenites quadrapollenites	Alnus sp.	93
18	Alnipollenites sp.	Alnus sp.	94
19	Alnipollenites verus	Alnus sp.	96
20	Alnus protomaximowizii	Alnus sp.	97
21	Alnus sp	Alnus serrulata	98
22	Alnus sp.	Alnus sp.	99
24	Amaranthaceae	Amaranthaceae	100
25	Anacardiaceae	Anacardiaceae	101
26	Anodendron sp.	Apocynaceae	102
27	Apocynaceae	Apocynaceae	103
28	Araliaceae	Araliaceae	104
29	Araucaria sp.	Araucaria sp.	106
30	Ardisia sp	Arducaria sp. Ardisia sp	107
32	Artemisia sp.	Artemisia sp.	108
33	Asplenium sp.	Asplenium sp.	109
34	Baeckea sp.	Myrtaceae	110
35	Bambusa sp.	Bambusa sp.	111
36	Berberis sp.	Berberis sp.	112
37	Berchemia miofloribungda	Berchemia sp.	114
38	Betula cf. utilis	Betula sp.	115
40	Betula mankongensis	Betula sp.	116
41	Betula sp.	Betula sp.	117
42	Betulaceae	Betulaceae	118
43	Bombacaceae	Bombacaceae	119
44	Bombacacidites sp.	Bombax sp.	120
45	Boraginaceae	Borraginaceae Provisionatia en	122
40	Buxanollis sp	Bioussonena sp. Buxus sp	123
48	Caesalpinia sp.	Caesalpinia sp.	124
49	Campanulaceae	Campanulaceae	125
50	Caprifoliaceae	Caprifoliaceae	126
51	Caprifoliipites	Viburnum sp.	127
52	Carpinipites sp.	Carpinus sp.	129
53 54	Carpinus ci, Jargesiana Carpinus grandis	Carpinus sp.	130
55	Carpinus granais	Carninus sp	131
56	Carya cathayensis	Carya sp.	132
57	Carya sp.	Carya sp.	133
58	Carya spp.	Carya sp.	134
59	Caryapollenites simplex	Carya cordiformis	135
60	Caryapollenites sp.	Carya sp.	130
61	Cassia obionga	Cassia sp.	138
63	Castanea miomollissima	Castanea sp	139
64	Castanea sp.	Castanea sp.	140
65	Castanea spp.	Castanea sp.	141
66	Castaneoideae	Fagaceae	142
67	Castanopsis miocuspidata	Castanopsis chrysophylla	143
68	Casuarinidites cainozoicus	Casuarinaceae	144
69	Cedripites sp.	Cedrus sp.	146
70	Celastração	Celastração	147
72	Celastrus sp	Celastraceae	148
73	Celtis sp.	Celtis sp.	149
74	Celtis spp.	Celtis sp.	150
75	Ceratopteris spp.	Pteridaceae	151

Table 2 (continued)								
Taxon number	Fossil taxon							

axon number	Fossil taxon	NLR
6	Phelline spp.	Phelline sp.
7	Chenopodiaceae	Chenopodiaceae
8	Chenopodipollis microporatus	Chenopodiaceae
9	Chenopodipollis multiplex	Chenopodiaceae
0	Chenopodipollis multiporatus	Chenopodiaceae
1	Chenopodipollis sp.	Chenopodiaceae
2	Chenopodium sp.	Chenopodiaceae
3	Cibotium sp.	Dicksoniaceae
4	Cibotiumspora sp.	Dicksoniaceae
5	Cinnamomum sp.	Cinnamomum sp.
7	Cinnamomum sp. 1	Cinnamomum sp.
7 8	Cinnamonum oguniense	Cinnamomum sp.
9	Clevera sp.	Clevera sp.
0	Compositae	Asteroideae
1	Coniogramme devolii	Polypodium sp.
2	Coniogramme sp.	Polypodium sp.
3	Convolvulus sp.	Convolvulus sp.
4	Cornaceae	Cornaceae
5	Cornus sp.	Cornus sp.
6	Corylopsis princeps	Corylopsis sp.
/	Corylopsis spp.	Corylopsis sp.
8 0	Corylus maequarii	Corylus sp.
9 00	Crassoretitriletes nanhaiensis	Lvgodium sp.
