Precipitation changes recorded in the sedimentary total organic carbon isotopes from Lake Poyang in the Middle and Lower Yangtze River, southern China over the last 1600 years

Xiangzhong Li ^{1*}, Hong Yang², Yuan Yao³, Yuwei Chen⁴, Weiguo Liu ^{1,3}

1. State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, 710061, China

2. Laboratory for Terrestrial Environments, College of Arts and Sciences, Bryant University, USA

3. School of Human Settlement and Civil Engineering, Xi'an Jiaotong University, Xi'an, 710049, China

4. Poyang Lake Lab for Wetland Ecosystem Research, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, China

*Corresponding author:

Li Xiangzhong

Institute of Earth Environment

Chinese Academy of Science

Xi'an, 710061, China

Email: lixiangzhong@ieecas.cn

Abstract: Lake Poyang, the largest freshwater lake of China, is well known for its ecological and hydrological importance as a dynamic wetland and lake system. The climatic change and its effect on ecological and hydrological system of the lake has aroused considerable interest in recent years. So, a sediment core from Lake Poyang was analyzed for $\delta^{13}\text{C}$ total organic matter ($\delta^{13}\text{C}_{\text{org}}$) to study the hydrological changes in the Lake Poyang catchment. By comparing with modern meteorological data (precipitation and temperature) and hydrological data (volume of runoff), the result showed that the $\delta^{13}\text{C}_{\text{org}}$ values in the sediment are negatively correlated with the total runoff of the 5 main rivers supplying water to Lake Poyang and precipitation in this area over the past 50 years. Therefore, the $\delta^{13}\text{C}_{\text{org}}$ values of the Lake Poyang sediment can serve as reliable proxies for reconstruction of river discharge and regional precipitation, with negative $\delta^{13}\text{C}_{\text{org}}$ values representing increased precipitation in the Lake Poyang area. On this basis, the river discharge and regional precipitation variation in the Lake Poyang catchment over the past 1600 years were discussed. The $\delta^{13}\text{C}_{\text{org}}$ values suggest that the precipitation was highest in the period 340-880 AD, and then decreased with fluctuations to the minimum at approximately 1110 AD. During the period of Medieval Warm Period (1110-1350 AD, MWP), the precipitation was generally in the high level except low amount during period of 1140 AD to 1220AD. The precipitation was in low amount during the Little Ice Age (1350-1620 AD, LIA), except for a sudden increase at approximately 1550-1560 AD. The precipitation continuously increased with little fluctuation from 1610 AD until now. In general, changes in regional precipitation and river discharge were dominated by variations in the Asian Summer Monsoon (ASM) precipitation in the Lake Poyang area, consistent with other records from the ASM-controlled areas of China.

Keywords: Precipitation, total organic matters, $\delta^{13}\text{C}_{\text{org}}$, Asian Summer Monsoon, Lake Poyang

1. Introduction

The Middle and Lower Yangtze River is recognized as the cradle for the development of Chinese civilization with a flourishing rice agriculture that is strongly affected by climate change. Frequent flood/drought hazards directly threaten the food security and social stability of this area. Therefore, it is important to improve our understanding of the past and prospective changes in precipitation and to explore their factors to effectively manage water resources under the anticipated global warming in this region on a longer time-scale.

As the largest freshwater lake in China, Lake Poyang in the Middle and Lower Yangtze River, provides resources for local economic development, although multiple stressors from human activities and abiotic factors are imposed on the lake's ecosystem. Since its sensitivity to regional climate change, in recent decades, Lake Poyang has been chosen as an ideal place to investigate regional hydrological changes under climate changes at different time scales (Min and Wang 1992; Jiang and Piperno 1999; Gong 1999; Wu et al. 1999; Ma et al. 2004; Hu et al. 2007; Guo et al. 2011; Hu and Lin 2012; Han et al. 2015; Yao et al. 2015; Zhang et al. 2015). Multiple proxies, including grain size, pollen assemblage, magnetic susceptibility and TOC content, have indicated that Lake Poyang formed its water table through climatic changes 1500 years ago (Wu et al., 1999). The total organic carbon (TOC) content and its carbon isotopic compositions in Lake Poyang have been widely used to interpret paleoclimatic changes in this area because carbon isotope analysis of total organic matter from lake sediments is simple, dependable and efficient (Zeng et al., 2012; Liu et al., 2013; Lim et al., 2015). In one study, the carbon isotopic composition of lacustrine sedimentary total organic matter (TOM) from a 5 ka core was used to indicate relative changes in paleotemperature (Peng et al. 2003). One study of a long core

collected from Lake Poyang suggested that the carbon isotopic composition of TOM might reflect variation in both temperature and precipitation related to the intensity of the East Asian summer monsoon since the middle Holocene (Ma et al. 2004). In these two studies, the changes of organic $\delta^{13}\text{C}$ in lacustrine sediments were frequently explained by variations in the biomass of the terrestrial plants and the related climatic changes in the catchment based on the hypothesis that the sedimentary TOM was generated from terrestrial sources in the Lake Poyang area (Peng et al. 2003; Ma et al. 2004). However, this hypothesis remains uncertain because little information was available regarding the carbon isotopic significance of TOM in modern Lake Poyang (Wang et al. 2014a, 2014b).

