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Quantitative Reconstruction of Paleoclimatic Changes in the Late Miocene Eastern Zhejiang Based on Plant Fossils

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Abstract: With a series of Cenozoic climate fluctuations, the global paleoclimate shifted from a warm climate to a cold climate, causing Arctic ice caps to be formed. The Late Miocene is a critical time in this transition period, in which the climate was rapidly cooling. Plant fossils from this epoch could be used as ideal indicators for reconstructing climate change throughout this time interval. In this study, plant fossils were collected from the Shengxian Formation in Ninghai and Tiantai of eastern Zhejiang. We divided the fossiliferous strata of the Shengxian Formation into five layers according to different lithology and chronological order, which were named: JHU0, DLX, JHU1, JHUW, and JHU3 from old to new geological times, respectively. We used Leaf Margin Analysis and Climate Leaf Analysis Multivariate Program to reconstruct paleoclimatic changes in eastern Zhejiang during the Late Miocene. The paleoclimatic information of the five stages from old to new times was obtained based on the plant fossils of each layer. The mean annual temperature values in eastern Zhejiang were reconstructed using the Climate Leaf Analysis Multivariate Program and Leaf Margin Analysis at the same time. However, the former mean annual temperature values are lower than the latter values. After comparing the two sets of mean annual temperature data with previously reported values, it is found that the results obtained by Climate Leaf Analysis Multivariate Program are more reliable, whose values are 18.05 °C, 16.03 °C, 17.96 °C, 16.57 °C, and 15.52 °C from old to new times, respectively. Moreover, 11 climatic parameters were reconstructed using the Climate Leaf Analysis Multivariate Program PhysgAsia2 calibration, among which the growing season precipitation was found to be 195.54 cm, 181.25 cm, 207.99 cm, 180.7 cm, and 165.07 cm; while the difference between the coldest and warmest months was found to be 22.14 °C, 23.4 °C, 22.07 °C, 21.36 °C, and 23.37 °C. The relatively low difference between the coldest and warmest months values and the growing season precipitation values during the Late Miocene might be due to a weaker East Asian monsoon system in the Late Miocene than in modern times.

Keywords: late miocene; paleoclimatic reconstruction; eastern zhejiang; leaf margin analysis; climate leaf analysis multivariate program

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1. Introduction

During the Neogene, the global climate underwent a series of warming and cooling cycles [1]. The Miocene was a warm period at 5–8 °C warmer than modern times, which would be equivalent to warming temperatures about a century into the future without slowing carbon emissions. By the Late Miocene, the globe was in a period of cooling, and subsystems of the modern Earth, such as the Antarctic ice cap and perennial Arctic ice floes, had formed [2]. The study of Late Miocene climate change is crucial to predict future climatic change and improve the living environment of human beings. Moreover, the morphology and distribution of plants are more sensitive to climate change and are ideal indicators for reconstructing paleoclimate [3]. The leaf characteristics of terrestrial plants have been shown to be influenced by climate change and are ideal indicators for studying climate change [4].

A large number of plant fossils are preserved in sedimentary strata of the Shengxian Formation, Zhejiang, including leaves, e.g., *Alseodaphne, Ilex, Liquidambar, Cunninghamia, Fokienia, and Bambusium* [5–10], fruits, e.g., *Pinus, Paliurus, Castanopsis, Podocarpium, Quercus, Diploclisia,* and *Choerospondias* [11–18] and pollen [6,19], which provides valuable materials for the study of the Miocene climate and environmental change in eastern China. Researchers have conducted an abundance of paleoclimatic studies based on the plant fossils discovered in the region. Li [20] reported *Betula mioluminifera* in the Miocene of Tiantai and reconstructed the paleoclimate of eastern Zhejiang during the Late Miocene using the nearest living relative techniques (NLR), which suggested this period was warmer and wetter than modern times. Ding [21] applied a coexistence approach (CA), overlapping distribution analysis (ODA), Leaf Margin Analysis (LMA), and Climate Leaf Analysis Multivariate Program (CLAMP) for the quantitative paleoclimatic reconstructions of 46 genera from 29 families found at the site, and found that the Miocene climate was similar to that of modern times. Yang et al. [22] identified 35 pollen taxa and used CA to reconstruct the Late Miocene climate in Zhejiang with subtropical characteristics. Based on 83 plant macrofossils from the Shengxian Formation, He [23] used CA to reconstruct the Late Miocene climate in Zhejiang, which was found to be not too distinct from the present, although with more humid summers. Xiao et al. [18] used climate analysis of endemic species (CAES) based on *Choerospondias* to reconstruct the Late Miocene climate in Zhejiang, which was similar to or warmer and wetter than the present. However, in previous studies using plant fossils to reconstruct the paleoclimate of eastern Zhejiang during the Late Miocene, these plant fossils were usually selected from the entire second sedimentary horizon without further differentiating the specific stratum from which the fossils were collected. This has led to the usual use of mixed plant fossils over time intervals for paleoclimatic reconstruction in most studies, and the accuracy of the quantitative paleoclimatic reconstruction of individual layers needs to be improved.

