Changes in Paleovegetation and Paleoclimate in China since the Late Middle Pleistocene: A Case Study of the Dajiuhu Basin

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Abstract: The East Asian monsoon system is an important part of global atmospheric circulation; however, records of the East Asian monsoon from different regions exhibit different evolutionary rhythms. Here, we show a high-resolution record of grain size and pollen data from a lacustrine sediment core of Dajiuhu Lake in Shennongjia, Hubei Province, China, in order to reconstruct the paleovegetation and paleoclimate evolution of the Dajiuhu Basin since the late Middle Pleistocene (~237.9 ka to the present). The results show that grain size and pollen record of the core DJH-2 are consistent with the δ18O record of stalagmites from Sanbao Cave in the same area, which is closely related to the changes of insolation at the precessional (~20-kyr) scale in the Northern Hemisphere. This is different from the records of the Asian summer monsoon recorded in the Loess Plateau of North China, which exhibited dominant 100-kyr change cyclicities. We suggest that the difference between paleoclimatic records from North and South China is closely related to the east–west-oriented mountain ranges of the Qinling Mountains in central China that blocked weakened East Asia summer monsoons across the mountains during glacial periods.

Keywords: Asian summer monsoon; precessional; Dajiuhu; pollen; late Middle Pleistocene

1. Introduction
The East Asian monsoon system is an important part of global atmospheric circulation and plays a major role in controlling precipitation in China and driving climate change in East Asia [1–6]. Numerous studies have reconstructed regional climatic change in East Asia and the spatio-temporal evolution of the Asian monsoon on multiple time scales, using various proxies [7–14]. However, records of the East Asian monsoon from different regions exhibit different evolutionary rhythms [10,15], which cause an important controversy. For example, the Chinese loess deposit sequences [16] were found to be dominated by eccentricity (100 kyr) variations, which were closely linked to the high latitude ice-volume dynamics. In high-resolution records from stalagmites in South China, including those from Hulu Cave in Jiangsu Province [7,17] and Sanbao Cave in Hubei Province [10,18], the most striking feature was the changes of ~20 kyr precessional cycles, which indicates that the tropical/subtropical monsoons responded dominantly and directly to the changes of summer insolation in the Northern Hemisphere. Therefore, it is important to obtain a great number of continuous and high-resolution records of monsoonal climate change from East Asia district in order to resolve these differences.
In this study, we used high-resolution grain size and pollen records from the Dajiuhu Basin in the eastern monsoon region of China to reconstruct the regional vegetation and climate changes since the late Middle Pleistocene. The basin is formed by lacustrine and peat sediments. Our aims were to determine the periodic components of the record, as well as to consider their implications for the East Asian monsoon, both in the past and the future.

2. Study Site

The Dajiuhu Basin (Figure 1) is located in the southwest part of Shennongjia in China (31°24′–31°33′ N, 109°56′–110°11′ E). It lies within a closed sub-alpine basin, which consists of the eastern range of the Daba Mountains. The altitude of the basin floor is 1730 m a.s.l. (a.s.l., above sea level) and it covers an area of ~16 km². The basin floor is flat and is surrounded by steep mountains with altitudes of 2200 to 2400 m a.s.l. At present, the basin is occupied by relatively undisturbed peats deposited within wetlands which occupy 47.4% of the basin area. Dajiuhu is a closed alpine lake basin that is recharged by atmospheric precipitation and a stream from the surrounding mountains [19].

![Figure 1. Environmental setting of the study area.](Image)

Figure 1. Environmental setting of the study area. (A) Map of East Asia showing the current northern limit of the East Asian summer monsoon and the locations of the sites mentioned in the text. EASM: East Asian Summer Monsoon. ISM: Indian Summer Monsoon. (B) Satellite image of the Dajiuhu Basin showing the location of core DJH-2. The yellow line is the shoreline. (C) Schematic diagram showing vertical vegetation zones around Dajiuhu. m a.s.l.: meter above sea level. (I) Evergreen broad-leaved forest; (II) mixed evergreen and deciduous broad-leaved forest; (III) broad-leaved deciduous forest; (IV) mixed broad-leaved-coniferous forest; (V) sub-alpine coniferous forest.