To study the modern processes, carbon and nitrogen isotopes of surface sediments and suspended matter were used to determine the organic carbon sources of surface sediments in Lake Poyang (Wang et al. 2014a, 2014b). The results of the studies showed that the C_3 plant is the main organic carbon source of suspended matter, and the terrestrial soils carried by the river water are the main organic carbon source of surface sediment in Lake Poyang (Wang et al. 2014a, 2014b). However, the previous results were based on the carbon isotopic composition of total organic matter from lake sediment cores, and little information is available regarding the environmental significance of the carbon isotopic composition of total organic matter in modern lakes. The climatic implications of the carbon isotopes of TOM in the lake sediments are worthy of further study.

In this study, we evaluate the climatic significance of the carbon isotopes of TOM from the lake-sediment from Lake Poyang in the Middle and Lower Yangtze River zone, assisted by modern meteorological (precipitation and temperature) and hydrological data (volume of runoff)

collected over the past 50 years, and water discharge of 5 rivers around Lake Poyang over the last millennium based on numerical simulation (Gao et al., 2015) and the organic carbon records from a sediment core. On this basis, the precipitation variability in the Middle and Lower Yangtze River recorded by the total organic carbon isotopes of a sedimentary core from Lake Poyang was reconstructed to better understand the local hydrological changes and their forcing factors in the monsoon-dominated southeastern region of China during the last 1600 years.

2. Study sites

Poyang Lake (28°22'-29°45'N, 115°47'-116°45'E), the largest fresh water body in China, is located in northern Jiangxi Province, south of the Yangtze River (Fig. 1). It is a graben-type basin formed by the rifting of the South China anticline during the late Mesozoic as a result of the Yanshan tectonic movement. The lake covers an area of ca. 3,900 km² and reaches its maximum water depth of 21 m during the rainy season, which normally lasts from April to September. During other parts of the year, the lake is generally less than 10 m deep. Several rivers contribute sediment to the lake, of which the Ganjiang River system is the most important (Fig. 1). Because Poyang Lake is slightly higher than the Yangtze River, the Poyang Lake water normally flows into the Yangtze, except during the flood stage of the river. The catchment runoff from the five main rivers plays a primary role in influencing the lake water level and the development of severe floods, whereas the Yangtze River plays a complementary role of blocking outflows from the lake (Hu et al. 2007).

The climate of the region is humid subtropical and is strongly influenced by the East Asian monsoon. The mean annual temperature is 18°C, with a mean maximum temperature of 37°C in July and a mean minimum temperature of -3°C in January (Guo et al. 2008; Yao et al. 2015). The

July and January mean temperatures are 29.6° and 5.0°C, respectively. Annual precipitation is approximately 1528 mm, with most of the rain falling between April and September, and the average surface evaporation is 1044 mm. Poyang Lake is in the northern vegetation subzone, also referred to as the mixed deciduous-evergreen forest subzone, of the subtropical evergreen broad-leaved forest region of China (Hou 1988). The characteristic tree taxa of the northern subzone are mostly deciduous species of *Quercus*, along with *Castanopsis* (e.g., *C. eyrei*, *C. sclerophylla*), *Liquidambar* (sweetgum), *Tilia* (linden), and *Ilex*(holly). Several species of bamboos (e.g., *Bambusa* and *Phyllostachys*) are native to the region (Hou 1988). Today, much of the deltaic plain of the Ganjiang River and the southwestern coast of Poyang Lake are under cultivation (mostly rice) or covered by herbaceous plants and cultivated trees.

3. Materials and methods

Lake Poyang has unique water environment characteristics, namely, a river in the dry season and a lake in the wet season, with high fluctuation of the water levels. The site of the core used to study the hydrological changes is very important because the water table undergoes large changes in Lake Poyang. Because Lake Poyang is a river-type lake and the deeper lake water has higher water fluidity along the river channel, a shallow water site was chosen in a sub-basin, where the water's fluidity is relatively steady. In general, changes of the water depth at the selected site (approximately 2-3 m) are smaller than the average varied annual water depth of the Lake Poyang (over 10 m) because the altitude of the bottom sediment is high at this site. It is important that the selected site was always covered by water, and the sediment has been rarely disturbed by human

activity according to our investigation from local people. Two long sedimentary cores were retrieved in August 2013 from the eastern sub-basin of Poyang Lake at a water depth of approximately 2 m (29°9'N, 116°25'E; Fig. 1). Although the cores were collected in August, the water table was still not very high (the average lake level of Lake Poyang was only approximately 15.3 m in August 2013, which was largely lower than normal value of 17.2 m) due to lower precipitation (70% less than normal) and high temperature at this time period. One of the approximately 770 cm long sedimentary cores (PYC13-3) was used in this study. The entire core was continuously sub-sampled at 1 cm intervals in the top 500 cm. The upper ~300 cm sediments mainly consisted of green-brown mud with no obvious sediment bedding, whereas there was a general alternation from mud to silty sand at the depth intervals of ~300 to 500 cm.