In this study, quantitative paleoclimatic reconstruction was carried out using plant fossils collected from the Shengxian Formation in eastern Zhejiang. The sedimentary strata are widely exposed in the Ninghai and Tiantai areas of Zhejiang and are horizontally distributed. We converted the sedimentary strata from elevation scale to time scale so that fossil localities could be divided into the following five layers in the order of stratigraphy from old to new times: JHU0, DLX, JHU1, JHUW, and JHU3. This study combined the leaves of terrestrial dicotyledonous plants from five fossil collection layers and integrated leaf physiognomic characteristics for morphological classification and delineation. Using LMA and CLAMP, quantitative paleoclimatic reconstruction of eastern Zhejiang during the Late Miocene was carried out, and the results were further compared with previous studies to explore paleoclimatic trends and their causes on a short time scale in the Late Miocene.

2. Materials and Methods

2.1. Geological Setting

The plant fossils were collected from the Shengxian Formation in Tiantai and Ninghai areas, eastern Zhejiang, China (Figure 1). The Shengxian Formation in eastern Zhejiang is a set of continental strata with polycyclic eruption of basalt embedded within the lacustrine sedimentary rocks. Plant fossils are mainly yielded in siltstone layers, diatomite mudstone layers, and lignite layers in hydrodynamically stable fluvial or lacustrine depositional environments (Figure 2) [21]. The plant fossils collected in this study were located in the second sedimentary horizon of the Shengxian Formation. The geological age of this fossil collection layer was tentatively determined to be Late Miocene based on the macrofossil and pollen fossil collection stratigraphy [24,25]. He [23] applied the ^{40}Ar-^{39}Ar dating method to date the overlying and underlying basalts exposed in the Jiahu outcrop and Huangnitang outcrop as 10.2/9.2–10.8 Ma, thus determining that the fossil collection layer in this study should be dated to the early Late Miocene.

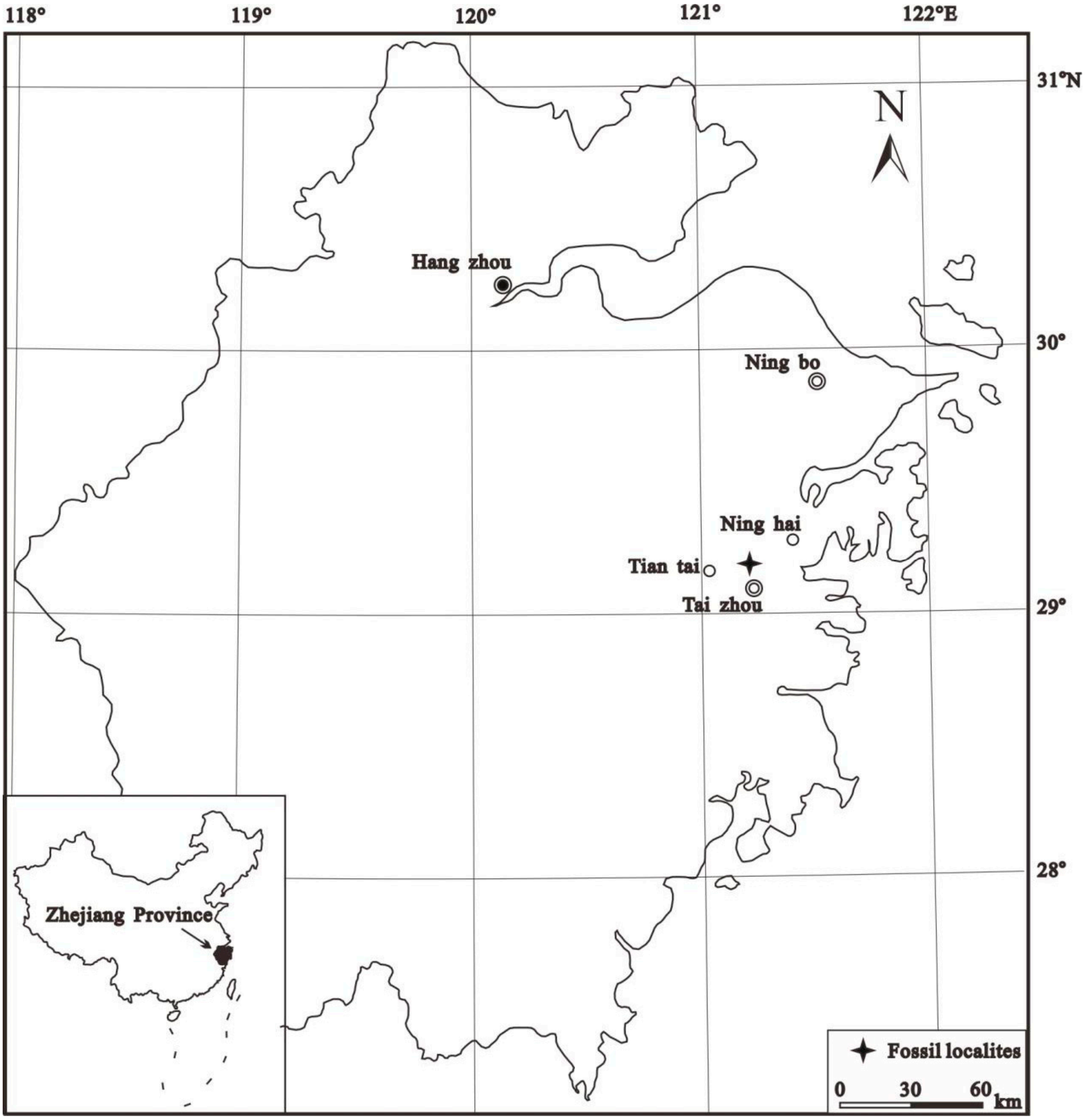

Figure 1. The position of current fossil site in China (four-pointed star representing the fossil site).

