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The evolution of Miocene climates in North China: Preliminary results of quantitative reconstructions from plant fossil records

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ABSTRACT

The Miocene climate evolution in North China is preliminarily discussed by means of comparisons in seven climate parameters quantitatively reconstructed by the Coexistence Approach on 34 selected macro- and microfloras over North China. The Miocene temperatures show no great difference in the western and eastern part of North China. Temperature fluctuations, particularly in mean annual temperature, are found within floras from several sites. The fluctuation pattern, from a climate optimum in the Mid Miocene to cooling decline in the Late Miocene, is generally consistent with the global trend of Miocene temperature change. The reconstructed precipitation from all the sites studied shows much wetter conditions in North China during the Miocene than at present, which corroborates the results from paleoprecipitation proxy of fossil mammals. Like the situation in paleo-temperature, the Miocene precipitation from North China shows no distinct difference between the western and eastern regions. It is suggested that North China, particularly in the western part, was by no means under an arid or semi-arid environment during the Miocene. North China is an ideal region for study of the impact of the East Asian monsoon system, however, the pattern of precipitation change derived from the monsoon index (MSH) and mean annual precipitation (MAP) shows contradictory results. Therefore, there appears no definite conclusion on when the East Asian summer monsoon intensified. Possible reasons for inconsistency in temperature and precipitation changes are discussed. Directions of future work to improve the resolution of climate evolution are also pointed out.

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1. Introduction

Miocene floras are widely distributed throughout China (Liu and Zheng, 1995). As early as in 1986, Guo (1986) discussed the evolution of Tertiary climates in China based on plant macrofossils, although his discussion was largely a qualitative analysis. He concluded that the Miocene floras in northeastern China were developed under humid warm-temperate to subtropical climates, while those in northwestern China represented sub-arid temperate climates due to the presence of microphyllous and chartaceous leaves and absence of evergreen and thermophilous plants. This "wet" east and "arid" west condition during the Miocene was the first picture regarding Miocene vegetation and climates in China. This picture was painted even finer with other evidence such as lithological data by P. Wang (1990), who suggested that in the Neogene the arid zone was restricted to northwest China and the climate in east China came under the influence of the monsoon circulation system. In other words, the movement of the arid zone to northwest China in the Early Miocene presumably indicates the onset of the monsoon circulation system.

Recently, based on a comprehensive compilation of paleobotanical and lithological data from 125 sites over China, Sun and Wang (2005) further confirmed that the Miocene climate pattern shows an arid northwest and a humid northeast China. However, this opinion is in contradiction with data from fossil mammals in China. The higher temporal resolution offered by the mammal record reveals that the earlier Miocene environments did not yet have such a 'monsoonal' distribution. The mammal data have shown that the west–east gradient pattern did not develop until the later Late Miocene (Liu et al., 2009).

The most conspicuous event during the Neogene period in China was undoubtedly the uplift of the Tibetan Plateau. The uplift played a crucial role in the magnification of the aridity/humidity contrasts between the southern and northern part of China (Raymo and Ruddiman, 1992; An et al., 2001). In addition, other factors, such as the Paratethys retreat and the South China Sea expansion, interacted with each other to cause the formation of the aridity/humidity contrasts between eastern and western China (Zhang et al., 2007). It is still not known how arid or humid climates could have been in China

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during the Miocene, largely because few attempts have been made on quantitative reconstruction of Miocene climates (Liu et al., 2009).

The past decade has witnessed a rapid development of quantitative approaches for paleoclimate reconstructions using fossil plants. The application of these approaches makes direct comparison of climate parameters possible (e.g. Utescher et al., 2007). The main purpose of this study is to use one of the approaches, the Coexistence Approach (CA), to reconstruct Miocene climate parameters and to discuss the climate evolution in North China, from where many disputes on the development of monsoon and presence of wet vs. arid environments have arisen.

2. Methods

Fossil plants provide one of the best proxy data for paleoclimate reconstruction. Three approaches have been developed and are now widely used for quantitative estimation of paleoclimatic parameters by using fossil plants (Uhl, 2006; Xia et al., 2009). They include the Coexistence Approach (CA), Leaf Margin Analysis (LMA), and Climate-Leaf Analysis Multivariate Program (CLAMP) (Xia et al., 2009). Each approach has its own pros and cons (see discussion in Uhl, 2006).

The CA is chosen in the present study, mainly because this approach is independent of the fossil plant organs studied. Therefore, the CA works for both macrofossils and pollen/spores as long as they are identified and their botanical affinities have been determined (Mosbrugger and Utescher, 1997). In the present study, most plant fossil data used are from fossil pollen floras, simply because they are mostly available in China (Sun and Wang, 2005). Due to the difficulty of linking the exact taxonomical affinities of fossil pollen/spores, the determination of nearest living relatives (NLRs) of these fossils is just designated to the generic level, sometimes only to the family level (Liu et al., 2007, 2008). We follow the treatment of botanical affinities for the Chinese pollen fossil taxa provided by Song et al. (1999, 2004) and Wang (2006), who comprehensively reviewed the Late Cretaceous to Tertiary pollen/spore records in China and the correlation of pollen sequences in the Neogene palynofloristic regions throughout China, respectively.

The implementation of quantitative reconstructions was conducted through querying the PALAEOFLORA database, which contains more than 4000 Cenozoic plant taxa, the corresponding NLRs, and about 1000 climatic data sets of these NLRs (Utescher and Mosbrugger, 1997–2006). For taxa not available in the database, we follow the procedures stated in detail in Xia et al. (2009) and Jacques et al. (2011) to supplement the database. Climatic intervals were calculated by the ClimStat program. Seven quantitative climatic parameters representing temperature and precipitation are reconstructed, i.e. mean annual temperature (MAT, °C), mean temperature of the coldest month (CMMT, °C), mean temperature of the warmest month (WMMT, °C), mean annual precipitation (MAP, mm), mean precipitation of the driest month (MP-DRY, mm), mean precipitation of the warmest month (MP-WARM, mm), and mean precipitation of the wettest month (MP-WET, mm).