The total organic carbon of seven samples, including two terrestrial wood fragments and five sediments, were measured by radiocarbon dating by acceleration mass spectrometry (AMS) at the Beta Analytic Laboratory (Florida, USA) and Xi'an AMS Center, China (Table 1). All samples for radiocarbon dating were treated chemically according to the standard acid-alkali-acid procedure based on the labs' analytic standard pretreatment protocols. The reservoir effect (560 ± 30 years) of old carbon was calculated from the offset in radiocarbon ages between paired sediment (301 cm depth) and terrestrial wood fragments (302 cm depth) collected from almost identical stratigraphic horizons. The radiocarbon ages of four sediments were then corrected using the corresponding reservoir ages (Table 1). The radiocarbon ages of two wood fragments and reservoir-corrected radiocarbon ages of four sediments were converted to calendar ages (Table 1) using the software Calib601 (Reimer et al., 2009).

The wet sediments were freeze-dried. The samples were then ground in an agate mortar, sieved

through a 200 mesh screen and homogenized. Approximately 1 g of the sieved sediment sample was treated with 2 M HCl for 24 h at room temperature to remove carbonates. Subsequently, the samples were rinsed to a pH of approximately 7 with deionized water and dried at 40 °C. The dried samples were combusted for 4 h at 850 °C in evacuated sealed quartz tubes in the presence of 1 g of CuO, 1 g of Cu and Pt foil. The carbon dioxide was then cryogenically purified. The isotopic ratios of the purified CO₂ were measured using a Finnigan MAT 251 gas source mass spectrometer at the Institute of Earth Environment, Chinese Academy of Sciences (IEECAS). Isotopic ratios are reported using δ -notation as per mil (‰) differences relative to the V-PDB standard for C. The overall precision of the $\delta^{13}\text{C}$ analyses was less than 0.20‰ (Liu et al. 2013).

The modern meteorological data (precipitation and temperature) and hydrological data (volume of runoff) are from data published in previous studies (Guo et al., 2011; Zhan et al., 2011; Hu and Lin, 2012). Considering the differences in topography, contour microclimate and spatial and temporal distribution of rainfall and temperature in Lake Poyang Basin (Zhan et al., 2011; Hu and Lin, 2012), the annual precipitation and temperature are the average values of 78 meteorological stations located in the Lake Poyang Basin from 1959 to 2008 in Jiangxi Province (Fig. 1). Although the sediments in the core site are mainly contributed by three of the five main rivers, including the Raohe River, Xinjiang River and Fuhe River, the branches of Ganjiang River also carry matter to the core site (Fig. 1).

4. Results

Based on the calendar ages from the total organic carbon of two terrestrial wood fragments and four sediments, the age model for the Poyang Lake sedimentary core was constructed (Fig. 2). We obtained six calendar age dates between the 127 cm and 498 cm intervals and used a linear

interpolation to construct the age model for the top 500 cm of the core. Extrapolation from this record shows that the base of the core dates to over 1600 yr BP. According to this age model, the sedimentary rate of the core changes from 0.10 cm/yr to 0.95 cm/yr in this study (Fig. 2). Although we admit that the age model used in this study might contain uncertainties due to limited reliable materials for radiocarbon dating, the age of two terrestrial wood fragments suggest that age model used in this study are still enough for the discussion of climatic change on centennial time scales.

The $\delta^{13}\text{C}$ values of the total organic matter ($\delta^{13}\text{C}_{\text{org}}$ values) from core PYC13-3 range from -26.96‰ to -23.20‰, and the mean value is approximately -24.57‰ (Fig. 3a). The $\delta^{13}\text{C}_{\text{org}}$ values in PYC13-3 are the most negative, with a mean value of -26.45‰ (varied from -26.98‰ to -24.95‰) in the period 340-580 AD (Fig. 3a). Then, the $\delta^{13}\text{C}_{\text{org}}$ values show an increasing trend with little fluctuation, and the values vary from -26.10‰ to -23.85‰ in the period 580-1110 AD. In the period from 1110-1480 AD, the $\delta^{13}\text{C}_{\text{org}}$ values (varying from -24.94‰ to -23.32‰) first show a decreasing trend, reaching a minimum value of -24.94‰ in approximately 1350 AD, and then show a rising trend (Fig. 3a). Between 1480 AD and 1610 AD, the $\delta^{13}\text{C}_{\text{org}}$ values varied from -25.13‰ to -23.06‰, with large fluctuations, and the $\delta^{13}\text{C}_{\text{org}}$ value reached a minimum value of -25.13‰ in approximately 1560 AD (Fig. 3a). From 1610 AD until now, the variation in $\delta^{13}\text{C}_{\text{org}}$ values shows a continual decreasing trend with little fluctuation, and the $\delta^{13}\text{C}_{\text{org}}$ values vary from -25.15‰ to -23.42‰ in this period (Fig. 3a).