The region belongs to the warm temperate monsoon climate zone and has four distinct seasons. At the closest meteorological station in Jiuhu town, the mean annual temperature averages 7.4 °C, with a mean warmest month (July) temperature of 17.2 °C and mean coldest month (January) temperature of −4.3 °C. The mean annual precipitation is 1560 mm, most of which falls during April to October [19]. The vegetation of the area exhibits a
distinct altitudinal zonation, as follows (Figure 1C): (I) Below 900 m a.s.l. the vegetation is evergreen broadleaved forest dominated by Lauraceae and Fagaceae. (II) Within the ranges of 900–1500 m a.s.l., the vegetation is evergreen and deciduous broadleaved mixed forest dominated by *Quercus aliena*, *Quercus serrata*, Carpinus spp., *Castanea seguinii*, *Betula luminifera*, and *Toxicodendron vernicifluum*. (III) Within the ranges of 1500–1800 m a.s.l., the vegetation is broadleaved forest dominated by *Fagus engleriana* and *Fagus pashanica*. (IV) Within the ranges of 1800–2400 m a.s.l., the vegetation is coniferous and broadleaved mixed forest. Among the broadleaved trees, deciduous broadleaved trees such as trees of *Quercus aliena* are the most common. Coniferous trees include *Pinus*, *Abies*, *Picea*, and *Tsuga chiensis*. (V) Above 2400 m a.s.l., the vegetation is subalpine coniferous forest, with *Pinus*, *Abies*, *Picea*, and *Tsuga chiensis*. The understory includes *Fargesia spathacea*, *Lespedeza bicolor*, and other shrubs, as well as numerous ferns [20,21]. Bogs and peat deposits are widely distributed in the lake basin, and many aquatic and wetland plants occur, such as *Carex argyi*, *Sanguisorba*, *Juncus effuses*, *Festuca rubra*, and *Sphagnum palustre* [22].

3. Materials and Methods

3.1. Core Acquisition

In July 2006, sediment sampling was conducted at the depocenter of Dajiuhu Lake using a drill rig with casing. Sediment cores were extracted to a maximum depth of 43.6 m and designated as DJH-2 (31°29′28″ N, 109°59′40″ E) (Figure 1). The sediment recovery rate was greater than 95%. The sediments of the core mainly contained clay and peat, which deposits in a lacustrine sedimentary environment.

3.2. Chronology

The determination of the chronostratigraphic sequence of the core was based on accelerator mass spectrometry (AMS) $^{14}$C dating [23] and amino acid racemization (AAR) dating [24–26]. The AMS$^{14}$C dating was conducted at the Keck Carbon Cycle AMS facility at the University of California, Irvine (KCCAMS/UCI). The AMS$^{14}$C ages were corrected to calendar years using the tree ring curve and OxCal program (version 4.1 online, https://c14.arch.ox.ac.uk/oxcal.html, accessed on 25 April 2021). The AAR dating was conducted in the Chromatography Laboratory, College of Life Sciences, Nanjing Normal University. A total of 10 samples collected from peat or organic-rich horizons of the upper 545 cm were used for AMS$^{14}$C dating. In addition, 5 samples were collected from organic-rich horizons below the depth of 545 cm for AAR dating. AAR dating is a method of determining the geological age using the racemization of residual amino acids in geological bodies (such as fossils). If the sample is not selected properly, it will directly affect the reliability of the age data. Most areas of the Dajiuhu Basin are in a marsh sedimentary environment, and plants are often buried quickly after death, and then forming peat in a marsh hypoxia environment. In this study, the layers with high content of peat or organic matter and plant residue samples were selected to ensure the reliability of the dating age. The sedimentation rate and the dating of the core indicated that the onset of this section of core DJH-2 occurred at ~237.9 ka [27,28]. A detailed chronological framework was established for regional paleovegetation research. The results for all of the dating samples are listed in Table 1.
### Table 1. Dating results for samples from the core DJH-2.

| Depth (cm) | Dating Method | Age (cal. Year B.P.) |
|------------|---------------|---------------------|
| 33         | AMS$^{14}$C   | 1115 ± 37           |
| 51         | AMS$^{14}$C   | 1635 ± 9            |
| 83         | AMS$^{14}$C   | 2600 ± 20           |
| 99         | AMS$^{14}$C   | 3300 ± 37           |
| 117        | AMS$^{14}$C   | 3865 ± 53           |
| 144        | AMS$^{14}$C   | 7410 ± 35           |
| 270        | AMS$^{14}$C   | 16,650 ± 80         |
| 396        | AMS$^{14}$C   | 23,730 ± 80         |
| 517        | AMS$^{14}$C   | 35,790 ± 300        |
| 545        | AMS$^{14}$C   | 39,140 ± 350        |
| 560        | AAR           | 40,935              |
| 573.8      | AAR           | 83,209              |
| 729.1      | AAR           | 53,441              |
| 1030.1     | AAR           | 75,737              |
| 3110.6     | AAR           | 191,005             |