Located in East Asia, China has been under a strong influence of monsoons through the late Cenozoic, largely due to the uplift of the Tibetan Plateau, the Paratethys retreat, and the South China Sea expansion (Fig. 1; Zhang et al., 2007; Guo et al., 2008). It is highly significant to study when the monsoons were developed and how strong the monsoons were in the Miocene (Guo et al., 2008 and references cited therein). Monsoon intensity indices have therefore been developed to measure the impact of monsoons (Liu and Yin, 2002). Various indices have been proposed and used in climate modeling (Liu and Yin, 2002). In a monsoon system, winds with nearly opposite directions in winter and summer often bring dramatically different temperature and precipitation between the

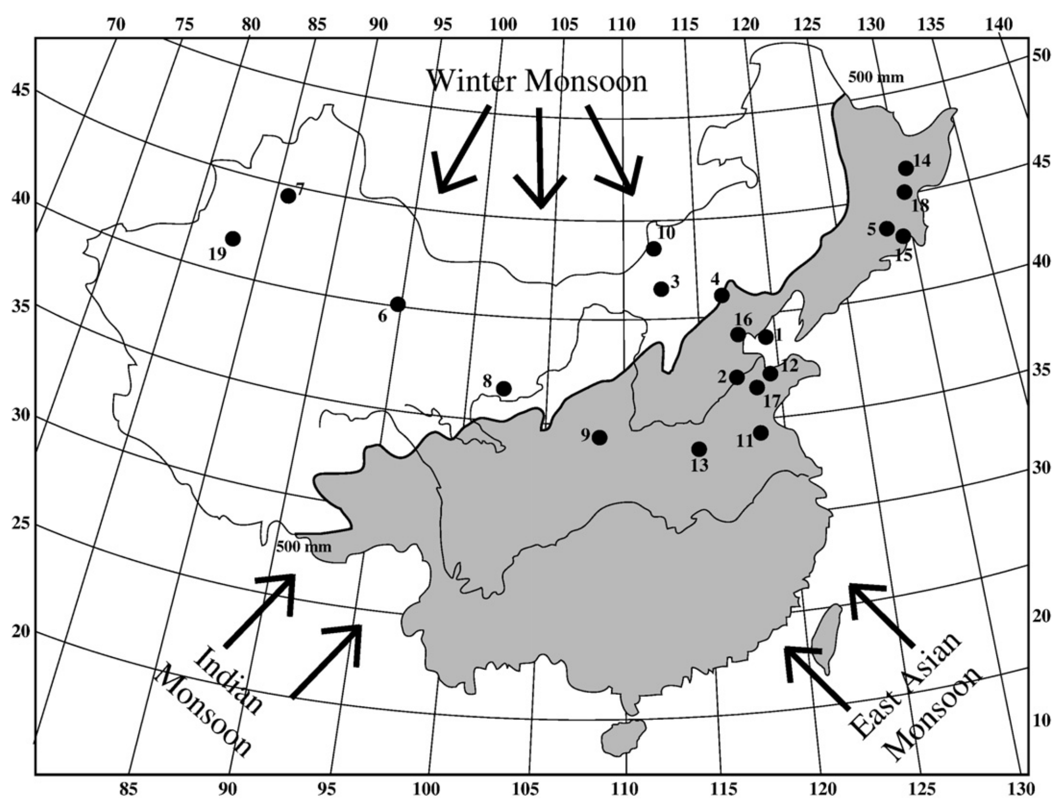

Fig. 1. Location of plant fossil sites. The number representing each site is listed in Table 1. The 500 mm isoline of annual precipitation marks the modern-day boundary between humid-semihumid (grey-shaded) and arid–semi-arid (white) areas. Arrows denotes summer (Indian and East Asian) and winter monsoon systems at the present time. Modified from Sun and Wang, 2005.

winter and summer. Based on seasonal temperature and precipitation differences, Liu and Yin (2002) defined a monsoon index (MSH) which can be applied to our study.

$$MSH = (T_s - T_w)(R_s - R_w),$$

where T_s and T_w are summer and winter mean temperature, and R_s and R_w are summer and winter mean precipitation, respectively. Among the seven climatic parameters reconstructed by the CA, WMMT and CMMT may be comparable to T_s and T_w, respectively, whereas WP-WARM and WP-DRY could be considered to roughly represent R_s and R_w, respectively. As noted by Liu and Yin (2002), MSH may be biased toward the mid-latitude regions where the annual range of temperature is much greater than that in low-latitude regions. For the present study, however, we focus on the fossil floras from North China, from where these floras may well represent mid-latitude regions. The higher the index value, the greater the differences between summer and winter temperature and precipitation, indicating a stronger monsoon regime (Liu and Yin, 2002).

3. Fossil floras selected

Neogene deposits are widely distributed in both North and West China, whereas in Southeast China they are confined to isolated basins (Guo, 1986; P. Wang, 1990; Liu and Zheng, 1995). The Neogene in China is generally dominated by non-marine facies, which are largely fluvial and lacustrine in origin (Sun and Wang, 2005). In North and Northwest China, Lower and Middle Miocene deposits are scattered in some sedimentary basins with local occurrences of basalt, whereas the Upper Miocene is much better developed and consists mainly of red clay with occasional interbeds of sand, gravel and marl (P. Wang, 1990). Neogene deposits contain rich floras (Liu and Zheng, 1995). However, the resolution of age assignments for these floras is generally poor (Liu and Zheng, 1995). Recent improvements in the Chinese Neogene vertebrate biochronology (Qiu and Qiu, 1995; Flynn et al., 1997; Zhang et al., 2002; Deng, 2006; Liu and Pickford, 2007) have brought opportunities to redefine the age of some floras from East China (Deng et al., 2003), because in China reliable chronologic subdivision of Neogene terrestrial sediments is best provided through the application of fossil mammals (Qiu and Qiu, 1995).

Thirty-four floras in North China were carefully selected in the current study based on two criteria stated below. Some of these floras, represented by different pollen sequences and assemblages, are from the same site; therefore, 19 fossil sites in total are recorded (Fig. 1; Table 1). As discussed above, the age control for the Chinese Neogene floras is poor due to their terrestrial origin and lack of extensive geochronological investigation, making the correlation between floras and accurate assignment of ages to them extremely difficult. Important attempts to define a better geological age of these floras were made through comparing with vertebrate biochronology (Liu, 1988; Wang, 1994, 2006). The floras selected for the present study were solely from those which have been comprehensively reviewed by the Chinese authorities while pursuing qualitative, instead of quantitative, climate studies (Liu, 1988; Wang, 1994, 2006; Sun and Wang, 2005). In a recent synthesis, Sun and Wang (2005) re-checked the age of each flora in the Tertiary of China based on three lines of evidence available, i.e. 1) paleomagnetism, thermolumniescence or radioactive datings; 2) biostratigraphy based on vertebrate fossils; and 3) biostratigraphy based on paleobotanical fossils. It is believed that these floras represent the best dataset of fossil floras in China with up-to-date age assignment. Practically, our selection is first based on the assemblage zones recognized and reviewed in these studies, supplemented by a more comprehensive summary in Sun and Wang (2005) regarding the age control of each flora. Secondly, we select a flora in which the fossil plant taxa, either macrofossils or pollen grains, were botanically identified. This means that the botanical affinities of the fossils were discussed in the original research. As discussed under the section of Methods, Song et al. (1999, 2004) and Wang (2006) have provided a thorough review concerning the botanical affinities on fossil pollen and spore species described in China. Their works helped us finalize our selection of floras, particularly from northern China. A list of these floras can be found in Table 1 and a list including fossil taxa and their NRLs of each fossil flora is also made in Appendix A. For convenience in discussion, these floras are artificially divided into the two regions, western and eastern North China, in which the boundary is set about 105° east longitude (Fig. 1).