5. Discussions

5.1 The climatic implications of the total organic matter $\delta^{13}\text{C}$ values in Lake Poyang

The knowledge of how the carbon isotopic composition of total organic matters (TOM) varies in lakes is fundamental to understand the paleoclimate implications of the carbon isotopic composition from TOM in lakes. However, the interpretation of $\delta^{13}\text{C}_{\text{org}}$ from TOM in lake sediments is complex and depends on many factors. The $\delta^{13}\text{C}_{\text{org}}$ values from TOM in lake sediments can be interpreted in multiple ways, including as representing changes of temperature, contributions of terrestrial C_3 plants and precipitation, lake level changes and biologic sources (Stuiver 1975; Talbot and Johannessen 1992; Hammarlund 1993; Meyers and Horie 1993; Piovano et al. 2004; Teranes 2005; Shen et al. 2005; Diefendorf et al. 2007; Machiwa 2010; Mackay et al. 2012; Liu et al. 2013; Wang et al. 2013a). Lacustrine sedimentary TOM consists of a mixture of organic materials from both internal (e.g., aquatic plants and microorganisms in lakes) and external sources (e.g., terrestrial vegetation, soils and aeolian dust). The sources of sedimentary TOM should be evaluated before evaluating the climate implications of $\delta^{13}\text{C}_{\text{org}}$ from sedimentary TOM in the modern Lake Poyang area.

Fortunately, studies tracing the sources of stable organic carbon in surface sediments and suspended particulate organic matter (SPOM) of Lake Poyang were conducted in recent years (Wang et al. 2014a, 2014b). The results from these studies will help us to distinguish the sources of sedimentary TOM in Lake Poyang. Although the TOM of surface sediments are from both aquatic plants living in the lake and the terrestrial soils carried by the water to Lake Poyang, the C_3 plant is the major organic carbon source of SPOM. In the wet season, more C_3 plants are carried into the lake by increasing river discharge of Lake Poyang, resulting in more negative $\delta^{13}\text{C}_{\text{org}}$ values of SPOM in the wet season (varied from -28.07‰ to -26.02‰) than in the dry season (varied from

221 -27.79‰ to -25.22‰) (Wang et al. 2014b).

222 Many environmental conditions, including temperature, precipitation, relative air humidity, soil
223 moisture, irradiance and the concentration of atmospheric CO₂, influence the rate of
224 photosynthesis or stomata conductance and can also affect the carbon isotopic compositions of
225 terrestrial plants (Ehleringer and Cooper, 1988). For instance, the $\delta^{13}\text{C}$ values of plant leaves
226 increase by 2.0‰ for a 100 ppm decrease in atmospheric CO₂ concentration (Feng and Epstein,
227 1995). However, over the past 1600 years, atmospheric CO₂ variation was smaller than 20 ppm
228 most of the time and increased by ~100 ppm over the last ~100 years due to the increasing
229 anthropogenic input (Ahn et al., 2012). Thus, the large $\delta^{13}\text{C}_{\text{org}}$ changes (~ 4‰) in core PYC13-3
230 could not be fully explained by variations in the atmospheric CO₂ concentration over the past 1600
231 years. In addition, the $\delta^{13}\text{C}$ values of the atmospheric CO₂ decreased by 1~2‰ in the past 100
232 years (Friedli et al., 1986; Affek and Yakir, 2014). If the $\delta^{13}\text{C}_{\text{org}}$ values of terrestrial plants were
233 mainly controlled by the atmospheric CO₂ concentration and its carbon isotope, the $\delta^{13}\text{C}_{\text{org}}$ values
234 of TOM in core PYC13-3 should have decreased by 2~3‰ over the past 100 years because the
235 sedimentary total organic matter is mainly from terrestrial plants in Lake Poyang (Wang et al.
236 2014a, 2014b). However, the $\delta^{13}\text{C}_{\text{org}}$ values of TOM in core PYC13-3 only varied by ~ 1.1‰ over
237 the past 100 years (Fig. 3a). Therefore, the variation in the $\delta^{13}\text{C}_{\text{org}}$ values of PYC13-3 core was
238 not mainly controlled by changes in the atmospheric CO₂ concentration and its carbon isotope.