3.3. Sample Processing and Analysis

The core sections were split, photographed, and described, and then cut into segments at 2–13 cm intervals. The particle size analysis was performed using a Malvern Mastersizer 2000 laser particle size analyzer. A total of 2096 samples were used for grain-size analysis. The sediments of core DJH-2 were divided into 3 grades: clay (<4 $\mu$m, 8 phi), fine silt (4–16 $\mu$m, 8–6 phi), and silt (16–63 $\mu$m, 6–4 phi) according to grain size [29]. Samples were sequentially treated with H$_2$O$_2$ and HCl to remove organic matter and carbonates, respectively, and grain-size frequency distributions were measured with a laser particle analyzer. The measurements were made at the Academy of Geographical Sciences, Nanjing Normal University. Pollen analysis was conducted on 362 samples with intervals of about 12 cm, which were pretreated using a modified HCl–NaOH–HF procedures [30]. Pollen identifications were made in the Institute of Northeast Geography and Agricultural Ecology, Chinese Academy of Sciences. Pollen was mounted in glycerin and counted under the light microscope with $\times$400 magnification. For most samples, more than 300 pollen grains were counted. The identification of pollen grains was performed using the Pollen Flora of China [31] and An Illustrated Handbook of Quaternary Pollen and Spores in China [32], together with the use of the modern pollen reference collection (Environmental Archaeology Laboratory of Hebei Normal University).

4. Results

4.1. Lithology

The core can be divided into the following five sedimentary units: 43.6–37.0 m: sand and gravel layers; most gravels are angular, with average diameters of ~2–20 mm, and a maximum of ~80 mm, which shows a decreasing trend from bottom to top. It is interpreted as a pluvial fan (a fan-like accumulation terrain that is formed after a temporary or seasonal river rushes out of the mountain pass) environment. 37.0–29.4 m: alternating layers of gray silty clay and peat, interpreted as a lacustrine sedimentary environment. 29.4–14.9 m: gray and yellow-gray clay or silty clay with occasional gravel layers (average diameters of ~1–3 mm with a maximum of 30 mm); interpreted as shallow water faces. 14.9–2.3 m: alternating gray silty clay and peat, with occasional angular gravels with average diameters of ~6–7 mm and a maximum of 20 mm; interpreted as a lacustrine sedimentary environment. 2.3–0 m: peat, deposited within a lacustrine sedimentary environment.

4.2. Environmental Implications of the Grain-Size Record

The Dajiuhu Basin is located in a typical East Asian monsoon-dominated region, where precipitation is regarded as one of the best proxies for summer monsoon intensity [33–35], and it has been widely used in studies of both the modern summer monsoon and the paleo-
monsoon [36–41]. The grain size of the clastic component of loess and aquatic sediments is widely used to gain insights into hydrological activity within the catchment [42,43]. The Dajiuhu has no inflowing or outflowing rivers, and is fed by precipitation and the stream from the surrounding mountains. In humid regions, the grain size of clastic material is mainly affected by variations in slope flow intensity, with coarser particles primarily reflecting high rainfall [44,45]. The greater the hydrodynamic force, the stronger the carrying capacity of coarse particles. High content of clay indicates stable sedimentary environment and weak hydrodynamic conditions. Depth plots of various grain-size fractions of the core DJH-2 are shown in Figure 2, and the grain-size characteristic of specific intervals of the core are described below.

![Depth plot of various grain-size components of core DJH-2](image)

**Figure 2.** Depth plot of various grain-size components of core DJH-2. Data points with stars in front of them are the time interval of MIS 5 boundaries adjusted with the 250 ka interval of the stalagmites δ¹⁸O in Sanbao Cave. MZ: median grain size.

43.6–31.1 m (237.9–191.0 ka). The proportion of the 4–16 μm fraction decreased, and that of the fraction >16 μm increased sharply and fluctuated frequently. The median grain size (MZ) ranged from 6.2 to 47.6 μm, and the average was 11.4 μm.

31.1–14.9 m (191.0–130.0 ka). The proportion of the 4–16 μm fraction increased and maintained high values and the proportion of the >16 μm fraction decreased. The median grain size (MZ) ranged from 6.8 to 52.5 μm, and the average was 11.7 μm.

14.9–7 m (130.0–71.0 ka). The proportion of 4–16 μm fraction first decreased and then increased, while that of the fraction >16 μm first increased and then decreased. The median grain size (MZ) ranged from 7.3 to 35.8 μm, and the average was 15.3 μm.