The fossils of dicotyledonous leaves from the Shengxian Formation in the Tiantai and Ninghai areas of Zhejiang are also extremely abundant, with angiosperm leaves occupying a high proportion. Leaf physiognomic characteristics, such as apex shape, margin type, base shape, vein characteristics, and serrations on woody dicotyledons, are also well preserved, allowing direct observation of their macroscopic features. The number of dicotyledon leaf species in each fossil collection layer also exceeds 20, meeting the need for paleoclimatic reconstruction.

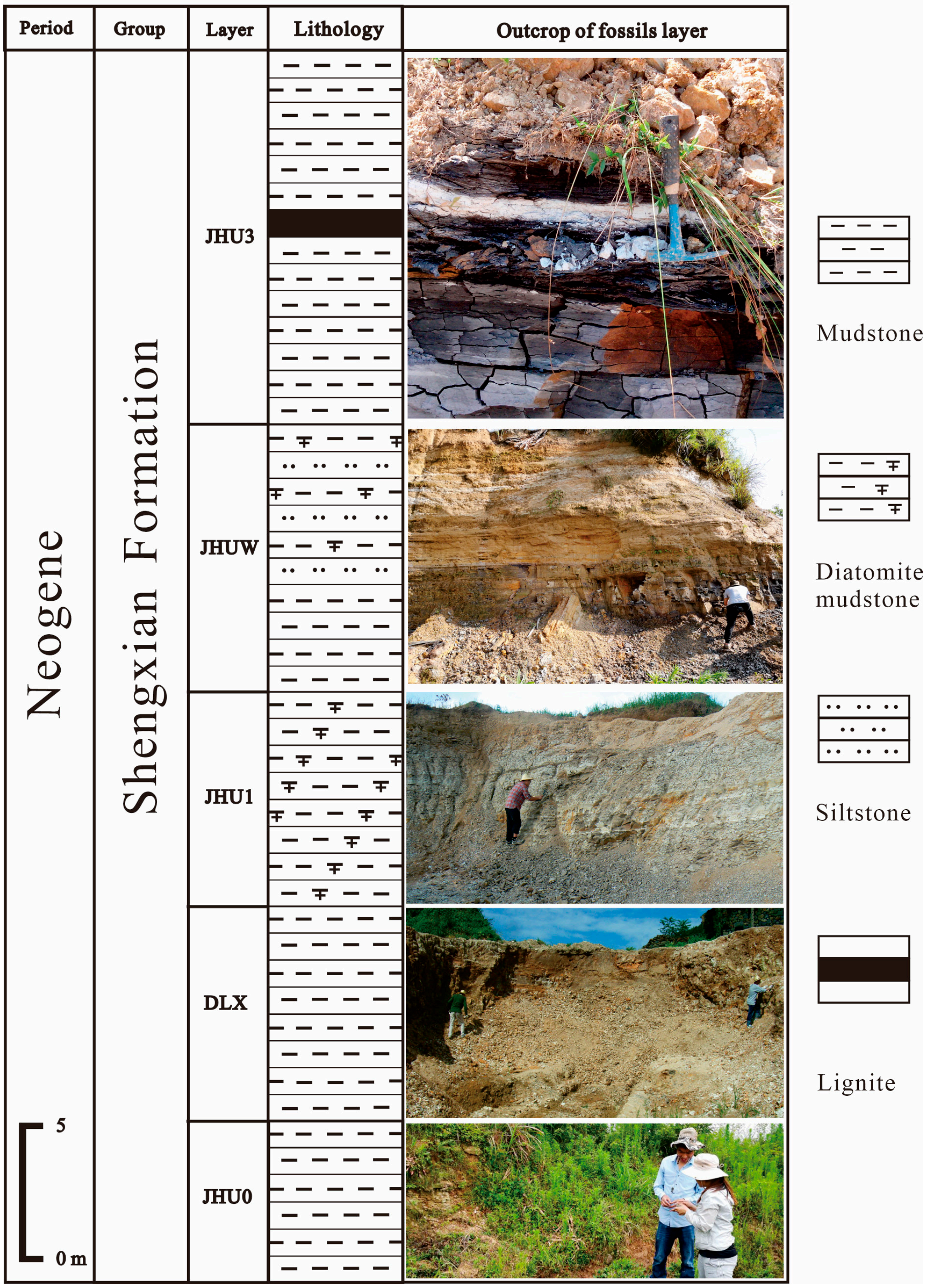

Figure 2. The stratigraphic column of five fossiliferous layers and outcrop photograph in the Shengxian Formation of Ninghai and Tiantai, eastern Zhejiang, China.