4. Results and discussion

The reconstructed results of both temperature and precipitation of each flora are given in Table 2, where the locality number and its representative flora are grouped in geological age and two geographic regions (e.g. eastern part and western part of North China).

It is quite clear that the climate results appear in a wide range, making the comparison of climate evolution impractical (Table 2). Therefore, a simplified table (Table 3) is made, in which the medium value of each climate parameter and its change range are calculated. Also, in Table 3 only those floras representing a complete duration of the Early, Middle and Late Miocene and being from more or less the same area are included to facilitate the discussion of climate evolution. This results in 24 floras, representing 7 different areas in North China for further climate comparisons. Four areas are from the eastern part, while three other areas are in the western part of North China (Table 3). Each area is represented by at least 3 floras from different periods of Miocene. In the following, discussion on both temperature and precipitation will be made by using Table 3.

4.1. Temperature

The CA results in 3 temperature parameters for each fossil flora, viz. MAT, CMMT, and WMMT. Among the 7 areas from both eastern and western North China, the reconstructed temperature parameters, particularly MAT and CMMT, appear warmer than those of today (Table 3), indicating the Miocene temperatures in North China were warmer than those of today. Furthermore, the Early Miocene temperatures were mainly higher than those in Late Miocene (Figs. 2–6), corresponding to the global cooling trend in the Miocene (Flower and Kennett, 1994; Zachos et al., 2001). Concerning the temperature condition in the Mid Miocene, we have to admit that the results seem to be inconsistent (Table 3). On one hand, the so-called "Mid-Miocene Climate Optimum" does occur in terms of MAT in two areas in the eastern part of North China, e.g. Bohai and Shandong (Figs. 2, 3) and WMMT in western North China, e.g. Gansu (Fig. 4). On the other hand, the climate optimum appears not to occur in areas such as Jilin/Heilongjiang (loc. Nos. 5 and 15 for Jilin and 14 and 18 for Heilongjiang, Fig. 1 and Table 3), Xinjiang (loc. No. 7), and Qinghai (loc. No. 8). In addition, the temperature parameters of Wulougong (loc. No. 4) and Huanghua (loc. No. 16) from Hebei appear barely to be changed (Table 3). Possible reasons of these "abnormal" results include that little diversified fossil pollen assemblages uncovered from different sequences in many studied areas fail to reveal the temperature fluctuations. Secondly, the age assignments for several assemblages may not be as accurate as claimed, causing the climate optimum event to appear not to occur.

It is also interesting to note that the change patterns of 3 temperature parameters from each area are more or less consistent (Figs. 2–6). Moreover, the Miocene MATs in North China are similar, suggesting that North China was under a similar temperature condition in the Miocene, which totally contrasts the situation of modern days (Table 3).

Table 1
List of selected fossil sites in North China, location numbers as in Fig. 1, representative formations, location coordinates, fossil organ preserved, methods of age control, and references. Legends for age control (after Sun and Wang, 2005): A—paleomagnetism, thermoluminescence or radioactive datings; B—biostratigraphy based on vertebrate fossils; C—biostratigraphy based on paleobotanical fossils.