7.0–2.3 m (71.0–13.8 ka). Both the 4–16 μm and >16 μm fractions fluctuated frequently but exhibited trends of decreasing, increasing, and then decreasing values. The median grain size (MZ) ranged from 8.0 to 40.6 μm, and the average was 14.2 μm.

2.3–0.3 m (13.8–1.0 ka). The proportion of the 4–16 μm fraction decreased, and that of the fraction >16 μm increased. The median grain size (MZ) ranged from 10.1 to 53.9 μm, the average was 19.5 μm.
4.3. Pollen Source Area and Vegetation Implications of the Pollen Assemblages from Dajiuhu Lake

Within the 362 pollen samples analyzed, 126 taxa were identified. Tree and shrub pollen types included *Abies*, *Picea*, *Pinus*, *Acer*, *Tsuga*, *Betula*, *Carpinus*, *Corylus*, *Fagus*, deciduous *Quercus* (*Quercus* (D)), *Juglans*, *Pterocarya*, *Ulmus*, evergreen *Quercus* (*Quercus* (E)), *Rhus orientalis*, *Euphorbia*, and *Sapium*. Herbaceous pollen types included *Cyperaceae*, *Asteraceae*, *Poaceae*, and *Ranunculaceae*. Aquatic hygrophyte pollen types included *Cyperaceae*, *Typhaceae*, *Myriophyllum*, and *Potamogeton*. Fern spores included *Loxogrammae*, *Polypodiaceae*, and *Humata*.

Dajiuhu is a closed alpine lake, and we inferred that pollen is transported to the lake from different vegetation zones on different altitudes surrounding the Dajiuhu Basin. According to the distribution of modern vegetation and its composition in the study area, we combined the major pollen types into three ecological groups: (1) Coniferous forest, consisting of, e.g., *Pinus*, *Picea*, and *Abies*, which are often used as indicators of a cold environment. (2) Broadleaved forest comprising *Betula*, *Carpinus*, *Corylus*, etc., and warm-and-humid broadleaved forest such as *Quercus* (E), *Euphorbia*, *Fagus*, *Pterocarya*, and *Sapium*. Warm-and-humid broadleaved forest was used as indicators of a warm and humid paleoenvironment. *Quercus* (E) belongs to subtropical broadleaved trees, whereas *Carpinus* belongs to temperate broadleaved trees. If *Carpinus* appears in the place of *Quercus* (E), it indicates that the climate is getting colder. (3) Subalpine meadow, dominated by *Artemisia*, *Chenopodiaceae*, *Asteraceae*, *Poaceae*, *Sanguisorba*, and *Cyperaceae*. The pollen diagram for core DJH-2 is shown in Figure 3, and a detailed description of the pollen zones is given in the Supplementary Materials.

The modern vertical vegetation distribution surrounding the Dajiuhu Basin suggests that broadleaved forest, coniferous forest, subalpine meadow with increasing of elevation, and the basal vegetation zone are occupied by broadleaved forest. As the climate warms up, the content of broadleaved trees in vegetation assemblage will increase. As the climate cools down, the content of coniferous trees will increase, with the tree line moving down.
According to the grain size records and pollen assemblage characteristics of core DJH-2 (see Supplementary Materials), we were able to divide the evolution of the vegetation and climate of the study area into five periods, which are equivalent to the pollen zones described in the Supplementary Material; these areas are summarized below.

Zone I (43.6–31.1 m, 237.9–191.0 ka). The percentage of coniferous trees was highest (average 22.6%) in the record. The average percentage of warm-and-humid broadleaved tree pollen was 15.2%. There were secondary fluctuations within the zone. At 43.6–35.5 m, the coniferous trees such as *Picea* (average 12.3%) and *Abies* (average 9.7%) were abundant. Moreover, the percentages of herbaceous types such as A+C (*Artemisia*+Chenopodiaceae, average 3.5%) and Asteraceae (average 7.1%) were high. At 35.5–31.1 m, *Picea* (average 6.3%) and *Abies* (average 4.1%) decreased sharply. Meanwhile, the A+C (average 1.1%) and Asteraceae (average 0.9%) decreased sharply. However, the warm-and-humid broadleaved trees such as *Quercus* (E) (average 7.7%) and *Fagus* (average 6.9%) were increased.

Zone II (31.1–14.9 m, 191.0–130.0 ka). The percentage of coniferous trees (average 18.5%) increased, and that of the warm-and-humid broadleaved trees (average 14%) decreased substantially.