01	Crassoretitriletes sp	Lygodium sp.
02	Crassoretitriletes vanraadshooveni	Lvgodium sp.
03	Cruciferae	Brassicaceae
04	Cupuliferoipollenites	Cupuliferae
05	Cupuliferoipollenites oviformis	Cupuliferae
06	Cupuliferoipollenites pusillus	Cupuliferae
07	Cupuliferoipollenites sp.	Cupuliferae
08	Cyathea sp.	Cyatheaceae
09	Cyathidites minor	Cyatheaceae
10	Cyclobalanopsis manaraliscae	Fagaceae
11	Cyclobalanopsis sp	Fagaceae
13	Cyperaceae	Cyperaceae
14	Cyperacites sp.	Cyperaceae
15	Cyrillaceaepollenites megaexactus	Cyrillaceae
16	Dacrydiumidites	Podocarpaceae
17	Dacrydiumites florinii	Podocarpaceae
18	Dalbergia lucida	Dalbergia sp.
19	Daphne sp.	Daphne sp.
20	Davallia sp.	Davallia sp.
21	Dennstaedtlaceae	Dennstaeatia sp.
22	Desmos kaisunanensis	Apopaçoao
23 74	Dicksonia sp	Leguminosae
25	Dicolpopollis kockelii	Palmae
26	Diospyros sp.	Diospyros sp.
27	Dodonaea japonica	Dodonaea sp.
28	Echinatisporis	Selaginellaceae
29	Elaeagnus sp.	Elaeagnus sp.
30	Engelhardtia spp.	Engelhardtia sp.
31	Engelhardtioidites levis	Engelhardtia sp.
32	Engelhardtioidites sp.	Engelhardtia sp.
37	Equisatum sp.	Epileuru sp.
35	Fricaceae	Equiserum sp. Fricaceae
36	Ericaceoipollenites sp.	Ericaceae
37	Ericipites	Ericaceae
38	Erythrophleum ovatifolium	Fabaceae
39	Euphorbiaceae	Euphorbiaceae
40	Extrapunctatosporis megapunctos	Polypodiaceae
41	Extrapunctatosporites sp.	Polypodiaceae
42	Fagara sp.	Zanthoxylum sp.
43	Fagopyrum sp.	Fagopyrum sp.
44	Fagus sp.	Fagus sp.
40	Florechuatzia of Javineli	Ficus sp.
47	Florschuetzia levipoli	Sonneratiaceae
48	Florschuetzia semilohata	Sonneratiaceae
49	Florschuetzia sp.	Sonneratiaceae
50	Florschuetzia trilobata	Sonneratiaceae
51	Fraxinoipollenites sp.	Fraxinus sp.

Table 2 (continued)

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133Cirkitan sp.Cirkitan sp.Ci	-	152	Gentianaceae	Gentianaceae		229	Myrtaceidites sp.	Mvrtaceae				
154Clackensing op controls sp.Clackensing op controls sp.211Mutherplow provementsNumber op topplower155Controls op controls op controls op controls op 		153	Gleditsia integra	Gleditsia sp.		230	Neolitsea sp.	Neolitsea sp.				