No.	Site	Formation	Location	Type of fossil (Age control)	Reference
Early Miocene					
Eastern part					
1	Bohai Gulf Basin	Guantao[a]	39°N, 119°E	Pollen (C)	Guan et al., 1982; Liu, 1988; Liu and Zheng, 1995; Wang, 2006
2	Jiyang/Bozhong Basins, Shandong	Guantao	36°58′N, 117°12′E	Pollen (C)	Yao et al. (1994)
3	Shangdou-Huade Basin, Inner Mongolia		41°21′–42°N, 113°30′–114°15′E	Pollen (C)	Wang and Zhang, 1990; Wang, 2006
4	Wulougong, Hebei		41°30′N, 117°E	Pollen (A, C)	Gan (1982)
5	Dunhua, Jilin	Qiuligou	43°21′N, 128°11′E	Leaf (C)	Li and Yang (1984)
Western part					
6	Dunhuang, Gansu		40°N, 94°43′E	Pollen (C)	Ma (1991)
7	Southern Junggar Basin, Xinjiang	Dushanzi Assemblage	44°30′N, 85°30′E	Pollen (A, B, C)	Sun and Wang (1990)
7	Southern Junggar Basin, Xinjiang	Huoerguosi Assemblage	44°30′N, 85°30′E	Pollen (A, B, C)	Sun and Wang (1990)
7	Southern Junggar Basin, Xinjiang	Shanwan-Taxihe	44°30′N, 85°30′E	Pollen (A, B, C)	Sun and Wang (1990)
8	Xining-Minhe Basin, Qinghai	Xiejia	36°18′–36°34′N, 101°44′–102°48′E	Pollen (B, C)	Sun et al. (1984)
Late Early Miocene–early Middle Miocene					
Eastern part					
9	Lantian, Shaanx	Lengshuigou	34°N, 108°E	Pollen (B, C)	Sun et al., 1980; Wang, 2006
9	Lantian, Shaanxi	Lower part Gaoling Group	34°N, 108°E	Pollen (B, C)	Sun et al., 1980; Wang, 2006
3	Shangdou-Huade Basin, Inner Mongolia		41°21′–42°N, 113°30′–114°15′E	Pollen (C)	Wang and Zhang, 1990; Wang, 2006
Middle Miocene					
Eastern part					
1	Bohai Gulf Basin	Lower part Minghuazhen[b]	39°N, 119°E	Pollen (C)	Guan et al., 1982; Wang, 2006
10	Erlian Basin, Inner Mongolia	Tonggure	43°39′N, 111°58′E	Pollen (B, C)	W. Wang (1990)
11	Tianchang, Jiangsu	Yancheng	33°N, 118°E	Pollen (C)	Zhang et al. (1993)
12	Bozhong, Shandong	Lower Minghuazhen	36°58′N, 119°E	Pollen (C)	Yao et al. (1994)
13	Zhoukou Basin, Henan	Guantao	33°38′N, 114°38′E	Pollen (C)	Zhang et al. (1993)
14	Huanan, Heilongjiang	Daodaiqiao	47°N, 130°E	Pollen/leaf (C)	Liu et al., 1995; Liu, 1998
15	Hunchun, Jilin	Tumenzi	42°51′N, 130°E	Pollen (C)	Zhao et al. (2004)
Western part					
6	Dunhuang, Gansu	40°N, 94°43′E		Pollen (C)	Ma (1991)
7	Southern Junggar Basin, Xinjiang	Shanwan-Taxihe	44°30′N, 85°30′E	Pollen (A, B, C)	Sun and Wang (1990)
8	Xining-Minhe Basin, Qinghai	Chetougou	36°18′–36°34′N, 101°44′–102°48′E	Pollen (B, C)	Sun et al. (1984)
Late Middle Miocene					
Eastern part					
16	Huanghua, Hebei		39°30′N, 117°30′E	Pollen (A, C)	Li and Liang (1981)
17	Shanwang, Shandong	Yaoshan	36°30′N, 118°21′E	Pollen (C)	Liu (1986)
18	Jidong, Heilongjiang		45°12′N, 131°E	Pollen (C)	Shu et al. (2008)
Mid–Late Miocene					
Western part					
19	Kuqa, Xinjiang	Kurha KH50	41°41′N, 82°58′E	Pollen (A, C)	Jin et al. (2002)
Late Miocene					
Eastern part					
4	Huanghua, Hebei		39°30′N, 117°30′E	Pollen (C)	Li and Liang (1981)
1	Bohai Gulf Basin	Upper Minghuazhen	39°N, 119°E	Pollen (C)	Guan et al. (1982)
2	Bozhong Basin, Shandong	Upper Minghuazhen	36°58′N, 117°12′E	Pollen (C)	Yao et al. (1994)
14	Huanan, Heilongjiang	Daotaiqiao	47°N, 130°E	Pollen (C)	Liu et al., 1995; Liu, 1998
Western part					
6	Dunhuang, Gansu	Xishuigou	40°N, 94°43′E	Pollen (C)	Ma (1991)
7	Southern Junggar, Xinjiang	Shanwan-Taxihe	44°30′N, 85°30′E	Pollen (A, B, C)	Sun and Wang (1990)
19	Kuqa, Xinjiang	Kurha KH-44	41°41′N, 82°58′E	Pollen (A, C)	Jin et al. (2002)
8	Xining-Minhe Basin, Qinghai	Xianshuihe	36°18′–36°34′N, 101°44′–102°48′E	Pollen (B, C)	Sun et al. (1984)

[a] It was reported as the Mid Miocene, but now is assigned to be early Miocene (Wang, 2006).
[b] It was reported as the late Miocene by Guan et al. (1982), but is reassigned as Mid Miocene (Wang, 2006).

As mentioned above, the general trend of cooling temperature in North China during the Miocene appears to be comparable with the global trend. Also, the Miocene temperatures in North China are generally warmer than those of today. However, the details of temperature change among the floras are somewhat different, some of which do not show the match with the global trend, such as the Mid-Miocene Climate Optimum. This is possibly due to the poor resolution of geological age of the floras and difficulty in determining the botanical affinities based on pollen grains, many of which are assigned only to form-genus. In addition, many pollen assemblages appear to be so homogeneous that the CA could not detect any fluctuation in temperatures.

4.2. Precipitation

Four parameters regarding precipitations were reconstructed (Tables 2 and 3). The most evident aspect concerning the reconstructed MAPs is that all the studied areas had much wetter MAPs in the Miocene than those of today (Table 3). If an amount of 500 mm MAP is considered as the boundary between wet and arid environments in

Table 2
Quantitative reconstructions of climate parameters for all the fossil sites, which are arranged by the geological time and geographic region.