2.2. Methods of Paleoclimatic Reconstruction

2.2.1. Leaf Margin Analysis (LMA)

LMA is a unitary linear regression analysis based on the percentages of modern woody dicotyledonous entire leaf species and mean annual temperature (MAT), and has been widely used in paleoclimatic reconstructions [26,27]. For the definition of toothed leaf species, the criteria of Ash et al. [28] were used, i.e., the length of the projection of the leaf margin is less than 1/4 of the length of the primary vein to the tip of the projection (Figure 3). The scoring criteria for LMA are generally 1 point for species with all entire leaf forms, 0.5 points for a species with both entire and serrate leaf forms, and 0 points for a species with all serrate leaf forms [26,29]. The 0.5-point scoring category was discarded because fossil leaves are less well preserved than modern leaves, and it is difficult to classify serrated leaves into the same species as entire leaves, resulting in fossil leaves with serrated and entire leaf forms often being classified as two species. The models developed for the percentage of entire leaves versus MAT are inconsistent across regions, and paleobotanists have developed appropriate models for the analysis of LMA in different regions. There are two models suitable for the paleoclimatic reconstruction of China, one for the East Asia model and one for the China model. Both LMA models have been widely used to reconstruct the paleoclimate of China, and the MAT reconstructed by the China model tends to be slightly lower than that of the East Asian model. In this study, these two models were used to reconstruct the Late Miocene climate of eastern Zhejiang.

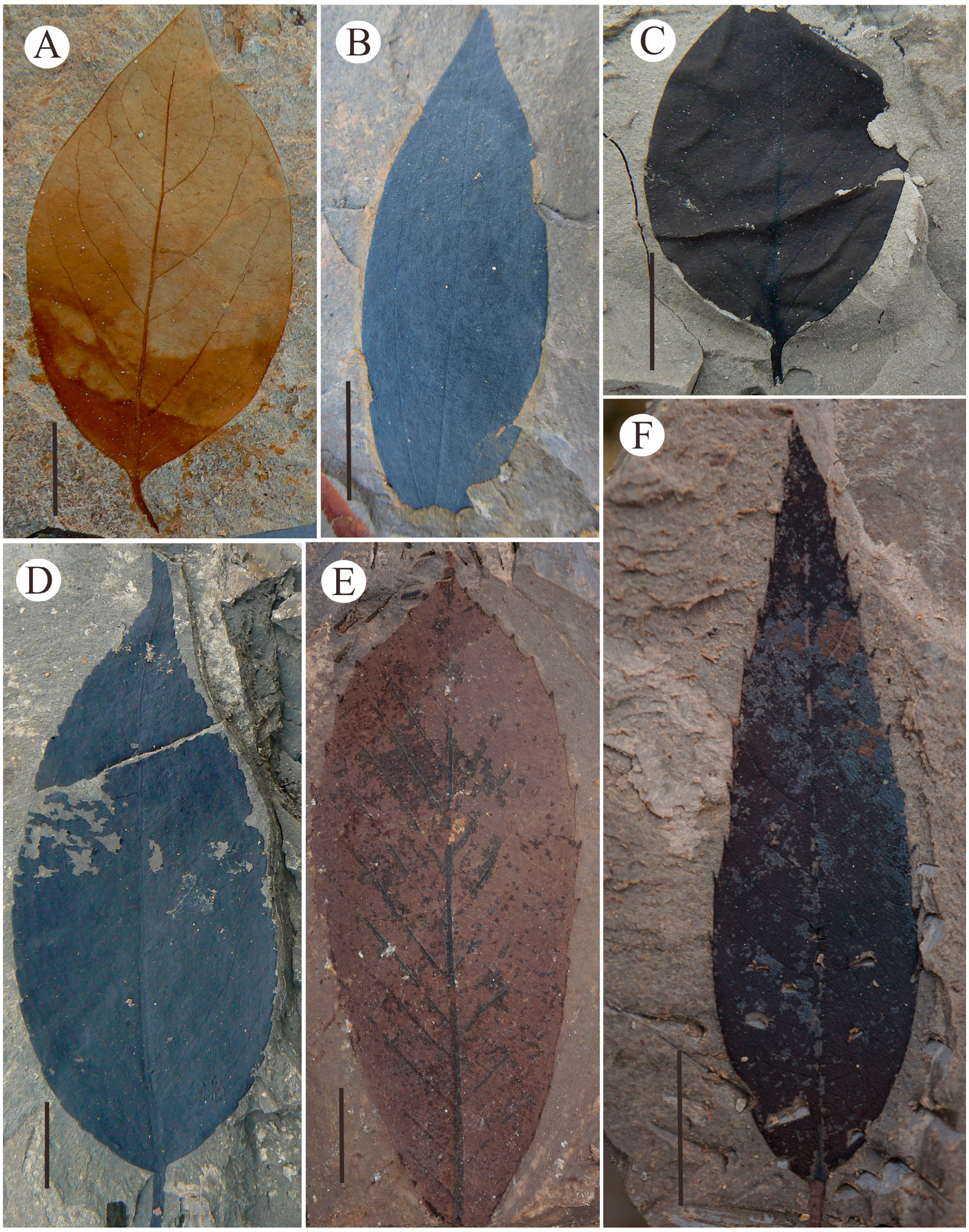

Figure 3. Representative fossil leaves from the Shengxian Formation of Zhejiang, eastern China. (**A**–**C**): entire leaves. (**D**–**F**): toothed leaves. Scale bars: (**A**–**F**), 1 cm.

