RETRACTED ARTICLE: Organic carbon isotope record since the Late Glacial period from peat in the North Bank of the Yangtze River, China

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ABSTRACT

Detailed organic carbon isotope (δ13Corg) measurements were conducted on two peat sequences recovered from the north bank of the Yangtze River, East China. Seven radiocarbon dates provided firm age control of this δ13Corg record and reveal palaeoclimatic changes since the Late Glacial period. The results show that the Holocene Megathermal Maximum occurred between 8385 and 7040 cal. yr BP. The Late Glacial climate was generally cold but fluctuated frequently between 12940 and 11815 cal. yr BP. The Older Dryas (from 12940 to 12810 cal. yr BP) and the Younger Dryas (from 12645 to 12170 cal. yr BP) were characterised by cold climate conditions. In contrast, 12810 to 12645 cal. yr BP (corresponding to the Allerød Warm Period) and 12170 to 11815 cal. yr BP (corresponding to a rapid warming period after the Younger Dryas, marking the beginning of the Holocene) were relatively warm phases. In contrast to other high-resolution records, it shows that the δ13Corg records of our study peats are largely controlled by a common forcing mechanism of solar insolation changes in the Northern Hemisphere, and exhibit similar variability to δ18O records obtained from stalagmites and GISP2 during the Late Glacial and early-mid Holocene.

Introduction

Peat is a soft organism accumulation that is mainly composed of vegetable organic matter (Rao et al. (2019)). It is generated under some swampy climatic and hydrologic conditions. Typically, peat occurs when dead plant remnants accumulate on a swamp surface over hundreds to thousands of years. Therefore, copious information about climatic changes is stored in this special natural complex (Zhang et al. (2016), Magnan et al. (2018)). Specifically, δ13C measurements of organic carbon reflect the relative contribution of plant species to peat in a given area. These measurements have been utilised to document vegetation history and climate change (Zheng et al. (2018), Zhang et al. (2018)). Recently, with the extensive use of isotopic analytical techniques, organic carbon isotope (δ13Corg) records in peat have been used to report palaeoclimatic changes (Hong et al. (2005), Yamamoto et al. (2010)). These reports show that peat δ13Corg values are a good source of information about the palaeoclimate.

In this paper, we report δ13Corg analyses of palaeoclimatic changes in two peat layers from the north bank of the Yangtze River. Previous studies of pollen, grain-size and geochemistry have been conducted on environmental changes (Shi et al. (2007), Zhu et al. (2014)). Our results indicate that the peat is an ideal material for studying climate change since the Late Glacial period.

Materials and methods

Sampling site

The Linfengqiao profile is in the second terrace of the Yangtze River (Figure 1), located at approximately 32°09′ 13″N, 118°41′23″E. It is located within the Dongmen Town of Nanjing, 4 km north of the Nanjing Yangtze River Bridge. The elevation is approximately 10 m above sea level. The section is well exposed along the north bank due to long-term incision of streams containing carbonised woods and spring-deposited tufa. The thickness of the Linfengqiao profile is approximately 4.68 m, and can be subdivided into 15 layers from bottom to top (Figure 2). Field investigations indicate that there are two peat layers within the Linfengqiao profile. Between these two peat layers, horizons of yellowish coarse sand and gravel mixed with carbonised wood are repeatedly sandwiched with dark clay layers. The top of this profile is overlaid by late Holocene secondary loess, while the gravel is a local Cretaceous conglomerate. The carbonised wood is from the trunks of oak trees, which were...
cover the Late Glacial and the early-middle Holocene periods (Shi et al. (2007), Zhu et al. (2014)).

Methodology

Subsamples for $\delta^{13}$C$_{\text{org}}$ analysis were generally taken at 2 cm intervals in both the upper peat layer (the 3rd layer, 158–240 cm) and the lower peat layer (the 15th layer, 392–468 cm) of the Linfengqiao profile. A total of 81 samples were collected, of which 42 samples were obtained from the upper peat layer and 39 samples were obtained from the lower peat layer.