Loc. No.	Flora	MAT	CMMT	WMMT	MAP	MP-WET	MP-DRY	MP-WARM
Eastern part of North China								
Early Miocene								
1	Guantao, Bohai	11.5–20.8	−1.0–13.3	23.0–28.1	735.0–1520.0	109.0–195.0	18.0–30.0	70.0–111.0
2	Jiyang, Shandong	13.6–18.4	1.8–12.5	23.6–28.2	735.0–1520.0	109.0–195.0	18.9–41.0	49.0–154.0
3	Shangdou, Inner Mongolia	11.5–20.8	1.7–13.3	23.0–28.1	652.0–1724.0	109.0–236.0	16.0–59.0	47.0–154.0
4	Wulougong, Hebei	15.7–16.1	3.8–7.8	24.9–25.6	1122.0–1206.0	117.0–143.0	19.0–30.0	85.0–95.0
5	Dunhua, Jilin	15.7–20.8	5.5–13.3	28.0–28.1	1242.0–1281.0	164.0–236.0	25.0–50.0	118.0–173.0
Late Early Miocene–early Middle Miocene								
9	Lengshuigou, Shaanxi	15.7–20.8	3.8–13.3	21.7–28.1	1096–1520	216–236	16–45	47–173
9	Gaoling, Shaanxi	16.8–18.4	10.6–12.5	23–28.1	1096–1577	216–236	9–41	47–61
3	Shangdou, Inner Mongolia	13.9–19.2	2.2–13.3	25.7–28.1	897–1179	110–157	9–24	58–60
Middle Miocene								
1	Lower Minghuazhen, Bohai	11.5–21.7	1.7–14.8	23–28.2	652–1724	109–340	16–67	47–189
10	Erlian Basin, Inner Mongolia	13.3–21.1	−0.1–13.3	24–28.3	897–1355	109–196	8–64	45–154
16	Huanghua, Hebei	15.7–16.1	5–7.1	24.7–24.9	1122–1215	116–153	19–24	82–94
11	Tianchang, Jiangsu	15.7–16.1	3.8–7.8	23–25.6	1096–1206	109–143	18–24	49–175
12	Lower Minghuazhen, Shandong	13.6–18.4	1.8–12.5	23.6–28.2	735–1520	109–195	18–41	49–154
17	Yaoshan, Shandong	15.7–20.8	4.3–7.8	24.9–25.6	1187–1206	117–195	19–55	118–143
13	Zhoukou Basin, Henan	12.5–16.1	1.7–7.1	24.9–25.6	1122–1206	117–143	19–24	85–143
18	Jidong, Heilongjiang	11.5–15.8	1.7–5.6	23.0–25.6	652–1206	109–143	16–24	55–141
14	Huanan, Heilongjiang	14–16.1	−0.5–6.2	24.7–25.6	735–1206	116–143	18–25	108–143
15	Hunchun, Jilin	16.5	5.5–7.1	27.3–27.4	1096–1298	187–195	9–24	85–175
Late Miocene								
4	Huanghua, Hebei	15.7–16.1	5–7.1	24.7–24.9	1122–1215	116–153	19–24	81–94
1	Upper Minghuazhen, Bohai	9.1–16.1	−2.7–7.8	19.3–25.6	735–1206	73–143	18–30	49–111
2	Upper Minghuanzhen, Shandong	11.6–18.4	−0.3–12.5	23–28.2	735–1520	109–195	18–41	49–154
14	Huanan, Heilongjiang	14–16.1	−0.5–7.1	24.7–25.6	735–1206	116–143	18–39	108–143
Western part of North China								
Early Miocene								
6	Dunhuang, Gansu	15.7–22.2	3.8–14.8	21.6–28.3	1122–1632	115–257	19–29	45–154
7	Dushanzi, Xinjiang	9.4–16.5	−0.1–5.2	19.6–23.3	374–980	68–118	9–24	45–61
7	Huoerguosi, Xinjiang	15.7–18.4	3.8–12.5	20.2–28.5	1096–1577	216–257	8–41	47–175
7	Shanwan-Taxihe, Xinjiang	15.6–20.8	5–13.3	24.7–28.1	622–1520	90–236	9–24	45–172
8	Qinghai	15.6–21.1	5–13.3	24.7–28.1	897–1298	109–196	16–24	47–154
Middle Miocene								
6	Dunhuang, Gansu	12.5–21.1	0.7–16.6	24.9–28.3	622–1335	117–172	8–43	45–154
7	Shanwan-Taxihei, Xinjiang	11.6–18.4	−0.1–12.5	21.7–28.1	622–774	90–172	9–24	45–61
8	Chetougou, Qinghai	9.4–21.7	−0.1–15.6	22.8–28.1	373–1520	84–245	8–24	45–61
Middle–Late Miocene								
19	Kuqa, Xinjiang	15.7–18.4	3.8–12.5	23.6–28.1	652–1355	109–236	16–24	51–61
Late Miocene								
6	Xishuigou, Gansu	12.5–16.1	0.7–7.8	24.9–25.6	622–1206	117–143	8–43	45–143
7	Shanwan-Taxihe, Xinjiang	15.7–18.4	3.8–12.5	21.7–28.1	1096–1355	216–236	16–24	173–175
19	Kuqa, Xinjiang	11.6–18.4	−0.1–12.5	19.4–28.1	735–774	90–172	18–24	49–154
8	Xianshuihe, Qinghai	9.4–21.7	−0.1–15.6	18.8–28.1	581–1741	91–262	8–24	27–61

China (Sun and Wang, 2005), all the studied areas would certainly be under wet conditions in the Miocene (Table 2). In Table 2, there are only two floras with minimum MAP lower than 500 mm, e.g. Early Miocene Dushanzi Formation from Xinjiang (loc. No. 7) and Middle Miocene Chetougou Formation of Qinghai (loc. No. 8).

A comparison of MAPs among the 7 selected studied areas is made in Fig. 7. For the 4 sites in eastern North China, the MAPs were generally highest in the Early Miocene (Fig. 7), indicating the wettest conditions, while the MAPs decreased in the Middle Miocene and further declined in the Late Miocene (Fig. 7), denoting drier conditions than in the previous period which correspond to the global cooling trend. The fluctuating precipitation in wettest, driest, and warmest months in Bohai during the Miocene is along with the climate optimum in the Middle Miocene and then cooling down in the Late Miocene (Fig. 8). On the other hand, two of the 3 sites in western North China (i.e. Xinjiang and Qinghai; Nos. 6 and 7 in Fig. 7) appear to show a different trend, viz. the transition of MAPs from the Middle to Late Miocene witnessed a dramatic shift to much wetter conditions, probably indicating the intensification of the East Asian summer monsoon which could bring plenty of rainfall into the interior of the western part of China (Fig. 7). This trend is also supported by the occurrence of a highest summer precipitation (MP-WARM) shown in floras from Xinjiang (Fig. 9).

Generally speaking, there is no consistent trend in Miocene precipitation throughout North China. It seems that the Early and Middle Miocene MAPs are comparatively wetter than the Late Miocene MAPs in two sites from northeastern and northwestern China (Nos. 4 and 5 in Fig. 7), while the Late Miocene MAPs appear the wettest in another two sites in western North China (Nos. 6 and 7 in Fig. 7). If the former situation is true, it would suggest that the precipitation brought by the East Asian summer monsoon was high during the Early and Middle Miocene and then decreased in the Late Miocene, a pattern favored by increasing evidence (e.g. Clift et al., 2008; Steinke et al., 2010). However, if the latter precipitation change is true, it would indicate the late intensification of the East Asian summer monsoon (see discussion below).

Monsoon influence on vegetation is mainly expressed as rainfall (Sun and Wang, 2005). To find out the evolution of East Asian and Indian monsoon systems, we apply the monsoon index (MSH), developed by Liu and Yin (2002), to examine the development of

Table 3
Medium values and their change range of the seven climate parameters reconstructed by the CA on the selected Miocene floras from North China. The modern values of the climate parameters are from Müller (1996).