155Cipytanubas spinCipytanubas spinCipytanubas spinNapina spinNapina spin156GenerationGenerationStatubas spinStatubas spinStatubas spinNapina spin157GenerationGenerationStatubas spinNapina spinNapina spin158GenerationGenerationControl spinNapina spinNapina spin158HamanelidarsaHamanelidarsa217OleansaDiagram158HamanelidarsaHamanelidarsa218OleansaDiagram158HamanelidarsaHamanelidarsa218OleansaDiagram159HamanelidarsaHamanelidarsa218Ommals spinDiagram151HamanelidarsaHamanelidarsa218Ommals spinDiagram153HamanelidarsaHamanelidarsa218Ommals spinDiagram154HamanelidarsaHamanelidarsa218Ommals spinDiagram155HamanelidarsaHamanelidarsa218Ommals spinDiagram156HamanelidarsaHamanelidarsa218Ommals spinDiagram157HamanelidarsaHamanelidarsa210HamanelidarsaPalana158HamanelidarsaHamanelidarsa210HamanelidarsaPalana159HamanelidarsaHamanelidarsa210HamanelidarsaPalana150HamanelidarsaHamanelidarsa210HamanelidarsaPalana151HamanelidarsaHamanelidarsa		154	Gleicheniidites sp.	Gleichenia sp.		231	Nothaphoebe precavaleriei	Lauraceae				
155ColuminationLocatillance23NymplenemesNymplenemes157CananataCananata234NysakcaraNymplenemes158GaminationGamination234NysakcaraNymplenemes158HamachicaceHamachicace237OkacsakGamination151Hammeris sp.Hamachicace238OkacsakGamination151Hammeris sp.Hamachicace234OkacsakGamination151HamachicaceHamachicace234OkacsakGamination153HamachicaHamachicace244Omandacidies wellmaniGamination154HamachicaHamachicace246Omandacidies wellmaniGamination155HamachicaHarper241Omandacidies wellmaniGamination156HamachicaHarper246Omandacidies wellmaniGamination157HamachicaHarper247Patalons inPatalons in158HarperHarper250Patalons inPatalons in159HarperHarper250Patalons inPatalons in151HarperHarper250Patalons inPatalons in151HarperHarper250Patalons inPatalons in151HarperHarper250Patalons inPatalons in153HarperHarper250Patalons inPatalons in154HarperHarper250Patalons in		155	Glyptosrobus sp.	Glyptostrobus lineat		232	Nuphar sp.	Nuphar sp.				
167Contineor214NysakaeNysakae168ContrologicContrologicNysakaeNysakae169HamanefissonHamanefisson200NysakaeNysakae161HamanefissonHamanefisson200ObservationObservation162Hompfels p.Hompfels dirik200ObservationNysakae163Hompfels p.Hompfels dirik200ObservationObservation164Hompfels p.Hompfels dirikSakataSakataSakata165Hydroprist p.Hydroprist dirikSakataSakataSakata166Hydroprist p.Hydroprist dirikSakataSakataSakata167Hydroprist lirikSakataSakataSakataSakata168Hydroprist lirikSakataSakataSakataSakata170Hompfelsinis magnifishinaHospicSakataSakataNysakae171Hompfelsinis magnifishinaHospicSakataNysakaeNysakae172Hompfelsinis magnifishinaHospicSakataNysakaeNysakae173Hompfelsinis magnifishinaHospicSakataNysakaeNysakae174Hompfelsinis magnifishinaHospicSakataNysakaeNysakae175Hompfelsinis magnifishinaHospicSakataNysakaeNysakae176Hompfelsinis magnifishinaHospicSakataaNysakaeNysakae177Hompfelsinis magnifishina<		156	Gothanipollis bassensis	Loranthaceae		233	Nymphaeaceae	Nymphaeaceae				
198 Graninalders Graninalde		157	Gramineae	Gramineae		234	Nyssaceae	Nyssaceae				
1916 Communitation Containines 254 Operation by, operation of the system		158	Graminidites media	Gramineae		235	Nyssapollenites	Nyssa sp.				
181 Hamanicula conditions Hamanicula conditions Object conditions Object conditions 183 Herringeness Herringeness Annother sp. Object conditions 183 Herringeness Herringeness Annother sp. Object conditions 184 Homaline sp. Herringeness Annother sp. Object conditions 185 Homaline sp. Herringeness 241 Ommunic sp. Ommunic sp. 186 Homaline sp. Herringeness 242 Ommunic sp. Ommunic sp. 186 Homaline sp. Herringeness Annother sp. Annother sp. 187 Hopoleherins ingeness Herringeness Annother sp. Annother sp. 188 Hopoleherins ingeness Herringeness Annother sp. Annother sp. 179 Hopoleherins ingeness Herringeness Annother sp. Annother sp. 171 Hopoleherins ingeness Herringeness Annother sp. Annother sp. 171 Hopoleherins ingeness Herringeness Annother sp. Annother sp. 173 Hopoleherins ingeness Herringeness Annother sp. Annother sp. 174 Hopoleherins ingeness Herringeness Herringeness Herringeness <t< td=""><td></td><td>159</td><td>Graminidites</td><td>Gramineae</td><td></td><td>236</td><td>Oenanthe sp.</td><td>Oenanthe sp.</td></t<>		159	Graminidites	Gramineae		236	Oenanthe sp.	Oenanthe sp.				