239 Based on the investigation of $\delta^{13}\text{C}$ signal on C₃ and C₄ plants across temperature gradient along
240 the 400 mm mean annual precipitation isoline in north China, a strong positive relationship was
241 found between the $\delta^{13}\text{C}$ values of C₃ plants averaged for each site and the mean annual
242 temperature, with a coefficient of approximately 0.1‰/°C after eliminating the effect of

precipitation (Wang et al., 2013b). If the variation in the TOM $\delta^{13}\text{C}_{\text{org}}$ values in core PYC13-3 was affected by temperature, changes in temperature should exceed 35 °C for the last 1600 years. The TOM $\delta^{13}\text{C}_{\text{org}}$ values in PYC13-3 generally decreased with increased global temperature over the past 100 years, which contradicted the positive relationship between the C_3 plant $\delta^{13}\text{C}$ value and annual temperature (Wang et al., 2013b). In addition, there was no evident correlation between $\delta^{13}\text{C}_{\text{org}}$ values of sedimentary TOM from the PYC13-3 core and temperature record in the Lake Poyang Basin over the past 50 years (Hu and Lin, 2012). Thus, it was improbable that the temperature had such a large variation in the Lake Poyang region over the studied period. Numerous studies have shown that the relative humidity, as well as the amount of precipitation, is generally negatively related to the $\delta^{13}\text{C}$ of terrestrial plants (Farquhar et al., 1982; Liu et al., 2005; Ning et al., 2008). A shortage of water causes plants to close their stoma, reducing the intercellular partial pressures of CO_2 in the plants, which results in higher $\delta^{13}\text{C}$ values of plants growing in drier conditions (Farquhar et al., 1982). Increasing precipitation may cause low C_3 plant $\delta^{13}\text{C}$ values and higher influx of terrestrial organic matter into the lake through runoff, which may result in the low sedimentary TOM $\delta^{13}\text{C}_{\text{org}}$ values in Lake Poyang. The results of past study showed that the mean $\delta^{13}\text{C}$ values decrease 0.49-1.1‰ when the annual precipitation increased by 100 mm in the Chinese Loess Plateau (Wang et al., 2003; Liu et al., 2005). Therefore, the large $\delta^{13}\text{C}$ changes in the PYC13-3 core (almost 4 ‰) may be reasonably explained by changes in precipitation (~ 400 mm) over the past 1600 years.

On this basis, we inferred that the $\delta^{13}\text{C}_{\text{org}}$ of sedimentary TOM may be used to indicate variation in river runoff or precipitation around Lake Poyang. The negative $\delta^{13}\text{C}_{\text{org}}$ of the sedimentary TOM indicates high river runoff around Lake Poyang. To test our theory, the $\delta^{13}\text{C}_{\text{org}}$

values of sedimentary TOM from PYC13-3 were compared with annual precipitation and runoff data (Zhan et al. 2011) of the five main rivers supplying water to Lake Poyang over the past 50 years using an age-depth model that was developed using linear interpolation between calendar ages (Figs. 2 and 4). The total annual runoff of the five main rivers varied from 1341 m³/s to 7471 m³/s, with large fluctuations in the period of 1957-2008 AD (Fig. 4c). The annual precipitation also varied in a large range from 1103 mm to 2145 mm in the period of 1959-2008 AD in the Lake Poyang area (Fig. 4b). In general, the $\delta^{13}\text{C}_{\text{org}}$ values of the sedimentary TOM from PYC13-3 are negatively correlated with both the mean annual precipitation ($p < 0.05$, $r = -0.49$, $n = 25$) and the runoff of the 5 main rivers ($p < 0.05$, $r = -0.46$, $n = 25$) during the last 50 years in the Lake Poyang area (Fig. 4). In addition, the annual precipitation is also positively correlated with the runoff of the 5 main rivers during the last 50 years in the Lake Poyang area ($p < 0.05$, $r = 0.69$, $n = 50$) (Fig. 4). The good correlation between the runoff and annual precipitation suggested that the variation in annual runoff is mainly controlled by annual precipitation in the Lake Poyang area. In addition, a recent study found that the variation in annual runoff was mainly controlled by annual precipitation in the Yangtze River (Chen et al. 2014), which is similar with our result. Therefore, the results of the above correlation analysis suggested that the $\delta^{13}\text{C}_{\text{org}}$ values of the sedimentary TOM record changes in annual river runoff and precipitation in the Lake Poyang area (decreasing $\delta^{13}\text{C}_{\text{org}}$ values of sedimentary TOM correspond to increasing annual precipitation and runoff). In other words, the low $\delta^{13}\text{C}_{\text{org}}$ values of sedimentary TOM result in more terrestrial matter (mainly contributed by C₃ plants) with more negative $\delta^{13}\text{C}_{\text{org}}$ values (caused by increased precipitation) than was flushed into the lake by the increased river runoff related to increased precipitation in the Lake Poyang area.