The East Asian model was proposed by Wing et al. [30] and is specifically modeled as follows:

$$\mathrm{MAT} = 1.14 + 30.6\mathrm{P} \quad (1)$$

where P is the percentage of entire leaf species in dicotyledons out of the total species.

The China model was proposed by Su et al. [29] and is specifically modeled as follows:

$$\mathrm{MAT} = 1.038 + 27.6\mathrm{P} \quad (2)$$

where P is the percentage of entire leaf species in dicotyledons out of the total species.

The logistic normal variance function proposed by Miller et al. [31] was used for both model standard deviations (SDs), as follows:

$$\mathrm{SD} = \mathrm{b} \times \sqrt{[1 + \varphi(\mathrm{n}-1)\mathrm{P}(1-\mathrm{P})] \times \frac{\mathrm{P}(1-\mathrm{P})}{\mathrm{n}}} \quad (3)$$

where b is the slope of the LMA model, which is 30.6 for the East Asian model and 27.6 for the China model; φ is the coefficient of variation, a constant with a value of 0.052; and n is the total number of woody dicotyledon species.

2.2.2. Climate Leaf Analysis Multivariate Program (CLAMP)

The Climate Leaf Analysis Multivariate Program (CLAMP) was first proposed by Wolfe [26] and has been largely applied to global paleoclimatic reconstructions with the gradual addition of more climatic sampling sites and optimization and upgrading of the model [32–35]. CLAMP is a multivariate statistical analysis method with higher accuracy than LMA, which generates graphs of 31 leaf physiognomic characteristics of each species in the flora. It uses Canonical Correlation Analysis (CCA) to produce graphs based on various climatic data, allowing the following 11 climatic variables to be derived: mean annual temperature (MAT); warmest month mean temperature (WMMT); coldest month mean temperature (CMMT); length of the growing season (GRS); growing season precipitation (GSP); mean monthly growing season precipitation (MMGSP); precipitation during the three consecutive wettest months (3-WET); precipitation during the three consecutive driest months (3-DRY); relative humidity (RH); specific humidity (SH); and enthalpy (ENTHAL). The CLAMP requires that the flora must include more than 20 woody dicotyledonous species, and the samples collected from each stratum in this study met the requirements of the program. To extend the range of use and the accuracy of the climatic reconstruction, the CLAMP offers several calibration databases. In conjunction with the study area, we chose to use the PhysgAsia1 calibration and PhysgAsia2 calibration.

3. Results

3.1. MAT Reconstruction Based on LMA

In previous studies on Miocene plant fossils in eastern Zhejiang, no detailed classification has been made according to the stratigraphic sequence of the fossiliferous layers.

The study combines leaf characteristics (laminar shape; apex shape; base shape; vein features; and tooth features) to classify the collected fossils according to the leaf physiognomy of plant leaves. The MAT values were successfully reconstructed for five layers based on the calculations using the East Asian model and the China model (Table 1).

The percentage of entire leaf species in the five fossiliferous layers remained largely unchanged at around 60%, and the MAT reconstructed based on the LMA method showed a fluctuant trend of decrease over time. The highest MAT for the five layers reconstruction based on the East Asian model was 21.54 ± 3.31 °C and the lowest was 19.22 ± 3.61 °C. The highest MAT for the five layers reconstruction based on the China model was 19.44 ± 2.99 °C and the lowest was 17.35 ± 3.25 °C. The East Asian model reconstructs a higher MAT than the China model, but the East Asian model and the China model show the same trend in MAT on short time scales.

Table 1. Late Miocene MAT reconstruction in eastern Zhejiang based on LMA.

Fossil Collection Layer	Entire Leaf Species	Total Number Species	Entire Leaf Proportion (%)	East Asian MAT (°C)	East Asian SD (°C)	China MAT (°C)	China SD (°C)
JHU3	17	28	60.71	19.72	3.26	17.80	2.94
JHUW	13	22	59.09	19.22	3.61	17.35	3.25
JHU1	12	20	60.00	19.50	3.73	17.60	3.36
DLX	20	30	66.67	21.54	3.04	19.44	2.74
JHU0	16	24	66.67	21.54	3.31	19.44	2.99

3.2. Paleoclimatic Reconstruction Based on CLAMP

According to the scoring criteria of the CLAMP, the information on 31 detailed characteristics of fossil plant leaves from the Miocene Zhejiang was inputted into the CLAMP scoring table, and the ratios of 31 detailed features were obtained (Table 2).

Table 2. Percentage of traits of fossil leaves from five layers of Late Miocene Shengxian Formation in eastern Zhejiang.