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195Humiles op.Humiles op.242Ostanulas op.196Hydrosparites yphenetics withoutingOstanulas op.197Hydrosparites (reisSubiniscene244Otryru yn.Otryru yn.197Hydrosparites (reisSubiniscene245Otryru yn.Otryru yn.198Hydrosparites (reisSubiniscene246Otryru yn.Palmae199Hor xp.164 xp.Hor xp.246PalmaePalmae191Hor sp.248PalmaePalmaePalmae192Hydrosparites (reisTacodiscene250Politaling participPolitaling particip192Horpapilines marginationalHor xp.240Printomenietz sp.Politaling particip192HydrosparitesHorpapilinesTacodiscene251Politaling participPolitaling particip193HydrosparitesHydrosparites254Politaling participPalmasPalmas194HydrosparitesHydrosparites256PinacesPinacesPinaces193Jaglens palmLaris sp.256PinacesPinacesPinas sp.194LarisdordinLaris sp.254PinacesPinacesPinas sp.194LarisdordinLaris sp.256PinacesPinacesPinas sp.194LarisdordinLaris sp.256PinacesPinas sp.Pinas sp.194LarisdordinHydrosparitesSp.PinacesPinas sp.Pinas sp. </td <td></td> <td>164</td> <td>Homelium sp</td> <td>Homalium sp</td> <td></td> <td>240</td> <td>Ormosia xiaolongianensis Osmunda sp</td> <td>Osmunda sp</td>		164	Homelium sp	Homalium sp		240	Ormosia xiaolongianensis Osmunda sp	Osmunda sp				
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197 Prioragentia freis Salviniaccae 244 Ourry ag. Derys ag. 198 Highraprins y., Salviniaccae 246 Painas Painas 199 Hex sp. Hex sp. 246 Painas Painas 191 Hexpolinite singuination Hex sp. 246 Paination Painas 171 Hexpolinite singuination Hex sp. 248 Pentimumbulities sp. Paination 171 Hexpolinites singuination Hex sp. constructions Paination Painations Painations 173 Jospin sponition Hex sp. constructions Painations Painations Painations 174 Heigher proventinum paralancontainum Painations		166	Hydrocharis sp.	Hydrocharis sp		242	Osmundacidites wellmanii	Osmunda sp.				
188Informiprines sp.Solviniscence245Optisphilenites of chancesBetilance170Bexpollenites insignationanteBix sp.247Pasifora sp.Pasifora sp.171Bexpollenites insignationanteBix sp.248Palmake sp.Pasifora sp.173Besplicites insignationanteBix sp.240Palmake sp.Palmake sp.174Insignifora pressificanteBix sp.250Palmake sp.Palmake sp.175Jannitum Sp.252Palmake sp.Palmake sp.176JaginakaceseJaginakacese251Palmake sp.Palmake sp.177Jagina Sp.Jagina sp.254Palylestarbys sp.Pace sp.178JaginakaceseJaginakacese253Palma sp.Pace sp.179Jagina Sp.Jagina sp.254Palylestarbys sp.Pace sp.179Jagina Sp.Jagina sp.254Palylestarbys sp.Pace sp.179Jagina Sp.Jagina sp.257Palma sp.Palma sp.181Kardigeno prints sp.Jagina sp.251Palma sp.Palma sp.182LabiataLabiata251Palma sp.Palma sp.183Lardigeno prints sp.Jagina sp.251Palma sp.Palma sp.184Lardigeno prints sp.251Palma sp.Palma sp.184LabiataLabiata251Palma sp.Palma sp.184LabiataLabiataSchiaacacae250Palmakeinanta		167	Hvdrosporites levis	Salviniaceae		244	Ostrva sp.	Ostrva sp.				