Loc. No.	Age	Flora	MAT	Range	CMMT	Range	WMMT	Range	MAP	Range	MP-WET	Range	MP-DRY	Range	MP-WARM	Range	MSH
Eastern part of North China																	
1	Early Miocene	Guantao, Bohai	16.15	4.65	6.15	7.15	25.55	2.55	1127.5	392.5	152	43	24	6	90.5	20.5	1290.1
1	Middle Miocene	Lower Minghuazhen, Bohai	16.6	5.1	8.25	6.55	25.6	2.6	1188	536	224.5	115.5	41.5	25.5	118	71	1327.3
1	Late Miocene	Upper Minghuazhen, Bohai	12.6	3.5	2.55	5.25	22.45	3.15	970.5	235.5	108	35	24	6	80	31	1114.4
	Modern	Bohai region (Tianjian)	12.8		−4.1		26.8		528		177		3		177		
2	Early Miocene	Jiyang, Shandong	16	2.4	7.15	5.35	25.9	2.3	1127.5	392.5	152	43	29.95	11.05	101.5	52.5	1341.6
12	Middle Miocene	Lower Minghuazheng, Shandong	16	2.4	7.15	5.35	25.9	2.3	1127.5	392.5	152	43	29.5	11.5	101.5	52.5	1350
17	late Middle Miocene	Yaoshan, Shandong	18.25	2.55	6.05	1.75	25.25	0.35	662	544	156	39	37	18	130.5	12.5	1795.2
2	Late Miocene	Upper Minghuazhen, Shandong	15	3.4	6.1	6.4	25.6	2.6	1127.5	392.5	152	43	29.5	11.5	101.5	52.5	1404
	Modern	Jinan, Shandong	14.8		−1.2		28.4		631		185		7		185		
4	Early Miocene	Wulougong, Hebei	15.9	0.2	5.8	2	25.25	0.35	1164	42	130	13	24.5	5.5	90	5	1274
16	late Middle Miocene	Huanghua, Hebei	15.9	0.2	6.05	1.05	24.8	0.1	1168.5	46.5	134.5	18.5	21.5	2.5	88	6	1246.9
4	Late Miocene	Huanghua, Hebei	15.9	0.2	6.05	1.05	24.8	0.1	1168.5	46.5	134.5	18.5	21.5	2.5	87.5	6.5	1237.5
	Modern	Beijing	11.8		−4.7		26.1		619		243		3		243		
5	Early Miocene	Dunhua, Jilin	18.25	2.55	9.4	3.9	28.05	0.05	1261.5	19.5	200	36	37.5	12.5	145.5	27.5	2014.2
15	Middle Miocene	Hunchun, Jilin	16.5	0	6.3	0.8	27.35	0.05	1197	101	191	4	16.5	7.5	130	45	2389.2
14	Middle Miocene	Dadaiqiao, Heilongjiang	15.05	1.05	2.85	3.35	25.15	0.45	970.5	235.5	129.5	13.5	21.5	3.5	125.5	17.5	2319.2
18	late Middle Miocene	Jidong, Heilongjiang	13.65	2.15	3.65	1.95	24.3	1.3	929	277	126	17	20	4	98	43	1610.7
14	Late Miocene	Dadaiqiao, Heilongjiang	15.05	1.05	3.3	3.8	25.15	0.45	970.5	235.5	129.5	13.5	28.5	10.5	125.5	17.5	2119.5
	Modern	Changchun, Jilin	4.7		−16.8		23.5		632		172		5		172		
Western part of North China																	
6	Early Miocene	Dunhuang, Gansu	18.95	3.25	9.3	5.5	24.95	3.35	1377	255	186	71	24	5	99.5	54.5	1181.6
6	Middle Miocene	Dunhuang, Gansu	16.8	4.3	8.65	7.95	26.6	1.7	978.5	356.5	144.5	27.5	25.5	17.5	99.5	54.5	1328.3
6	Late Miocene	Dunhuang, Gansu	14.3	1.8	4.25	3.55	25.25	0.35	914	292	130	13	25.5	17.5	94	49	1438.5
	Modern	Jiuquan, Gansu	8.4		−8.3		23.6		84		28		2		13		
7	Early Miocene	Shanwan-Taxihe, Xinjiang	18.2	2.6	9.15	4.15	26.4	1.7	1071	449	163	73	16.5	7.5	108.5	63.5	1587
7	Middle Miocene	Shanwan-Taxihe, Xinjiang	15	3.4	6.2	6.3	24.9	3.2	698	76	131	41	16.5	7.5	53	8	682.6
7	Late Miocene	Shanwan-Taxihe, Xinjiang	17.05	1.35	8.15	4.35	24.9	3.2	1225.5	129.5	226	10	20	4	174	1	2579.5
	Modern	Urumchi, Xinjiang	5.3		−15.8		23.9		273		47		6		16		
8	Early Miocene	Xiejia, Qinghai	18.35	2.75	9.15	4.15	26.4	1.7	1097.5	200.5	152.5	43.5	20	4	100.5	53.5	1388.6
8	Middle Miocene	Chetougou, Qinghai	15.55	6.15	7.75	7.85	25.45	2.65	946.5	573.5	164.5	80.5	16	8	53	8	654.9
8	Late Miocene	Xianshuihe, Qinghai	15.55	6.15	7.75	7.85	23.45	4.65	1161	580	176.5	85.5	16	8	44	17	439.6
	Modern	Xining, Qinghai	6.9		−6.4		18.3		378		92		1		73		

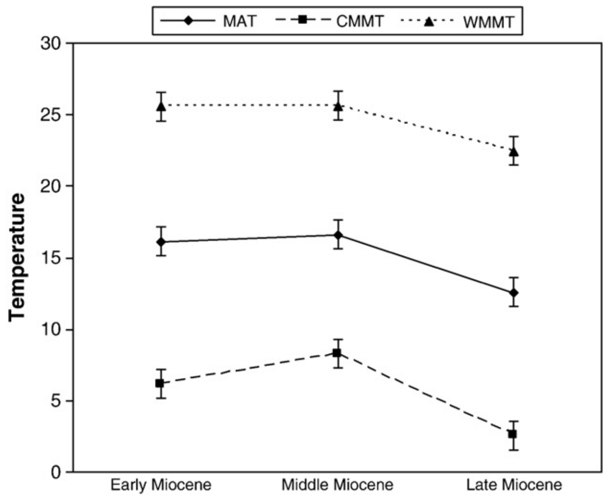

Fig. 2. Evolution of the temperatures (°C) in Bohai, eastern North China during the Miocene (loc. No. 1 in Table 1 and Fig. 1).

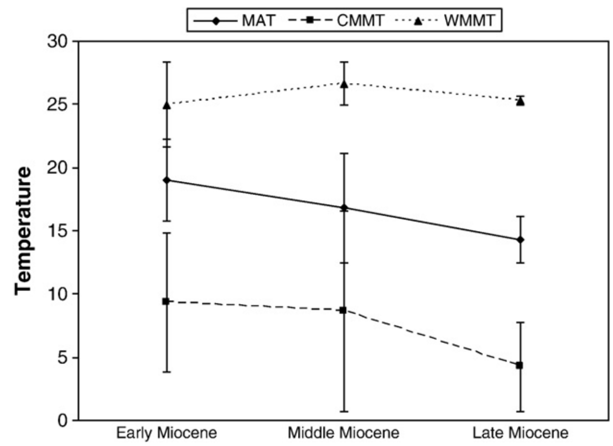

Fig. 4. Evolution of the temperatures (°C) in Gansu, western North China during the Miocene (loc. No. 6 in Table 1 and Fig. 1).