Organic materials in the peat sediments and carbonised wood were used for dating. Seven dates were determined using conventional radiocarbon methodology (i.e., the liquid scintillation counting method) at different depths of the profile. Measurements were made at the State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences (Table 1). Samples that could potentially be contaminated by 14 C-deficient tufa were avoided. The radiocarbon dates were calibrated using the computer calibration program CALIB 6.0.1 Reimer et al. (2009). The range of the calibrated ages is 2σ. The calendar age sequence of the whole profile is acquired by linear interpolation and extrapolation from known dates.

Testing of $\delta^{13}$C$_{\text{org}}$ was finished at State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences. For stable carbon isotopic analysis of organic matter in these peat sediments, visible roots from modern plants were removed. The analysed samples were dried at 50°C for 24 h and passed through an 80 mesh sieve. Then, 1–2 g of powdered sample was treated with HCl (5%) for 24 h at room temperature to remove carbonates. The sample was subsequently brought to pH = 7 with neutral deionised water and then dried at 50°C. Subsamples of approximately 0.1 g were combusted for 5–15 minutes at 800°C in an evacuated sealed quartz tube in the presence of silver foil and cupric oxide. The purified CO$_2$ was then analysed for stable carbon isotopes using a Delta-plus advantage IRMS gas mass spectrometer manufactured by Thermo.

| Lab. No  | Depth (cm) | Materials dated | $14$ C age (yr BP) | 2σ Calibrated age (cal. yr BP) |
|---------|------------|----------------|-------------------|--------------------------------|
| Kf03058 | 150        | Peat           | 5612 ± 179        | 6797–5991                      |
| Kf03056 | 205        | Peat           | 7122 ± 151        | 8214–7662                      |
| ND-9624 | 216        | Carbonized wood| 7560 ± 90         | 8524–8189                      |
| ND-9932 | 240        | Carbonized wood| 7640 ± 210        | 8992–8036                      |
| ND-8812 | 320        | Carbonized wood| 8200 ± 126        | 9477–8850                      |
| Kf03057 | 401        | Peat           | 10497 ± 261       | 12893–11398                    |
| Kf03059 | 461        | Peat           | 11109 ± 450       | 13962–11754                    |
Finningan Corporation. Carbon isotopic ratios in samples are expressed in per mil deviations relative to a VPDB standard with a precision better than 0.1‰. A state standard specimen GBW04408 was added to every fifth sample during the experiment. The results of $\delta^{13}$Corg testing are reported in Figure 3.

Results and discussion

Chronology and sedimentation rate

As shown in Figure 3, the calibrated radiocarbon ages are well ordered with no reversal occurring along the sequence. According to the dating results and previous studies (Shi et al. (2007), Zhu et al. (2014)), calculations of sedimentation rates indicate that the upper peat layer formed between 8514 and 6621 cal. yr BP, during the Holocene Megathermal Maximum (7200–6000 cal. yr BP). The lower peat layer was formed between 12941 and 11815 cal. yr BP, corresponding to the Younger Dryas event during the Late Glacial period. Sedimentation rates of the upper peat layer are variable; the fastest portion is 240–216 cm and accumulated at 0.153 cm/yr, while the slowest is 216–205 cm and accumulated at 0.026 cm/yr. In the lower peat layer, there is a consistent sedimentation rate of 0.084 cm/yr (Figure 3). Taken together, the average sedimentation rate of the Linfengqiao profile is 20.8 yr/cm, which meets the requirements of a high-resolution study.