168Incr sp.Incr sp.246PalmaPalmaPalma171Incrpolentics magaritatusIncr sp.248Petriamarotics sp.Petriamarotics sp.Petriamaro		168	Hydrosporites sp.	Salviniaceae		245	Ostryoipollenites cf. rhenanus	Betulaceae				
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17.3Incyclimics membranousIdes sp.249Perintamoneter sp.Phylociaccee17.4Indigero procesulfuticosFabaccae20Phote periadenceolataPhote sp.17.5Janitum paralecelatumJalancae21Photinia sp.Photinia sp.17.6JaglandsceeJaglandscee23Photinia sp.Photinia sp.17.6JaglandsceeJaglandscee23Photinia sp.Photinia sp.17.8JaglandsceeJaglandscee23Photinia sp.Photinia sp.17.8Jaglans spinJaglans sp.25Photos sp.Photos17.8Jaglans sp.Jaglans sp.25Photos sp.Photos17.8Jaglans sp.Jaglans sp.PhotosPhotosPhotos18.1Ectleria sp.Ketleria sp.25Photos photosPhotos18.2LabitateLabitateLabitate25PhotosphotosPhotos18.3LarvicoticsLarvis sp.26PhotosphotosPhotosPhotos18.4LarvicoticsLarvis sp.26PhotosphotosPhotosPhotos18.5LarvicoticsLarvis sp.26PhotosphotosPhotosphotosPhotosphotos18.6LarvicoticsLarvis sp.26PhotosphotosPhotosphotosPhotosphotos18.6LarvicoticsLarvis sp.27PhotosphotosPhotosphotosPhotosphotos18.6LarvicoticsLarvicoticsLarvicoticsPhotosphotosphotos<		171	Ilexpollenites margaritatus	llex sp.		248	Peltandripites sp.	Peltandra sp.				
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17.4Indigeter parestifutnessFabaceae251Photnins sp.Photnins sp.17.5JuglandscoveJuglandscove233Phylamitus sp.Phylamitus sp.17.6Juglans JuporitesJuglans sp.234Phylamitus sp.Phylamitus sp.17.7Juglans JuporitesJuglans sp.234Phylamitus sp.Phylamitus sp.17.8Juglans sp.256PinarcaePinarcae17.9Juglans sp.256PinarcaePinarcae17.8LabitateLabitate258Pinapolenites printingionitianPinars sp.18.1Kelekeris sp.Kelekeris sp.260Pinapolenites printingionitianPinars sp.18.2LabitateLabitateLabitate261Pinapolenites printingionitianPinars sp.18.4Laricoldites magnutsLarix sp.262Pinatogieness sp.Pinars sp.18.5Laricoldites magnutsLaura sp.262PinatoginaresePinars sp.18.6Laura elevantisLaura sp.264Pidegram sp.Pidegram sp.18.7Laura elevantisLaura elevantisPidegram sp.Pidegram sp.Pidegram sp.18.8Laura elevantisLaura elevantisPidegram sp.Pidegram sp.Pidegram sp.18.9Laura elevantisLaura elevantisPidegram sp.Pidegram sp.Pidegram sp.18.4Laricoletes sp.Laura elevantisLaura elevantisPidegram sp.Pidegram sp.18.5Lauricoletes sp.Laura ele		173	Inaperturopollenites	Taxodiaceae		250	Phoebe pseudolanceolata	Phoebe sp.				
1.75Jeanuan paraline jacutational jacutationa		174	Indigofera praesuffruticosa	Fabaceae		251	Photinia sp.	Photinia sp.				
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1/12Jugdini reginJugdini reginJugdini reginPolacede1/13Jugdini reginJugdini reginJugdini reginPrincesePrincese1/13Jugdini reginJugdini reginPrincesePrincesePrincese1/14Jugdini reginKelekovi sy.250PrincesePrincese1/15Labitate250Princepolentice minuticPrince sy.1/14Labitate250Princepolentice strubplicitPrince sy.1/15Labitate250Princepolentice strubplicitPrince sy.1/14LaricolditesLark sy.261Phincelolubini huckdamPabaceae1/15LauricolotitesLaura sy.PrincesePhinesePhinese1/16Laura sy.Laura sy.PhinesePhinesePhinese1/16Laura sy.Laura sy.PhinesePhinese <td></td> <td>176</td> <td>Juglandaceae</td> <td>Juglandaceae</td> <td></td> <td>253</td> <td>Phyllanthus sp.</td> <td>Phyllanthus sp.</td>		176	Juglandaceae	Juglandaceae		253	Phyllanthus sp.	Phyllanthus sp.				