Miocene monsoon system in China. Liu and Yin (2002) suggested that the higher the index value, the greater the differences between summer and winter temperature and precipitation and thus a stronger monsoon regime. A comparison of MSHs is made in Table 3. It is interesting that no great change in MSHs during the Miocene has been found from all 4 areas of eastern North China (Table 3), suggesting that this vast region had been wet during the Miocene and the monsoon influence was not outstanding in eastern North China (Sun and Wang, 2005). However, at 2 sites in western North China, i.e. Gansu (loc. No. 6 in Table 3) and Xinjiang (loc. No. 7 in Table 3), the MSHs had increased from the Mid Miocene to the Late Miocene (Fig. 10), indicating the differences between summer and winter temperature and precipitation became greater in the Late Miocene. In other words, the MSH indices from these two sites in western North China suggest the onset or intensification of the East Asian summer monsoon started as late as the Late Miocene. This conclusion appears consistent with the evidence from fossil mammals (Fortelius et al., 2002; Fortelius and Zhang, 2006; Fortelius et al., 2006; Liu et al., 2009) and the Chinese Loess Plateau (An et al., 2001; Vandenberghe et al., 2004). It must be pointed out that the results on precipitation changes demonstrated from MAPs and MSHs of two sites in western North China, Gansu and Qinghai, are contradictory (cf. Figs. 7 and 10). For example, the pattern from MAPs in Qinghai favoring a late impact of the East Asian summer monsoon (Fig. 7) appears to contradict with that of the MSHs of Qinghai showing a decreasing impact of the monsoon during the Miocene (Fig. 10). The reason for the overall inconsistency may be related to the validation of the monsoon index (MSH) developed by Liu and Yin (2002), who did warn that the index may be biased toward the mid-latitude regions where the annual range of temperature is much greater than that in low-latitude regions (cf. Jacques et al., 2011). In addition, the poor resolution of geological age and diversity of the individual flora available in the analysis may contribute the inconsistency as well.

Zhang et al. (2002) noted that, unlike the situation in Europe and western Asia, the shifts of climate and ecological environment in western North China in the early to late Late Miocene occurred from the dry and warm open habitats to the humid and wet closed conditions. The major mammal fauna turnover event that happened during the interval was ecological and taxonomic and it suggests a significant climatic change at this time, possibly driven by onset or intensification of the East Asian summer monsoon circulation system. Recently, Liu et al. (2009) presented a paleoprecipitation analysis based on mean molar tooth height of large herbivorous mammals to investigate the spatial pattern of humidity zonation in East Asia during the Miocene and concluded that in the later Late Miocene (7–8 Ma), North China became more humid, due to the onset or intensification of summer rains. If our results from the sites in Gansu and Xinjiang are more reasonable than those from Qinghai, the present study would provide extra evidence to support the late intensification of the Asian summer monsoon. It is certain that more fossil floras with better dating and high diversity from western North China are needed for further discussion.

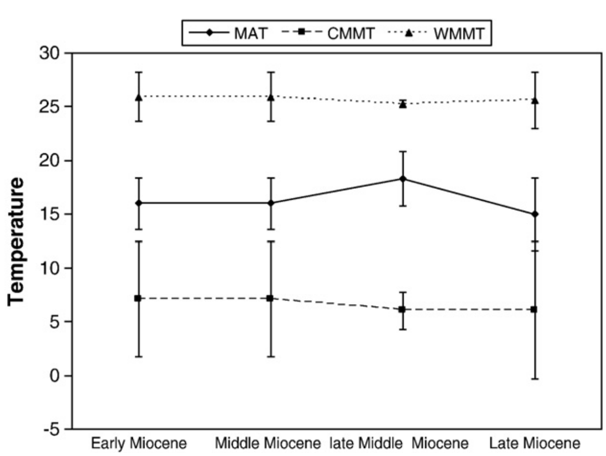

Fig. 3. Evolution of the temperatures (°C) in Shandong, eastern North China during the Miocene (loc. Nos. 2, 12, and 17 in Table 1 and Fig. 1).

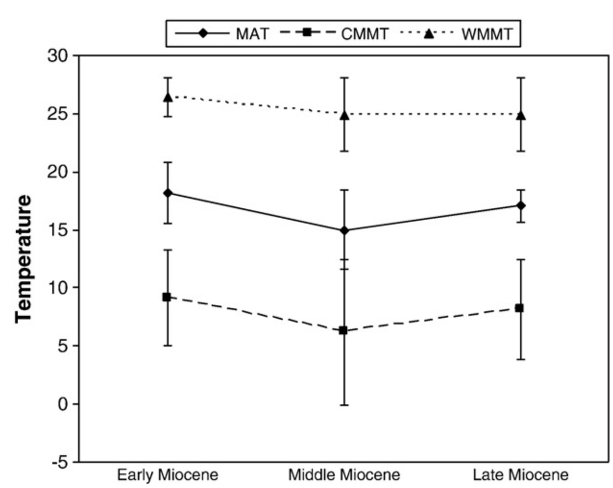

Fig. 5. Evolution of the temperatures (°C) in Xinjiang, western North China during the Miocene (loc. No. 7 in Table 1 and Fig. 1).

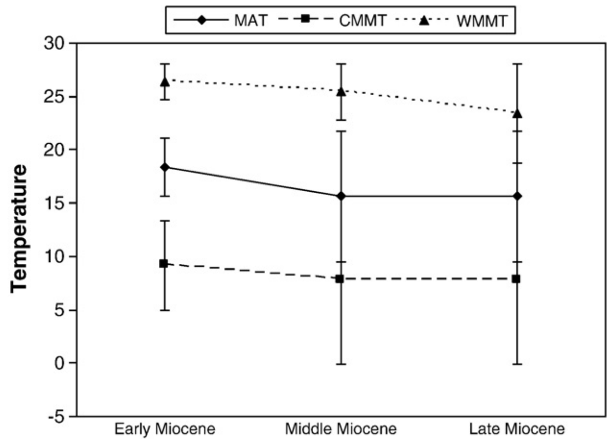

Fig. 6. Evolution of the temperatures (°C) in Qinghai, western North China during the Miocene (loc. No. 8 in Table 1 and Fig. 1).