Leaf Character	JHU0	DLX	JHU1	JHUW	JHU3
Lobed	5.71	3.57	6.45	5.56	2.04
No Teeth	62.86	55.36	61.29	61.11	55.10
Regular teeth	8.57	25.00	6.45	16.67	22.45
Close teeth	11.43	25.00	6.45	16.67	20.41
Round teeth	2.86	10.71	0.00	0.00	2.04
Acute teeth	34.29	33.93	38.71	38.89	42.86
Compound teeth	0.00	0.00	0.00	0.00	0.00
Nanophyll	0.00	0.00	0.00	0.00	0.00
Leptophyll 1	0.00	1.79	0.00	0.00	0.00
Leptophyll 2	2.86	5.36	0.00	0.00	6.12
Microphyll 1	17.14	1.79	6.45	2.78	34.69
Microphyll 2	45.71	46.43	48.39	30.56	46.94
Microphyll 3	28.57	41.07	41.94	61.11	10.20
Mesophyll 1	0.00	3.57	0.00	5.56	2.04
Mesophyll 2	2.86	0.00	3.23	0.00	0.00
Mesophyll 3	2.86	0.00	0.00	0.00	0.00
Emarginate apex	0.00	1.79	0.00	0.00	4.08
Round apex	2.86	8.93	9.68	22.22	14.29
Acute apex	91.43	80.36	64.52	75.00	77.55
Attenuate apex	5.71	8.93	25.81	2.78	4.08
Cordate base	0.00	1.79	0.00	0.00	0.00
Round base	45.71	42.86	48.39	50.00	53.06
Acute base	54.29	55.36	51.61	50.00	46.94
L:W < 1:1	0.00	0.00	0.00	0.00	2.04
L:W 1–2:1	17.14	30.36	32.26	36.11	34.69
L:W 2–3:1	42.86	46.43	38.71	33.33	34.69
L:W 3–4:1	22.86	8.93	22.58	25.00	16.33
L:W > 4:1	17.14	14.29	6.45	5.56	12.24
Shape obovate	5.71	8.93	6.45	13.89	6.12
Shape elliptic	71.43	58.93	58.06	50.00	61.22
Shape ovate	22.86	32.14	35.48	36.11	32.65

Each fossiliferous layer shows very few lobed leaves and approximately 60% of the no-teeth leaves. The laminar size is dominated by the Microphyll type, with Microphyll type 2 being the most abundant. The apex shape is mainly acute, and the base shape is dominated by round and acute bases. The laminar L: W ratio is concentrated at 1–2:1 to 3–4:1, with the 2–3:1 ratio being the most. The laminar shape is mainly elliptic, followed by an ovate shape, with the obovate shape being extremely rare.

Compared to the LMA, the CLAMP has a lower MAT value. A total of 11 climatic variables were obtained using the CLAMP based on two calibrations. Although they are slightly different in each fossiliferous layer, there are no significant fluctuations. All data based on the PhysaAsia1 calibration are lower than those based on the PhysaAsia2 calibration. The PhysaAsia1 calibration calculated a maximum MAT of 14.53 °C and a minimum of 12.7 °C for the five layers, and the PhysaAsia2 calibration calculated a maximum MAT of 18.05 °C and a minimum of 15.52 °C for the five layers. The MAT, WMMT, and CMMT obtained from both calibrations show a fluctuant decreasing trend over time (Tables 3 and 4).

Table 3. Paleoclimatic values of five layers based on the PhysgAsia1 calibration.

Climatic Variable	JHU0	DLX	JHU1	JHUW	JHU3
MAT (°C)	14.05	13.01	14.53	14.13	12.7
WMMT (°C)	24.56	23.58	24.33	23.51	23.24
CMMT (°C)	4.95	4	5.88	6.13	4.16
GROWSEAS (month)	8	7.49	8.18	7.88	7.23
GSP (cm)	148.35	123.78	150.53	127.25	120.71
MMGSP (cm)	15.15	14.26	15.25	14.03	13.64
3-WET (cm)	80.58	73.27	82.37	74.94	73.39
3-DRY (cm)	22.21	20.29	21.96	20.58	22.14
RH (%)	63.94	65.87	67.55	68.4	62.47
SH (g/kg)	6.29	6.34	7.02	7.16	5.78
ENTHAL (kJ/kg)	31.16	31.1	31.52	31.55	30.83

Table 4. Paleoclimatic values of five layers based on the PhysgAsia2 calibration.

Climatic Variable	JHU0	DLX	JHU1	JHUW	JHU3
MAT (°C)	18.05	16.03	17.96	16.57	15.52
WMMT (°C)	28.07	27.31	27.97	26.97	27.05
CMMT (°C)	5.93	3.91	5.9	5.61	3.68
GROWSEAS (month)	10.34	9.43	10.31	9.55	9.18
GSP (cm)	195.54	181.25	207.99	180.7	165.07
MMGSP (cm)	20.05	18.71	21.65	18.09	16.87
3-WET (cm)	83.68	78.52	87.88	77.5	70.74
3-DRY (cm)	27.25	27.53	33.43	29.11	25.8
RH (%)	68.08	68.3	70.77	70.09	66.1
SH (g/kg)	9.39	8.39	9.71	9.02	7.66
ENTHAL (kJ/kg)	32.84	32.23	32.94	32.53	31.9

4. Discussion

4.1. Comparison of Current Paleoclimatic Parameters with Previous Results

To gain a more comprehensive understanding of the paleoclimate in Zhejiang during the Miocene, we have linked and compared our findings with those of previous studies.