Peat $\delta^{13}$Corg records and palaeoclimate

The two peat layers of the Linfengqiao profile are mainly composed of organic matter from terrestrial plants, which can be divided into C3, C4 and CAM photosynthetic pathways based on differences in discrimination against $^{13}$C (Gong and Zhang (2014), Sun et al. (2014)). C3 plants tend to thrive in areas where sunlight intensity and temperature are moderate and ground water is plentiful, but cannot grow in hot areas. The $\delta^{13}$Corg values of C3 plants range globally from $\sim33$ to $\sim21‰$, averaging around $\sim27‰$. In contrast, C4 plants are adapted to growing in strong sunlight, high temperature and drought areas, and have $\delta^{13}$Corg values between $\sim21$ and $\sim9‰$, with a mean of $\sim14‰$. CAM plants have $\delta^{13}$Corg values similar to C4 plants; however, those with facultative CAM may range from $\sim30$ to $\sim10‰$, depending on the relative amount of carbon fixed by CAM versus C3 photosynthesis. The CAM plants are also adapted to hot and dry areas. Carbon isotopic compositions of peat reflect the carbon isotopic composition of plants growing at the time that organic matter is deposited, and usually have no or a little diagenetic process. Despite minor fractionation that occurs when plant material is decomposed in peat sediments, large contrasts in $\delta^{13}$Corg are preserved and can be used to infer information about past vegetation and environment.

In China, there have been several studies of environmental changes revealed by organic carbon isotopes in peat (Rao et al. (2019), Zhang et al. (2016), Zheng et al. (2018), Zhang et al. (2018), and Hong et al. (2005)). These studies have demonstrated that the $\delta^{13}$Corg value of C3 plants increases in environments featuring higher temperatures and precipitation. This result is consistent with recent studies (Margalef et al. (2014), Turu et al. (2018)). The measurements show that $\delta^{13}$Corg values of the upper peat layer range from $\sim27.70$ to $\sim23.79‰$ with a mean of $\sim26.15‰$. The lower peat layer features $\delta^{13}$Corg values between $\sim29.89$ and $\sim25.90‰$, averaging around $\sim28.42‰$. Thus, it can be seen that both the upper and lower peat layers have low $\delta^{13}$Corg values, suggesting that C3 plants were the main source of organic matter (Gong and Zhang (2014), Sun et al. (2014)). Therefore, $\delta^{13}$Corg values of peat sediments in the Linfengqiao profile are positively correlated to temperature. Comparatively speaking, $\delta^{13}$Corg values of the upper peat layer are higher, which indicates that the temperature of the upper peat formation period was higher than the temperature of the lower peat formation period. This is consistent with the previous hypotheses that the upper peat layer was mainly formed in the warmest and wettest stage of the Holocene Megathermal period, whereas the lower peat layer was formed in the Younger Dryas episode (M Wang et al. (2017), Renssen et al. (2018)).
Figure 4. Comparison of peat δ¹³Corg records in Linfengqiao with other high-resolution δ¹⁸O records obtained from the SB10 stalagmite from Shanbao (Wang et al. (2008)), the H82 stalagmite from Hulu (Wang et al. (2001)), and the Greenland Ice Sheet Project Two (GISP2) core (Stuiver et al. (1995)). Yellow bands indicate the timing and duration of the 8200 cal. yr BP Event and the Younger Dryas. The average number of years per δ¹⁸O analysis is 20 for SB10, 7 for H82, and 20 for GISP2.

Figure 4 illustrates the δ¹³Corg of Linfengqiao peat, as well as the δ¹⁸O of Chinese stalagmites and Greenland Ice as a function of time. The δ¹³Corg records from Linfengqiao peat exhibit similar variability to δ¹⁸O change as the SB10 stalagmite from Shanbao (Wang et al. (2008)), the H82 stalagmite from Hulu (Wang et al. (2001)), and Greenland Ice Sheet Project Two (GISP2) core (Stuiver et al. (1995)) from the Late Glacial and the early to middle Holocene periods. The main climate events are in concert with each other, especially the 8200 cal. yr BP Event and the Younger Dryas. Remarkably, the δ¹³Corg records of Linfengqiao peat feature better synchronous responses to the East Asian monsoon-induced δ¹⁸O changes of the two subtropical stalagmites, which link to solar changes and North Atlantic climate (Wang et al. (2005)). This correlation suggests that δ¹³Corg records of the Linfengqiao peat are largely controlled by a common forcing mechanism of solar insolation in the Northern Hemisphere.