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Table 2 (continued)

306Rhannaceidites sp.Rhannus sp.307Rhajs sp.Palmae308Rhadodendron sanzugawaenseRhadodendron sp.310Ricinus spp.Ricinus sp.311Robinia nipponicaRobinia sp.312Rosa sp.Rosa sp.313RubiaceaeRubiaceae314Rumex sp.Rumex sp.315RutaceaeRutaceae316Sagitaria sp.Sagitaria sp.317Salix miosinicaSalix sp.318Salixpollenites discoloripitesSalix sp.319Salixpollenites finatusSalix sp.320Salix sp.Salix sp.321SapodaceaeSapindaceae322SapindaceaeSapindaceae323Sapodaceideepollenites kirchheimeriSapotaceae324SapotaceaeSchizaeaceae325Schizaeiosporites sp.Satisaecae326ScrophulariaceaeSophora sp.331Sophora mingiaponicaSophora sp.332SparganiaceaeSparganiaceae333SparganiaceaeSpharganiaceae334SpharganiaceaeSpharganiaceae335Sterculia sp.Sterculia sp.336Sterculia sp.Sterculia sp.337SparganiaceaeSpharganiaceae338SymplocoipollenitesSpharganiaceae339TatigintesSapindaceae331Sophora pp.Spharganiaceae332SparganiaceaeSpharganiaceae333	Taxon number	Fossil taxon	NLR
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314Rumex sp.Rumex sp.315RutaceaeRutaceae316Sagitaria sp.Sagitaria sp.317Salix miosinicaSalix sp.318Salixipollenites discoloripitesSalix sp.319Salixipollenites hiatusSalix sp.320Salix sp.Salix sp.321Salvinia sp.Salvinia sp.322SapotaceaeSapotaceae323SapotaceaeSapotaceae324SapotaceaeSchizaeaceae325Schizaeoisporites sp.Schizaeaceae326ScrophulariaceaeSchizaeaceae327Selaginella sp.Selaginella sp.328Sequiapollenites sp.Taxodiaceae329Smilax sp.Smilax sp.331Sophora miojaponicaSophora sp.332Sophora miojaponicaSophora sp.333SparganiaceaeSpraganiaceae334Sphagnumsporites sp.Spinagnum sp.335Sterculia sp.Spinagnum sp.336SterculiaceaeSupplocos sp.337Stereisporites sp.Spinagnaceae343Thermopsis prebarbataFabaceae344Tilia sp.Taxodiaceae345Tiliacoleaepollenites hiasusTaxodiaceae346Trapa sp.Trupa sp.343Thermopsis prebarbataFabaceae344Tilia sp.Tsuga sp.345Tiliacepollenites maximusTsuga sp.346Trapa sp.Tsuga sp.347T	313	Rubiaceae	Rubiaceae
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364 Zonocostites cf. ramonae Rhizophoraceae	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. 297

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. 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.



WMP [mm]

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 $15 \,^{\circ}$ C and $1113 \,\text{mm}$, 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 $15 \,^{\circ}$ C and over 1000 mm, while at present the Lunpola Basin has an elevation of more than 4600 m a. s. l. with MAT $-1.2 \,^{\circ}$ 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	u.b.	l.b.	CMT	u.b.	l.b.	WMT	u.b.
					(°C)			(°C)			(°C)	
Farly Miocene												
Lunpola Basin	Dingging 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	21.20	6 60	9 55	12.50	24 70	26.40	28.10
Beibuwan Depression	Beihuwan 1	47	29	15.60	17.00	18.40	6.60	7 35	8 10	24.70	26.10	28.10
Vinggehai Depression	Vinggehai 1	30	16	14.80	16.60	18.40	13.60	14 20	14 80	24.70	20.40	28.10
Zhujiangkou Basin	7hujiangkou 1	55	35	15.60	18.80	22.00	1/ 30	14.20	1/1.00	28.10	20.10	28.10
Weizbou Island	Weizbou 1	117	55 64	15.00	17.05	18.40	6.60	9.55	12.50	25.10	25.10	25.10