Xiao [36] found that 66% of the plant fossils in Zhejiang belong to entire leaves, and based on LMA the MAT of 21.3 ± 1.6 °C was obtained using the East Asian model. Whereas a value of 19.3 ± 2.0 °C was obtained by Li [37] using the China model. Ding [21] counted 58 woody dicotyledonous plant fossils in Zhejiang during the Miocene and calculated the proportion of entire leaves to be 56%, based on which the MAT obtained was 20.6 ± 2.0 °C when using the East Asian model and 18.8 ± 2.4 °C when using the China model. The proportion of entire leaves obtained using LMA and CLAMP in this study was about 60%, indicating that morphology based on species delimitation is reasonable. This study obtained the MAT of 19.22–21.54 °C using the East Asian model and 17.35–19.44 °C using the China model. In previous studies, paleoclimatic reconstructions using whole plant fossils from the second sedimentary layer yielded MATs generally within the MAT interval reconstructed in this study.

Li [37] used CA to reconstruct a MAT of 16.3–20.3 °C based on 58 macrofossils from the Miocene of Zhejiang. Li [20] reconstructed a MAT of 12.5–20.8 °C using extant NLR based on three Miocene plants from Zhejiang. He [38] used CA to reconstruct a MAT of 14.4–18.9 °C in the Miocene of Zhejiang based on pollen fossils from the Shengxian Formation in Zhejiang. Yang [39] conducted a refinement study of pollen fossils from the Shengxian Formation of Zhejiang and applied CA to obtain the Miocene MAT of Zhejiang from 17.0 to 18.5 °C. According to 83 plant macrofossils from the Shengxian Formation, He [23] used CA to reconstruct a MAT of 16.3–20 °C. Ding [21] used 46 genera from the Miocene Zhejiang for paleoclimatic reconstruction and obtained a MAT of 14.1–18.5 °C by applying CA, 14.5–18 °C by applying ODA, and 15.89 °C by using the CLAMP. This study used the CLAMP to obtain an average MAT of 12.7–14.53 °C using the PhysaAsia1 calibration and an average of 15.52–18.05 °C using the PhysaAsia2 calibration.

The MAT results obtained from the East Asian model using LMA in this study are all high compared to previous studies, while the MAT results derived from the China model are closer to previous studies. The reconstructed MAT results using the CLAMP PhysaAsia1 calibration are low, while those obtained using the PhysaAsia2 calibration are more analogical to previous studies.

4.2. Comparison between the MAT Values Obtained Using LMA and CLAMP

The MAT of the East Asian model reconstructed by LMA in this study is higher than that of the China model, mainly because the East Asian model has a wider range of sampling points, whereas the China model has a smaller area focused on non-arid areas within China from south to north. The MAT obtained from the China model is in better agreement with the previous results, further demonstrating that the China model developed by Su et al. [29] based on LMA is more applicable to the reconstruction of Cenozoic paleoclimate in China.

The difference in the climatic data reconstructed using the CLAMP based on the two calibrations is mainly due to the addition of plants from two new tropical countries, India and Thailand, to the PhysaAsia2 calibration compared to the PhysaAsia1 calibration, resulting in a warmer and wetter climate obtained using the PhysaAsia2 calibration. Yang 40 obtained small MAT intervals using the wide distribution of pollen fossils, and He [23] used CA on the largest number of macrofossils for paleoclimatic reconstruction. Our results obtained using the CLAMP PhysaAsia2 calibration are the most closely matched to their results and are more accurate, as they are generally consistent with the MAT intervals obtained by other studies.

Compared to the CLAMP, the LMA reconstructs a higher MAT. LMA is a method that uses one leaf physiognomic characteristic (leaf margin) associated with a single climatic variable (MAT). The CLAMP uses multiple leaf physiognomy characteristics to derive up to 13 paleoclimatic data. Although the CLAMP is more complex, it is also more accurate and more suitable for paleoclimatic reconstruction of the Late Miocene in Zhejiang.

4.3. Climatic Change Trends in Eastern Zhejiang during the Late Miocene

Temperatures in the Late Miocene of eastern Zhejiang reconstructed layer by layer using the LMA and the CLAMP fluctuate slightly, with an overall decreasing trend in the MAT of each layer, which indicates an overall cooling period in the Late Miocene of Zhejiang. Zachos et al. [1] used marine benthic foraminifera as a study target and plotted δ^{18}O curves by counting foraminiferal oxygen isotopes at 40 Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) stations. The curves show a largely positive trend of δ^{18}O in the range of 10.2/9.2–10.8 Ma, indicating a slow decrease in global temperature during this period. For this study, the MAT, WMMT, and CMMT reconstructed using the CLAMP show the same trend as the global temperature change ranging from 10.2/9.2 to 10.8 Ma (Figure 4), indicating that paleoclimatic changes in Zhejiang during the Late Miocene corresponded the general trend of global cooling during this period. Overall, the Late Miocene climate was similar to the modern climate, with a decreasing trend in the Late Miocene climate over a short period of time.