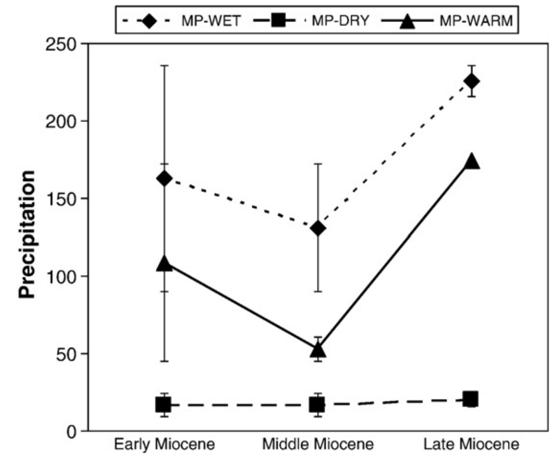

Fig. 9. Evolution of the precipitations (mm) in wettest, driest, and warmest months in Xinjiang during the Miocene.

The early time for the initiation of the Asian monsoon system in the Latest Oligocene–Early Miocene is based on evidence from Miocene loess (Guo et al., 2002) and pollen and plant macrofossils (Wang et al., 2005; Sun and Wang, 2005). The crucial criterion paleopalynologists normally use to judge if a pollen assemblage represents arid or semi-arid environments is the presence of over 15% of *Ephedripites* in a pollen assemblage (Sun and Wang, 2005). The wide application of this criterion in Chinese paleobotanical research has resulted in many and earlier presence of arid pollen floras from western North China. These studies, however, are solely based on single or few taxa, which may have survived in a physiologically dry region in the geological past, and/or just qualitative analysis. Our results at least provide quantitative data showing wetter than present environments in North China during the Miocene, though no conclusions can be made regarding how late the Asian summer monsoon intensified in North China.

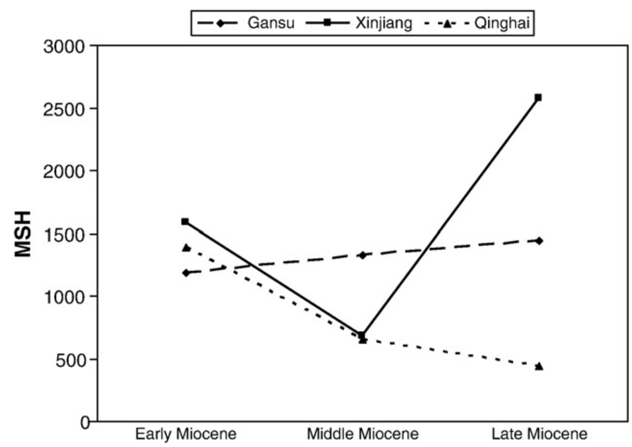

Fig. 10. Comparisons of monsoon index (MSH) among three sites in western North China (Gansu, Xinjiang, and Qinghai).

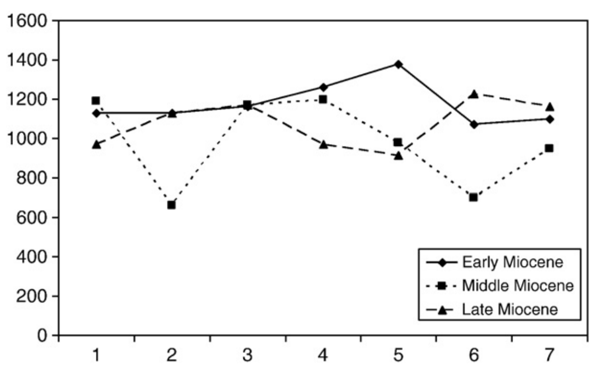

Fig. 7. Comparisons of MAPs from all the studied areas in North China. Numbers in X-axis denotes: 1–4. eastern North China; 1. Bohai; 2. Shandong; 3. Hebei; 4. Jilin/Heilongjiang; 5–7. western North China; 5. Gansu; 6. Xinjiang; 7. Qinghai.

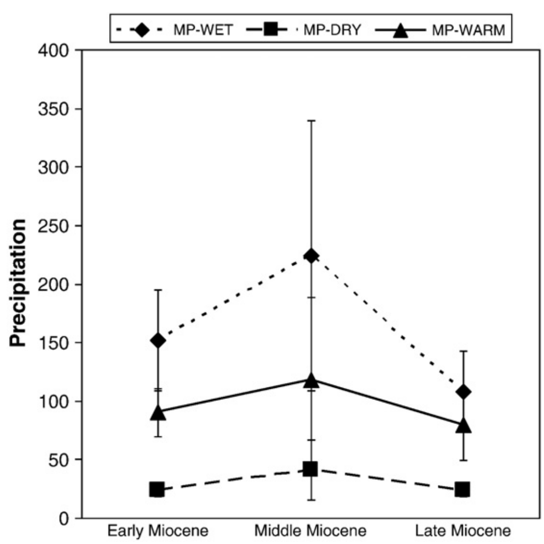

Fig. 8. Evolution of the precipitations (mm) in wettest, driest, and warmest months in Bohai during the Miocene.

5. Conclusions

Quantitative paleoclimate reconstructions on 34 selected Miocene floras representing 19 sites in North China have revealed for the first time the details of 7 climate parameters of temperature and precipitation. Generally speaking, the evolution of temperature reflects the climate optimum in the Middle Miocene and then cooling in the Late Miocene. This pattern is generally consistent with the global temperature change during the Miocene. Inconsistent results in temperature change with respect to the general global trend may be caused by insufficient sampling of fossil plants from different sequences and/or inaccurate identifications. Results from the precipitation monsoon index (MSH) in two sites of western North China appear to support the late onset or intensification of the East Asian summer monsoon. But the third site from western North China indicates a different trend. However, results from the MAPs could support a decreasing impact of the monsoon during the Miocene. Due to the limitation of the dataset available at the present, it would be impossible to draw a definite conclusion concerning the evolution of Miocene precipitations in North China. For a better understanding of the Miocene climate evolution in China, future work is urgently needed and should focus on careful sampling at a fossil site to increase the diversity of plant fossils, accurate determination of these fossils, and better age constraints on the fossiliferous layers, particularly correlation with fossil vertebrate biochronology.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.palaeo.2010.07.004.

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