VVCIZIIOU ISIdilu	WCIZIIOU I	117	04	15.70	17.05	10.40	0.00	5.55	12.50	23.00	25.00	23.00
Middle Miocene												
Xianiu	7hangijajing 1	28	20	15 70	15.90	16 10	3.80	5.80	7 80	23.60	24.60	25.60
Ninghai	Tonglingzhu 1	20	17	15.70	15.00	16.10	3.80	5.80	7.80	23.60	24.60	25.00
Touno Basin	Toupo 2	104	54	15.70	15.90	16.10	5.00	5.00	5 50	24.90	25.25	25.60
Shihti	Shihdi 1	10	12	15.70	18.05	22.20	2.50	9.55	16.60	25.00	26.55	23.00
Fushan Depression	Fushan 2	23	12	14.80	18.05	22.20	9.60	12 20	14.80	23.00	20.55	28.10
Leizhou Peninsula	Leizhou 2	65	40	15.60	17.00	18.40	9.60	12.20	14.00	28.10	28.10	28.10
Reibuwan Depression	Beibuwan 2	54	3/	15.00	17.00	18.40	6.60	7 35	Q 10	20.10	26.10	20.10
Vinggobai Depression	Vinggobai 2	22	19	14.90	19.50	22.20	12.60	14.20	1/ 20	24.70	20.40	20.10
Thiggenal Depression Thuijangkou Pacin	Thujiangkou 2	40	25	22.20	22.20	22.20	14.20	14.20	14.00	20.10	20.10	20.10
Zilujialigkou basili	Zilujialigkou z	40	23	22.20	22.20	22.20	14.50	14.55	14.00	20.10	20.10	20.10
Late Miocene												
Namling	Wulong 2	9	Not enough taxa									
Namling	Wulong 2	10	10	13 30	1470	16 10	1 70	175	7.80	22.80	24.20	25.60
Namling	Wulong b	21	10	15.50	15.00	16.10	2.90	5.80	7.00	22.00	24.20	25.00
Namling	Wulong c	21	11	12.70	17.05	20.90	1.70	7.50	12.20	22.00	24.20	20.00
Namling	Wulong d	25	14 Not onough taxa	15.50	17.05	20.80	1.70	7.50	15.50	22.80	25.45	26.10
Naming	Wulong a	17	Not enough taxa									
Ndilling	vvuiolig e	13	NOL EHOUGH LAXA	11.20	15 10	10.00	1.00	E 4E	12.50	24.00	20.15	20.20
Markam	Lawula I	14	12	11.20	15.10	19.00	- 1.60	5.45	12.50	24.00	26.15	28.30
Markann	Lawula a	10	10	13.30	14.70	10.10	1.70	4.75	7.80	22.80	24.20	25.60
Lunpola Basin	Dingqing Z	21	18	15.70	18.50	21.30	3.80	8.33	13.30	21.70	24.90	28.10
Xiaolongtan	Xiaolongtan I	48	35	20.60	20.70	20.80	5.60	10.20	14.80	27.20	27.65	28.10
Luhe	Luhe I	16	11	13.30	17.60	21.90	-0.10	1.75	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 u.b.	l.b.	HMP	u.b.	l.b.	LMP	u.b.	l.b.	WMP	u.b.
•	·		(mm)		(mm)			(mm)			(mm)	
Early Miscore												
Luny Millene	Dingging 1	705	1112 1530	100	174	245	0	16	24	02	107	170
Toupo Pasir	Tours 1	1100	1115 1520	102	174	245	0	10	24	02	127	1/2
Fuchan Donnession	Fuchar 1	1103	1200	109	172.5	230	10	42	57	108	124	162
Fushan Depression	Fushan I	1183	1352 1520	124	235	245	19	43	07	80	124	103
Leizhou Peninsula	Leiznou I	1035	1278 1520	134	189.5	245	12	27	41	93	128	163
Vingershall Depression	Belbuwan I	1122	1321 1520	148	196.5	245	19	30	41	120	142	103
Thiggenal Depression	Yinggehai I	1183	13/3 1562	225	265	304	19	30	41	120	148	1/5
Znujiangkou Basin	Zhujiangkou 1	1183	1352 1520	225	235	245	19	43	6/	120	142	163
weizhoù Island	Weizhou 1	1096	1151 1206	175	178	180	17	27	37	108	125.5	143
Middle Mires												
Maale Miocene	71	1000	1151 1000	100	170	207	11	27	40	70	100	1.40
Ninghai	Znangjiajing 1	1096	1151 1206	109	1/3	237	11	27	43	72	108	143
INIIIgiidi Tauna Davia	Tonglingzhu I	1096	1151 1206	109	126	143	11	18	24	12	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	u.b.	l.b.	HMP	u.b.	l.b.	LMP	u.b.	l.b.	WMP	u.b.
			(mm)			(mm)			(mm)			(mm)	
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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