Figure 4a shows the relationship between radiocarbon ages and organic carbon isotopic composition of the upper peat layer of the Linfengqiao profile. Three secondary climate stages can be divided according to the changes of δ¹³Corg values in this phase, indicating that climate fluctuations still occurred during the Holocene Megathermal period. These can be interpreted as follows.

Stage I: 8515–8385 cal. yr BP (240–220 cm). The δ¹³Corg values range between −27.52 and −26.10‰, which are obviously negative, with an average of −26.70‰. This short duration stage showed a relatively cool climatic environment. This stage can be considered to be a low temperature stage in the Holocene Megathermal, correlating with the 8200 cal. yr BP Event (M Wang et al. (2017), Paus et al. (2019)). Previous results of geochemical investigations in the Linfengqiao profile also recorded obvious nadir values of Fe₂O₃/FeO, TFe₂O₃ and Zn contents (Shi et al. (2007), Zhu et al. (2014)), reflecting a drying and cooling climatic process.

Stage II: 8385–7040 cal. yr BP (220–173 cm). Compared with the previous stage, the δ¹³Corg values are significantly increased and range from −26.78 to −23.79‰. These values are relatively positive, with an average value of −25.67‰. This stage experienced relatively long time spans characterised by a warm and humid climate, corresponding to the Holocene Megathermal Maximum. Pollen analysis from contemporary strata of the Longquzhuan Neolithic site indicate a mixed forest landscape dominated by evergreen broad-leaved and deciduous broad-leaved trees as well as grassland on the north bank of the Yangtze River in Gaoyou (Zhu et al. (2000)). In addition, woody plants such as Cyclobalanopsis, Quercus and Liquidambar, and herbs such as Gramineae, Cyperaceae, Artemisia, Polygonaceae, Typha, Ceratopteris and Trapaceae were present. The concentration of herb pollen was quite high with Gramineae as the dominant herb. This result is consistent with our study. However, there were four obvious climatic fluctuations during this stage. A peak δ¹³Corg value occurred at the depth of 176 cm (ca. 7125 cal. yr BP), reflecting a strong warming event at the end of the Holocene Megathermal Maximum (Wu et al. (2017)).

Stage III: 7040–6620 cal. yr BP (173–158 cm). The δ¹³Corg values range between −27.70 and −25.30‰, which are negative, with an average of −26.76‰. Compared with Stage I and Stage II, δ¹³Corg values and durations in Stage III are intermediate, but closer to Stage I. This stage could be considered to be a cooling stage after the Holocene Megathermal Maximum. Geochemical records from this stage indicate a small peak value of SiO₂/Al₂O₃, while all Fe₂O₃/FeO, TFe₂O₃, K₂O and Zn contents show consistently lower values (Shi et al. (2007), Zhu et al. (2014)). The grain-size characteristics of sediment from this stage show that it is primarily composed of sand and silt particles, with relatively small gravel and clay components (L H Zhang et al. (2002)). This indicates a dry and cold climate and a corresponding landscape with less surface runoff and small sedimentary dynamics. The pollen assemblages of the middle-upper strata (6300–5500 cal. yr BP by 14C dating) in the Longquzhuan profile are characterised by a substantial reduction in pollen quantities and species. There is no evidence of some pollen species such as Ceratopteris, Trapaceae, Cyclobalanopsis, Liquidambar and Cyperaceae in this stage (Zhu et al. (2000)), indicating that climate transformed gradually into an arid and cool pattern during this time. Palynological evidence in the Zhenjiang region demonstrates that the minimum value of Quercus and Pinaceae occurred in this stage and that the temperature dropped approximately 1–2°C (Xu and Zhu (1984)).

Figure 4b shows the relationship between radiocarbon ages and organic carbon isotopic composition
of the lower peat layer of the Linfengqiao profile. Four secondary climate stages can be detected by changes in δ\(^{13}\)C\(_{\text{org}}\) values in this phase. This indicates great fluctuations in Late Glacial climate, as marked by repeated abrupt events at millennial time scales. These fluctuations can be interpreted as follows.