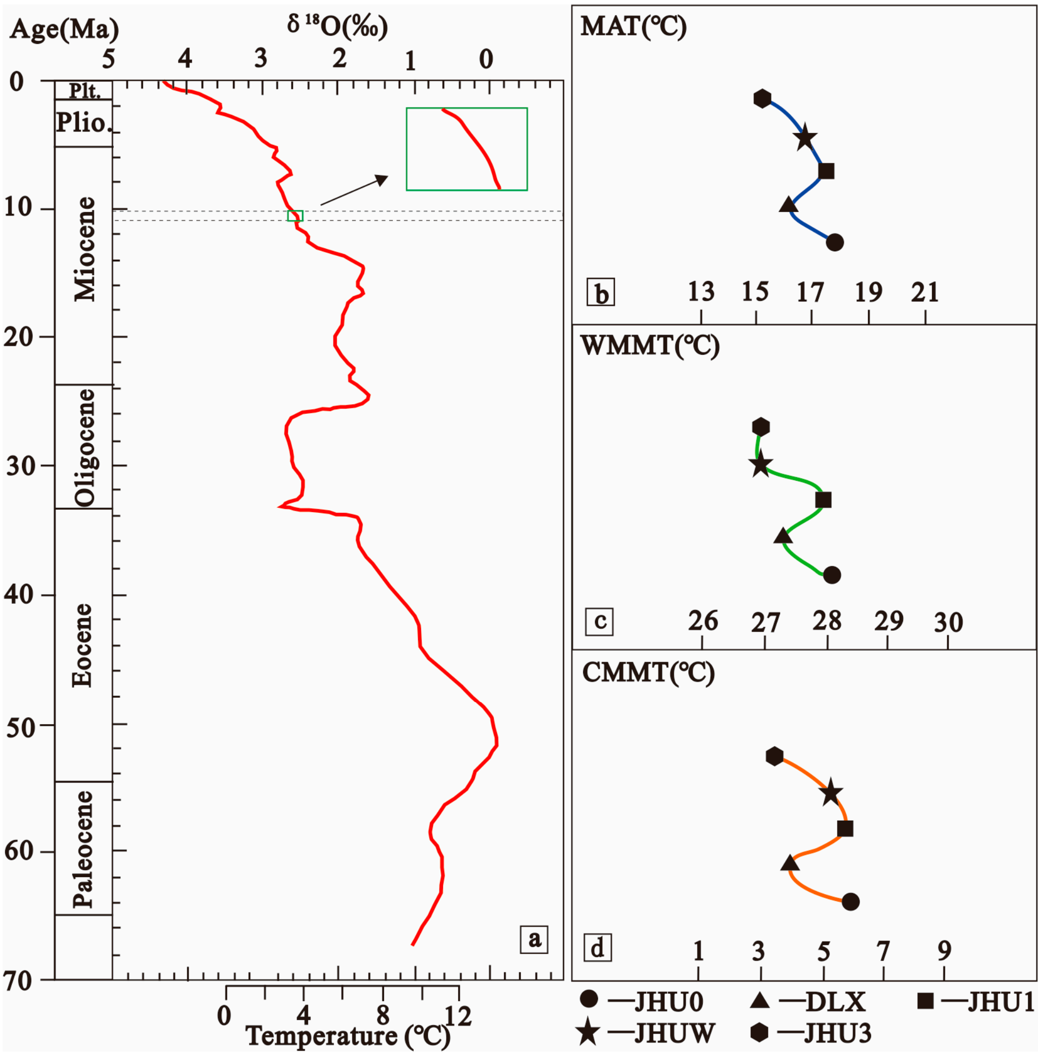

Figure 4. Comparison of the currently reconstructed temperature parameters with global temperature changes obtained from benthic foraminiferal $\delta^{18}O$. (**a**) Foraminiferal oxygen isotope plotted $\delta^{18}O$ and temperature curves from 40 DSDP and ODP stations worldwide [1]. (**b**) The MAT curves in the Late Miocene eastern Zhejiang. (**c**) The WMMT curves in the Late Miocene eastern Zhejiang. (**d**) The CMMT curves in the Late Miocene eastern Zhejiang. All climatic parameters in the Late Miocene eastern Zhejiang were reconstructed using the CLAMP (PhysaAsia2 calibration).

Global foraminiferal $\delta^{18}O$ and $\delta^{13}C$ curves [1], the origin of red clay eolian dust on the Loess Plateau, pollen and mammalian fossils, sedimentological evidence, stable isotope data of black carbon in the South China Sea, eolian dust in the North Pacific, paleovegetation, and lithology data [40–43], together suggest that the East Asian monsoon was probably prevalent in the late Oligocene and that the Late Miocene East Asian monsoon in Zhejiang was largely formed, with the monsoon strengthening at about 15 Ma, 8 Ma, and 3 Ma. It is noteworthy that the Late Miocene MAT of Zhejiang, reconstructed based on various methods, is almost higher than in modern times. The DT is slightly lower than in modern times, and the GSP is somewhat lower than in modern times, probably due to a weaker monsoon system in Zhejiang during the Late Miocene than in modern times.

5. Conclusions

Plant fossil records published previously were synthesized to reconstruct paleoclimatic changes in eastern Zhejiang during the Late Miocene, which showed that the paleoclimate in the Late Miocene was similar to that in modern times. We compared the MAT values obtained using the LMA and the CLAMP, showing that the MAT values obtained using the LMA are higher than those obtained using the CLAMP. After comparing the two sets of MAT data with previously reported values, it was found that the results obtained using the CLAMP PhysaAsia2 calibration are more reliable. In addition, the paleoclimate in eastern Zhejiang was variable on short time scales, which mainly presented a fluctuant decrease in temperature over time. Smaller DT and lower GSP in the Late Miocene eastern Zhejiang relative to the modern were obtained, which might be due to a weaker monsoon system in the Late Miocene.

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