Zone III (14.9–7.0 m, 130.0–71.0 ka). The percentage of coniferous trees (average 9.8%) decreased substantially, and that of warm-and-humid broadleaved trees (average 17.5%) increased sharply. There were secondary fluctuations within the zone. At 14.9–8.4 m, the coniferous trees such as *Picea* (average 4.1%) and *Abies* (average 3.8%) were higher. The warm-and-humid broadleaved trees such as *Quercus* (E) (average 5.5%), *Fagus* (average 4.5%), and *Euphorbia* (average 2.1%) were lower. At 8.4–7.0 m, the *Picea* (average 1.4%) and *Abies* (average 1.7%) decreased slightly. However, the *Quercus* (E) (average 11.4%), *Fagus* (average 7.6%), and *Euphorbia* (average 4.3%) were increased.

Zone IV (7.0–2.3 m, 71.0–13.8 ka). The percentage of coniferous taxa (average 14.1%) increased and that of warm-and-humid broadleaved taxa (average 12.8%) decreased slightly.

Zone V (2.3–0.3 m, 13.8–1.0 ka). The tree pollen representation reached its highest level within the core, and that of warm-and-humid broadleaved trees (average 31%) was also the highest; however, the percentage of coniferous trees (average 2.2%) was the lowest in this zone.

5. Discussion

5.1. Climate and Environmental Change within the Dajiuhu Basin since the Late Middle Pleistocene

According to the stalagmite δ¹⁸O record of Sanbao Cave [10,18], in the same area, together with the dating results for core DJH-2, we found that there was a close correspondence between the variations in the pollen record in core DJH-2 and the glacial and interglacial period for the last 240 ka. The grain-size record and pollen assemblages of core DJH-2 indicated that the environmental evolution of Dajiuhu Basin during the studied intervals underwent the following series of changes.

Period I (237.9–191.0 ka, 43.6–31.1 m). On the basis of the AAR dating, we found that this interval corresponded to MIS 7 (MIS, marine isotope stages). The median grain size (MZ) and the content of the fraction >16 µm increased substantially, which indicated increased precipitation and runoff; this indicated that the East Asian summer monsoon was stronger, which in turn led to a rise in lake level and an increase in hydrodynamic forces. The site was a lacustrine sedimentary environment within which alternating layers of dark gray or black organic clay or peat were deposited. The representation of coniferous trees decreased substantially, while that of warm-and-humid broadleaved trees increased. This indicates that the climate was temperate and wet, and the local vegetation was evergreen and deciduous broadleaved mixed forest.

Period II (191.0–130.0 ka, 31.1–14.9 m). On the basis of the AAR dating, we found that this interval corresponded to MIS 6. The content of the fraction >16 µm decreased substantially, which indicated relatively weak precipitation and runoff; this indicated that the East Asian summer monsoon weakened. The water level of the lake was dropped down, within which gray and yellow-gray clay or silty clay was deposited, with occasional
gravel layers. The tree pollen representation decreased substantially, and the pollen spectra were dominated by coniferous tree taxa; there were increases in *Artemisia*, Chenopodiaceae, and Cyperaceae. This suggests that vegetation landscape was dominated by coniferous forest with alpine meadow developed in some area.

**Period III** (130.0–71.0 ka, 14.9–7.0 m). This interval corresponded roughly to MIS 5. The median grain size (MZ) and the content of the fraction >16 µm fluctuated frequently but remained at an overall high level. These changes indicated fluctuations in precipitation and runoff, which indicated that there was an increase in the strength of the East Asian summer monsoon and hence in precipitation. The site was a lacustrine sedimentary environment within which alternating layers of gray silty clay and peat were deposited, as well as occasionally angular gravel. The representation of coniferous trees decreased substantially while that of warm-and-humid broadleaved trees increased, which indicates that the climate was temperate and wet. These vegetation characteristics showed that the climate of the Dajiuhu Basin had entered an interglacial period and that the landscape was occupied by evergreen and deciduous broadleaved forest.

**Period IV** (71.0–13.8 ka, 7.0–2.3 m). This interval corresponded approximately to MIS 4–2. The median grain size (MZ) and the content of the fraction >16 µm fluctuated frequently, with first an increasing and then a decreasing trend. These changes indicated fluctuations in precipitation and runoff. This indicated that the summer monsoon weakened, strengthened, and then weakened again. The sediments were mainly gray clay, silty clay, and dark organic clay. In the early period, the representation of coniferous tree taxa was high, and that of warm-and-humid broadleaved tree taxa was low. Steppe vegetation (e.g., Chenopodiaceae and *Artemisia*) predominated in the mountain foothills. These vegetation characteristics showed that the climate of the Dajiuhu Basin had entered a glacial period, and the vegetation was coniferous forest with mountain meadow. In the middle part, the vegetation changed substantially to broadleaved deciduous forest dominated by *Fagus* and *Quercus* (E), which indicated a substantial rise in temperature. In the late period, broadleaved forest was replaced by coniferous and broadleaved mixed forest.