Stage I: 12940–12810 cal. yr BP (468–457 cm). The δ\(^{13}\)C\(_{\text{org}}\) values range between −29.67 and −27.89‰, which are relatively negative with an average of −28.91‰. This was a low temperature stage, which roughly corresponded to the late Older Dryas stadial.

Stage II: 12810–12645 cal. yr BP (457–443 cm). The δ\(^{13}\)C\(_{\text{org}}\) values increase quickly and range between −28.13 and −26.11‰, which are obviously positive, with a mean of −27.01‰. This time interval can be considered to be a significant warming stage after the Older Dryas, corresponding to the Allerød event (Kelly and Passchier (2018), Gautam et al. (2019)). The pollen records in the desert-loess transition zone indicate that precipitation and humidity increased gradually during this time, and pollen species and deciduous broad-leaved trees such as *Betula* and *Corylus* as well as some aquatic herbs were common. However, terraneous herbs such as *Artemisia* and Chenopodiaceae were the dominant species during this stage (J Zhang et al. (2019), Camuera et al. (2019)). This relatively warm and humid climate prevailed in much of China during this time (Fan et al. (2019)).

Stage III: 12645–12170 cal. yr BP (443–403 cm). The δ\(^{13}\)C\(_{\text{org}}\) values range between −29.89 and −27.98‰, which are negative, with an average of −29.00‰. This indicates a low temperature climate. This time interval corresponding to the Younger Dryas, but featuring a short duration compared to other regions (Yuan et al. (2004)). The pollen assemblage of the contemporaneous strata (10850 ± 200–10380 ± 270 cal. yr BP by 14 C dating) indicates a savannah and coniferous forest grassland and cold-dry climate in the Zhenjiang area (Xiong et al. (2010)). The mean annual temperature at that time was 6.0–8.4°C lower than present day (M Wang et al. (2017), Renssen et al. (2018)).

Stage IV: 12170–11815 cal. yr BP (403–392 cm). The δ\(^{13}\)C\(_{\text{org}}\) values range between −28.92 and −25.90‰, with a single peak identified, indicating that a rapid warming process followed the Younger Dryas. This change marked the beginning of the Holocene, and also indicates that there was a rapid climatic conversion between the end of the Younger Dryas and the Holocene Optimum (X Wang et al. (2018), Pearce et al. (2014), Azharuddin et al. (2017), and L. Wang et al. (2018)).

**Conclusion**

The peat δ\(^{13}\)C\(_{\text{org}}\) records since the Late Glacial period derived from the north bank of the Yangtze River indicate that there were two obvious periods of peat formation. One period was from 12940–11815 cal. yr BP and the other was from 8515–6620 cal. yr BP. However, climate conditions during these two periods were very different. The upper peat layer was formed during the Holocene Megathermal Maximum, which was marked by a stable warm and moist climate. In contrast, the lower peat layer was formed around the Younger Dryas. Because the climate during the time of the upper peat formation period was significantly warmer than the climate during the lower peat formation period, it follows that peat formation is not entirely dependent on climate.

The δ\(^{13}\)C\(_{\text{org}}\) records of the upper peat layer indicate that the Holocene Megathermal Maximum occurred between 8385 and 7040 cal. yr BP in the Nanjing area. Before and after this phase, there were some microthermal climate fluctuations of relatively short duration in the background of an overall warm and moist climate. At least three variations in temperature have been identified during the formation period of the upper peat layer, especially some secondary temperature fluctuations between 8385 and 7040 cal. yr BP.

The δ\(^{13}\)C\(_{\text{org}}\) records of the lower peat layer indicate that the climate during the Late Glacial period was mostly cold, but fluctuated frequently between 12940 and 11815 cal. yr BP. The periods of 12940–12810 cal. yr BP and 12645–12170 cal. yr BP, corresponding to the Older Dryas and the Younger Dryas, respectively, were characterised by cold climate conditions. In contrast, 12810–12645 cal. yr BP (corresponding to the Allerød Warm Period) and 12170–11815 cal. yr BP (corresponding to the distinct warming period after the Younger Dryas, which marked the beginning of the Holocene) were relatively warm phases.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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