5.2. Precipitation changes recorded in the sedimentary TOM $\delta^{13}\text{C}_{\text{org}}$ for the last 1600 years in the Lake Poyang area

Based on the above discussion, sedimentary TOM $\delta^{13}\text{C}_{\text{org}}$ from core PYC13-3 was used to reconstruct the variability in precipitation over the past 1600 years in the Lake Poyang area (Fig. 3). In addition, the $\delta^{13}\text{C}_{\text{org}}$ record was also compared with variations in the water discharge of Lake Poyang based on numerical simulation for the last 1000 years (Gao et al., 2015) and the fragmentary historical document (Ma et al., 2004; Hu and Lin 2012) to prove the effectiveness of our result.

As shown in Fig. 3, the amount of precipitation was highest with a decreasing trend indicated by the lowest $\delta^{13}\text{C}_{\text{org}}$ values of sedimentary TOM in the period of 340-880 AD over the past 1600 years in the Lake Poyang area. The increased precipitation may result in the expansion of Lake Poyang, and the lake reached its present area in the period of 581-618 AD according to the history records (Ma et al., 2004). The two ancient counties named Chengyang and Haihun were also drowned because of the expansion of Lake Poyang in 420AD and 425 AD, respectively (Ma et al., 2004). After 880 AD, the precipitation sharply decreased, except for a slight increase in the period of 990-1060 AD and then reached a minimum at 1110AD (Fig. 3). From 610 to 880 AD, the precipitation was relatively stable at a high level, and the precipitation suddenly increased in 880AD in the Lake Poyang area (Fig. 3). During the period of 1110-1350 AD (Medieval Warm Period), the precipitation first increased slightly around 1140 AD, then gradually declined, and the precipitation continued to increase by small steps after 1220 AD (Fig. 3). After 1350 AD, the precipitation sharply decreased, as indicated by the increased $\delta^{13}\text{C}_{\text{org}}$ values of sedimentary TOM,

309 until a sharp increase in 1540 AD. Then, the precipitation declined again until 1610 AD (Fig. 3).

310 In general, the precipitation was very low during the period of 1350-1610 AD, generally

311 corresponding with the relatively dry 'Little Ice Age' (Zhang et al., 2008). However, the suddenly

312 decreased sedimentary TOM $\delta^{13}\text{C}_{\text{org}}$ showed that the climatic and hydrological condition

313 suddenly changed during the period of 1550-1560 AD. The decreased sedimentary TOM $\delta^{13}\text{C}_{\text{org}}$

314 was caused by increased terrestrial C_3 plants carried into the lake through river water. The low

315 $\delta^{13}\text{C}_{\text{org}}$ values of residual wood (-28.6‰) found at the 3.1 m depth of the PYC13-3 core (1560

316 AD) indicates the increased contribution of terrestrial C_3 plants. The precipitation and river runoff

317 suddenly increased in the period of 1550-1560 AD. The climate was very dry, as indicated by the

318 data from historical documents during the period of 1350-1610 AD, except for humid climate in

319 the period of 1550-1620AD (Hu and Lin 2012). The precipitation continuously increased with

320 little fluctuation, as indicated by the decreasing $\delta^{13}\text{C}_{\text{org}}$ values of sedimentary TOM from 1610

321 AD until now in Lake Poyang (Fig. 3). However, the precipitation was still low in the period of

322 1620-1720AD, as shown by the high $\delta^{13}\text{C}_{\text{org}}$ values of sedimentary TOM, and then the

323 precipitation increased from 1720 to 1790AD (Fig. 3). The variation in precipitation was also

324 consistent with a dry then humid climate recorded by the historical documents during the period

325 1620-1790 AD in the Lake Poyang area (Hu and Lin 2012). In addition, the reconstructed water

326 discharge of Lake Poyang showed a similar trend with the change of the sedimentary TOM

327 $\delta^{13}\text{C}_{\text{org}}$ values in core PYC13-3 in the last millennium (Fig. 3a, 3d) (Gao et al., 2015). The low

328 sedimentary TOM $\delta^{13}\text{C}_{\text{org}}$ values generally correspond with high water discharge of the 5 rivers

329 around Lake Poyang in the period of 1050 to 1350 AD (Fig. 3d) (Gao et al., 2015), and the low

330 water discharge corresponds with the high sedimentary TOM $\delta^{13}\text{C}_{\text{org}}$ values during the period of

1450-1850 AD, which corresponds to the period of the Little Ice Age (LIA) (Fig. 3a, 3d). After 1850 AD the sedimentary TOM $\delta^{13}\text{C}_{\text{org}}$ values decreased, corresponding with increased water discharge of the 5 rivers around Lake Poyang indicated by result of a numerical simulation (Gao et al., 2015) (Fig. 3). In general, the variation in TOM $\delta^{13}\text{C}_{\text{org}}$ values showed the opposite trends with changes of increased water discharge indicated by model result for past 1000 years in the Lake Poyang area (Fig. 3).