**Period V** (13.8–1.0 ka, 2.3–0.3 m). This interval corresponded to MIS 1. The median grain size (MZ) and the content of the fraction >16 µm increased substantially, which indicated increased precipitation and runoff; this indicated that the East Asian summer monsoon strengthened. The site was a lacustrine sedimentary environment within which peat and clay were deposited. The content of coniferous trees was the lowest. There was a rapid increase in evergreen and deciduous broadleaved forest, indicating a substantial rise in temperature.

5.2. Regional Vegetation Contrasted between Different Interglacial Periods

In Figure 4, selected indexes from core DJH-2 (coniferous trees, warm-and-humid broadleaved trees) and the median grain size (MZ) are compared with various paleoclimatic records from different latitudes. During MIS 7, MIS 5e, and MIS 1, the magnetic susceptibility of Lake El'gygytgyn [46], the magnetic susceptibility of Xifeng section [47], and $^{10}$Be rainfall record of Chinese loess [48] increased substantially, indicating that the East Asian Monsoon strengthened and that the climate was warm and wet. The $^{18}$O record of plankton in the South China Sea [49] and the stalagmite $^{18}$O record of Sanbao Cave was low, also showing that the climate warmed during these periods. The grain size record of Dajiuhu Lake indicated that the depositional environment during these periods was wetland with peat accumulation. The median grain size (MZ) and the representation of warm-and-humid broadleaved forest in core DJH-2 also suggested that climate was warm and wet at these times. The proportion of warm-and-humid broadleaved trees increased substantially, confirming that the climate in the Dajiuhu area was warm and wet, which is consistent with comparable records on a global scale.
The proportion of coniferous trees and warm-and-humid broadleaved trees from core DJH-2 was also compared with the trees and shrubs of the pollen record in Lake El'gygytgyn [50–52] (Figure 5). In Lake El'gygytgyn, the proportion of trees and shrubs also increased during MIS 7, MIS 5, and MIS 1. During MIS 1, the vegetation was characterized by deciduous forest and forest-tundra [50,51]. During MIS 5, the vegetation was dominated by deciduous taxa, with a high percentage of Betula and Alnus pollen [50,51]. During MIS 7, the vegetation was dominated by tundra, which was mainly alder and birch [52].

However, the response of the regional vegetation to climate change during the three interglacials in core DJH-2 was substantially different. During MIS 7 in core DJH-2, the regional vegetation consisted mainly of broadleaved forest with Fagus, Quercus (D), and
Quercus (E), and the proportion of coniferous forest was low. During MIS 5e in core DJH-2, the proportion of subtropical evergreen broadleaved forest, with *Rhus orientalis* and Euphorbiaceae, was greater than during MIS 7, while the amount of *Picea* and *Abies* forest was less than during MIS 7. We speculate that MIS 5e was warmer than MIS 7 in core DJH-2. The magnetic susceptibility of Xifeng section, the $^{10}$Be rainfall record of Chinese loess, and the $\delta^{18}$O record of plankton in the South China Sea also supported this interpretation. However, the magnetic susceptibility of Lake El’gygytgyn and the stalagmite $\delta^{18}$O record of Sanbao Cave during MIS 5e were not warmer than MIS 7. From the perspective of vegetation restoration at Dajiuhu, the pollen representation of broadleaved taxa was greatest during MIS 1, and it appeared that MIS 1 was the warmest and wettest interglacial within the studied interval. In terms of the conditions at the site of core DJH-2, a lacustrine environment was present during MIS 5e, while a wetland environment occurred during MIS 1. Since MIS 1, the pollen record of core DJH-2 indicated that a large amount of evergreen and deciduous broadleaved mixed forest had developed within the Dajiuhu Basin, which is the equivalent of the lowermost vegetation zone within the surrounding mountains. Thus, there would have been more broadleaved trees pollens entering Dajiuhu at this period.