5.3. Climate-forcing mechanism for the varied precipitation in Lake Poyang over the last 1600 years

The Asian summer monsoon (ASM) is one of the large-scale circulation patterns affecting the Yangtze River basin and determines the Yangtze River basin precipitation (Duan et al. 2004; Blender et al. 2011). The hydrology in the upper Yangtze River is mainly impacted by the Indian summer monsoon (ISM) and the middle and lower reaches are mainly influenced by the eastern Asian summer monsoon (Zhang et al. 2007; Zhou et al., 2016). Therefore, the varied pattern of precipitation recorded by the $\delta^{13}\text{C}_{\text{org}}$ values of sedimentary TOM was compared with records of ASM from central China (Zhang et al. 2008) to understand the relationship between changed precipitation and strength of ASM during the last 1600 years.

As shown in Figure 3, the varied pattern of precipitation recorded by the $\delta^{13}\text{C}_{\text{org}}$ values of sedimentary TOM in the Lake Poyang area generally corresponds to the intensity of the ASM since 340 AD, which was recorded by the oxygen isotopic compositions ($\delta^{18}\text{O}$) of stalagmites from Wanxiang Cave (33°19'N, 105°00'E; Fig. 1) in central China (Zhang et al. 2008). We found that the precipitation recorded by $\delta^{13}\text{C}_{\text{org}}$ in Lake Poyang is not parallel with the ASM intensity recorded by stalagmite $\delta^{18}\text{O}$ in central China (Fig. 3). The Wanxiang Cave is located in the

monsoon margin region; its 2-3-year high-resolution record has a more reliable chronology over the past 1600 years. The difference between these two records may be attributed to the relatively larger dating uncertainties in our record. In general, the $\delta^{18}\text{O}$ record of the stalagmites showed that the ASM was very strong in the period of 340-860 AD, which corresponded with high precipitation in the Lake Poyang area (Fig. 3). Then, the ASM intensity gradually weakened from 970AD to 1370 AD, and the precipitation also continually declined during this time stage in Lake Poyang (Fig. 3). The ASM intensity was weakest in the period of 1340-1620AD over the past 1600 years, which generally corresponded to the lowest precipitation in Lake Poyang at this time (Fig. 3). After 1620 AD, the ASM intensity gradually strengthened, as shown by the $\delta^{18}\text{O}$ record of stalagmites in Wanxiang Cave, which corresponded to an increasing precipitation since 1610 AD in Lake Poyang (Fig. 3). Therefore, we suggest that the ASM intensity is an important factor influencing the varied precipitation in Lake Poyang located at the Middle and Lower Yangtze River. Usually, intensified (weakened) ASM can cause more (less) water vapor to be transported from the sea to the inland, resulting in more (less) precipitation inland. Changes of precipitation or streamflow in most monsoon-dominated areas of China are associated with the ASM intensity, as shown by other paleoclimatic and instrument records (An et al. 2000; Wang et al. 2001; Tan et al. 2008; Liu et al. 2011; Zhou et al. 2012; Wei et al. 2014; Nan et al. 2014). Nan et al. (2014) confirmed that precipitation changes in the Pearl River basin are driven mainly by the monsoon intensity using grain size and organic geochemistry parameters (TOC and $\delta^{13}\text{C}_{\text{org}}$) from a sediment core collected in the Pearl River Estuary. Therefore, precipitation variability in response to ASM intensity was recorded by our $\delta^{13}\text{C}_{\text{org}}$ of sedimentary TOM from Poyang Lake during the past 1600 years, where more negative $\delta^{13}\text{C}_{\text{org}}$ values indicate an intensified ASM with increased

precipitation and river discharge, and enriched $\delta^{13}\text{C}_{\text{org}}$ values indicate a weakened ASM with decreased monsoon precipitation in Lake Poyang area.

In addition, precipitation or river discharge changes in our record appears to correspond to total solar irradiance changes as inferred from residual ^{10}Be and $\Delta^{14}\text{C}$ data on multi-decadal and centennial timescales (Fig. 3) (Steinhilber et al., 2012). Generally, high precipitation or larger river discharge in Lake Poyang area corresponds to higher solar irradiance and vice versa (Fig. 3). The results showed that the sudden increase of precipitation or river discharge was almost sensitively response to sudden change of TSI around AD 480, 880, 1060, 1310 and 1560 in Lake Poyang area (Figs. 3a and 3d). In general, considering chronology uncertainty, the changes in precipitation or river discharge are potentially corresponding to TSI changes (Fig. 3). Therefore, there appear to be a possible link between solar irradiance and precipitation or river discharge variability in the Lake Poyang area during the late Holocene.

Therefore, we concluded that the precipitation or river discharge changes may be primarily controlled by variation in the ASM intensity in the Lake Poyang area, but variation in TSI may also have large influences on the changes of precipitation or river discharge in Lake Poyang during the late Holocene.

6. Conclusions

With modern instrumental data (precipitation, temperature and river runoff), the $\delta^{13}\text{C}_{\text{org}}$ record of sedimentary TOM in the core PYC13-3, which was collected from Lake Poyang in the Middle and Lower Yangtze River in southern China, was used to analyze the variations in the precipitation in the studied area over the past 1600 years. Periods with increased precipitation are characterized

by depleted $\delta^{13}\text{C}_{\text{org}}$, attributed to increased terrestrial matter with negative $\delta^{13}\text{C}_{\text{org}}$ values carried by strong river runoff caused by heavy rain in Lake Poyang. The $\delta^{13}\text{C}_{\text{org}}$ values of sedimentary TOM for PYC13-3 are correlated with local precipitation data over the past 50 years, suggesting that the $\delta^{13}\text{C}_{\text{org}}$ of sedimentary TOM can be used as a proxy index for the amount of precipitation in Lake Poyang. In general, the PYC13-3 record demonstrates that the precipitation was highest with a decreased trend generally in the period of 340-880 AD over the past 1600 years in the Lake Poyang area. After 880 AD, the precipitation sharply decreased, except for a slight increase in the period of 990-1060 AD, and then reached a minimum near 1110 AD. During the period of MWP, the precipitation first increased slightly until 1140 AD, then gradually declined, and the precipitation continued to increase in small steps after 1220 AD in the Lake Poyang area. After 1350 AD, the precipitation sharply decreased, until a sharp increase in 1550 AD. Then, the precipitation declined again until 1610 AD. In general, the precipitation was very low during the period of LIA, except for a sudden increase around 1550 AD. The precipitation continued to increase with little fluctuation from 1610 AD until now in Lake Poyang area. Changes in precipitation were dominated by variations in the intensity of Asian Summer Monsoon in Lake Poyang area, as observed in other records from ASM-controlled areas of China. In addition, the total solar irradiance may also have large influences on the changes of precipitation or river discharge in Lake Poyang during the late Holocene.

Acknowledgments

The authors would like to thank Dr. Shangbin Xiao, Li Liu, Baogui Liu, and Sheng Liu for help with sample collection in the field. The two anonymous reviewers and Dr. Zhonghui Liu and

Min-Te Chen are thanked for their thoughtful and constructive suggestions to improve the clarity of this paper. This research was supported by the Chinese Academy of Sciences (CAS) Strategic Priority Research Program (No. XDA05120404), the National Science Foundation of China (no. 41373001) and CAS "Light of West China" Program (XAB2015A01).

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Tables, Figures Captions

Tab. 1 AMS radiocarbon dates and calendar ages for the Poyang Lake sedimentary core.

Fig. 1a) Lake Poyang and its surrounding environment. The red solid circle shows the location of the core PYC13-3, and the blue five pointed star shows the location of the Wangxiang Cave (Zhang et al. 2008); b) the distribution of the meteorological stations in Lake Poyang Basin (black solid circles) where the precipitation and temperature data were recorded (Zhan et al., 2011; Hu and Lin, 2012).

Fig. 2 Age model for the Poyang Lake sedimentary core based on the calendar ages of the four sediments (black solid circles) and the two terrestrial wood fragments (blue solid circles).

Fig. 3 Comparison of the $\delta^{13}\text{C}_{\text{org}}$ of sedimentary TOM values from the Poyang Lake sedimentary core (blue line and dots) and b) the $\delta^{18}\text{O}$ values of stalagmites from the Wanxiang Cave (green line)

(Zhang et al. 2008), c) total solar irradiance (purple line) (Steinhilber et al., 2012), d) the water discharge variation of the Lake Poyang catchment based on numerical investigation over the last 1000 years (red line) (Gao et al., 2015).

Fig. 4 Correlation of the $\delta^{13}\text{C}_{\text{org}}$ of sedimentary TOM values from Lake Poyang with a) temperature (red line and dots) (Hu and Lin, 2012), b) annual precipitation (green line and dots)(Zhan et al. 2011), and c)the runoff from the 5 main rivers (golden line and dots) (Guo et al., 2011) in the Lake Poyang area over the past 50 years.

Figure 1

Figure 2

Figure 3

Figure 4

Table 1

Lab. Code	Depth (cm)	Material	Measured ^{14}C age (BP)	Corrected by 560 yr age (cal. yr BP) (Median Probability)	Corrected age (cal. yr AD) (Median Probability)
367053	127	TOM	610 $\pm$ 30	71	1879 $\pm$ 30
367054	203	TOM	780 $\pm$ 30	184	1766 $\pm$ 30
367060	301	Wood	310 $\pm$ 30		1562 $\pm$ 30
367055	302	TOM	870 $\pm$ 30	388	1562 $\pm$ 30
367061	440	Wood	1160 $\pm$ 30		874 $\pm$ 30
XA13115	478	TOM	2118 $\pm$ 26	1464	486 $\pm$ 26
XA13116	498	TOM	2255 $\pm$ 32	1600	350 $\pm$ 32