5.3. Origin of the Observed Vegetation and Climate Changes within the Dajiuhu Basin

The record of the development of coniferous and warm-and-humid broadleaved forest in the Dajiuhu Basin is consistent with the stalagmite $\delta^{18}$O record of Sanbao Cave in the same area, the variations of which are closely related to changes in Northern Hemisphere insolation (21 July at 65° N) [53], which in turn are directly related to precession (Figure 4). When insolation was high, coniferous forest was poorly represented in the Dajiuhu Basin, while warm-and-humid broadleaved forest was well represented, and vice versa (Figure 4). An important feature of the pollen record from the Dajiuhu Basin is the occurrence of ~20-kyr precessional cycles in the vegetation record, which are clearly evident in the record of the percentages of warm-and-humid broadleaved trees in core DJH-2 (Figure 4g). The east–west-oriented mountain ranges (>1500 m a.s.l.) between South and North China tend to block the northward movement of near-ground airflows, and thus strong summer monsoon could cross the mountains during interglacial periods. During glacial periods, when the sea level was low and Northern Hemisphere ice volume was large, the Northern boundary of ITCZ (intertropical convergence zone) lay more south, and the East Asian Monsoon was too weak to cross the Qinling Mountains at these times. For these reasons, North China was beyond the northern limit of the summer monsoon during glacial periods; in contrast, however, the stronger summer monsoon during interglacial periods was able to reach North China. Thus, the paleoclimatic records from the region south of the Qinling Mountains, where the Dajiuhu Basin is located, exhibit a dominant 20-kyr precessional cyclicity, while in contrast the summer monsoon records from North China primarily show a cyclicity similar to that of ice volume variations.

6. Conclusions

(1) A ~240 kyr pollen record from the sediments of Dajiuhu Lake in Hubei Province indicates the occurrence of major fluctuations in the proportions of coniferous and warm-and-humid broadleaved forest. The fluctuations are consistent with the stalagmite $\delta^{18}$O record from Sanbao Cave in the same area, which are closely related to changes in precession-driven Northern Hemisphere insolation.

(2) The cyclicity of the East Asian summer monsoon evident in records from south of the Qinling Mountains is mainly controlled by precession, via a direct response to insolation at the precessional (~20-kyr) scale in the Northern Hemisphere. The difference between paleoclimatic records from North and South China is closely related to the east–west-oriented mountain ranges in central China that block the movement of near-ground airflows; thus, strong summer monsoon could cross the mountains during interglacial periods. During glacial periods, when the sea level
was low and Northern Hemisphere ice volume was large, the Northern boundary of ITCZ lay more south, and the East Asian Monsoon was too weak to cross the Qinling Mountains at these times.

(3) There were differences in the vegetation composition of the Dajiuhu Basin during the interglacial maxima of MIS 7, MIS 5e, and MIS 1. The extent of warm-and-humid broadleaved forest during the Holocene indicated peak conditions of warm and humid compared to the previous interglacial periods. During the Holocene, the Dajiuhu Basin was occupied by evergreen and deciduous broadleaved mixed forest, similar to the composition of the lowermost vegetation zone within the surrounding mountains.

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References
1. An, Z.; Wu, X.; Wang, P.; Wang, S.; Dong, G.; Sun, X.; Zhang, D.; Lu, Y.C.; Zheng, S.H.; Zhao, S.L. Paleomonsoons of China over the last 130,000 years—Paleomonsoon variation. Sci. China B 1991, 34, 1007–1015.
2. An, Z.S. The history and variability of the East Asian paleomonsoon climate. Quat. Sci. Rev. 2000, 19, 171–187. [CrossRef]
3. Chen, F.; Xu, Q.; Chen, J.; Birks, H.J.B.; Liu, J.; Zhang, S.; Jin, L.; An, C.; Telford, R.J.; Cao, X.; et al. East Asian summer monsoon precipitation variability since the last deglaciation. Sci. Rep. 2015, 5, 11186. [CrossRef]
4. Cheng, H.; Edwards, R.L.; Broecker, W.S.; Denton, G.H.; Kong, X.; Wang, Y.; Zhang, R.; Wang, X. Ice age terminations. Science 2009, 326, 248–252. [CrossRef]
5. Ding, Z.L.; Yang, S.L.; Sun, J.M.; Liu, T.S. Iron geochemistry of loess and red clay deposits in the Chinese Loess Plateau and implications for long-term Asian monsoon evolution in the last 7.0 Ma. Earth Planet. Sci. Lett. 2001, 185, 234–245. [CrossRef]
6. Wang, P.X. Global monsoon in a geological perspective. Chin. Sci. Bull. 2009, 54, 1113–1136. [CrossRef]
7. Wang, Y.J.; Cheng, H.; Edwards, R.L.; An, Z.S.; Wu, J.Y.; Shen, C.-C.; Dorale, J.A. A high-resolution absolute-dated Late Pleistocene monsoon record from Hulu Cave, China. Science 2001, 294, 2345–2348. [CrossRef]
8. Wang, P.; Clemens, S.; Beaufort, L.; Braconnot, P.; Ganssen, G.; Jian, Z.; Knies, P.; Sarnthein, M. Evolution and variability of the Asian monsoon system: State of the art and outstanding issues. Quat. Sci. Rev. 2005, 24, 595–629. [CrossRef]
9. Wang, Y.; Cheng, H.; Edwards, R.L.; He, Y.; Kong, X.; An, Z.; Wu, J.; Kelly, M.J.; Dykoski, C.A.; Li, X. The Holocene Asian monsoon: Links to solar changes and North Atlantic climate. Science 2005, 308, 854–857. [CrossRef] [PubMed]
10. Wang, Y.; Cheng, H.; Edwards, R.L.; Kong, X.; Shao, X.; Chen, S.; Wu, J.; Jiang, X.; Wang, X.; An, Z. Millennial-and orbital-scale changes in the East Asian monsoon over the past 224,000 years. Nature 2008, 7182, 1090–1093. [CrossRef]
11. Yuan, D.; Cheng, H.; Edwards, R.L.; Dykoski, C.A.; Kelly, M.J.; Zhang, M.; Qin, J.; Lin, Y.; Wang, Y.; Wu, J.; et al. Timing, duration, and transitions of the Last Interglacial Asian Monsoon. Science 2004, 304, 575–578. [CrossRef]
12. Cao, X.Y.; Ni, J.; Herzschuh, U.; Wang, Y.B.; Zhao, Y. A late Quaternary pollen dataset from eastern continental Asia for vegetation and climate reconstructions: Setup and evaluation. Rev. Palaeobot. Palynol. 2013, 194, 21–37. [CrossRef]
13. Ran, M.; Feng, Z. Holocene moisture variations across China and driving mechanisms: A synthesis of climate records. Quat. Int. 2013, 313–314, 179–193. [CrossRef]
45. Chen, J.A.; Wang, G.J.; Zhang, D.D. Environmental records of lacustrine sediments in different time scales: Sediment grain size as an example. *Sci. China Ser. D Earth Sci.* **2004**, *47*, 954–960. [CrossRef]

46. Melles, M.; Brigham-Grette, J.; Minyuk, P.S.; Nowaczyk, N.R.; Wennrich, V.; DeConto, R.M.; Anderson, P.M.; Andreev, A.A.; Coletti, A.; Cook, T.L.; et al. 2.8 Million Years of Arctic Climate Change from Lake El'gygytgyn, NE Russia. *Science* **2012**, *337*, 315–320. [CrossRef]

47. Guo, Z.T.; Berger, A.; Yin, Q.Z.; Qin, L. Strong asymmetry of hemispheric climate during MIS-13 inferred from correlating China loess and Antarctica ice records. *Clim. Past* **2009**, *5*, 21–31. [CrossRef]

48. Beck, J.W.; Zhou, W.; Li, C.; Wu, Z.; White, L.; Xian, F.; Kong, X.; An, Z. A 550,000-year record of East Asian monsoon rainfall from 10Be in loess. *Science* **2018**, *360*, 877–881. [CrossRef] [PubMed]

49. Caballero-Gill, R.P.; Clemens, S.C.; Prell, W.L. Direct correlation of Chinese speleothem δ¹⁸O and South China Sea planktonic δ¹³C: Transferring a speleothem chronology to the benthic marine chronology. *Paleoceanogr. Paleoclimatology* **2012**, *27*, 2203.

50. Lozhkin, A.V.; Anderson, P.M.; Matrosova, T.V.; Minyuk, P.S. The pollen record from El’gygytgyn Lake: Implications for vegetation and climate histories of northern Chukotka since the late middle Pleistocene. *J. Paleolimnol.* **2007**, *37*, 135–153. [CrossRef]

51. Lozhkin, A.V.; Anderson, P.M. Vegetation responses to interglacial warming in the Arctic, examples from Lake El’gygytgyn, northeast Siberia. *Clim. Past Discuss.* **2013**, *9*, 245–267.

52. Zhao, W.; Andreev, A.A.; Tarasov, P.E.; Wennrich, V.; Melles, M. Vegetation and climate during the penultimate interglacial of the northeastern Russian Arctic: The Lake El’gygytgyn pollen record. *Boreas* **2019**, *48*, 507. [CrossRef]

53. Berger, A.; Loutre, M.F. Insolation values for the climate of the last 10 million years. *Quat. Sci. Rev.* **1991**, *10*, 297–317. [CrossRef]