Evidence of Abrupt Climate Change during the Mid- to Late-Holocene Recorded in a Tropical Lake, Southern China

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Abstract: Research on abrupt paleoclimatic and paleoenvironmental change provides a scientific basis for evaluating future climate. Because of spatial variability in monsoonal rainfall, our knowledge about climate change during the mid- to late-Holocene in southern China is still limited. We present a multi-proxy record of paleoclimatic change in a crater lake, Lake Shuangchi. Based on the age-depth model from ^{210}Pb, ^{137}Cs and AMS^{14}C data, high-resolution mid- to late- Holocene climatic and environmental records were reconstructed using multiple indices (TOC, TN, C/N, $\delta^{13}C$ and grain size). Shuangchi underwent a marked change from a peat bog to a lake around 1.4 kaBP. The C_3 plants likely dominated during 7.0–5.9 ka and 2.5–1.4 kaBP, while C_4 plants dominated between 5.9–3.2 and 3.0–2.5 kaBP. Algae were dominant sources of organic matter in the lake sediments after 1.4 kaBP. Several intervals with high concentrations of coarser grain sizes might be due to flood events. These results reveal that several abrupt paleoclimatic events occurred around 6.6 ka, 6.1 ka, 5.9 ka, 3.0 ka, 2.5 ka and 1.4 kaBP. The paleoclimatic change recorded in the lake may be related to the migration of the Intertropical Convergence Zone (ITCZ) and El Niño - Southern Oscillation (ENSO) activity.

Key words: paleoclimatic events, ITCZ, ENSO, Holocene, Shuangchi Lake

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1 Introduction

Climatic and environmental change has become a major focus of human society. In order to predict future climate change, we need to study the history of past climate change and understand the mechanisms behind climate systems (An and Fu, 2001; Xie et al., 2018; Zhang et al., 2019). Research on the occurrence, causes and mechanism of abrupt climate events provides a historical reference for future climate prediction.

In southern China, abrupt paleoclimate events recorded in lakes show large differences among different localities. For example, the carbon and nitrogen indices of Shuangchi Lake showed that the water level rose and aquatic plants flourished at about 3.0 kaBP (Yang et al., 2014). High-resolution records of the magnetic properties in Huguanyan Maar Lake indicated an abrupt climatic shift around 6.4 kaBP (Wu et al., 2012; Wang et al., 2016). Isotopic and pollen evidence also showed this abrupt shift around 6.6–6.0 kaBP in Huguangyan Maar Lake (Jia et al., 2015; Sheng et al., 2017). Bond et al. (1997) and Wang et al. (2009) have highlighted the youngest paleoclimatic event around 1.4 kaBP; however, this event has been reported less often in tropical regions probably due to extensive human activity and a weaker climatic response.

The mechanism of climate change is not fully understood. Many studies suggest that the paleoclimate record in southern China primarily reflects an evolution history of the Asian Summer Monsoon, but weakly links with the Intertropical Convergence Zone (ITCZ), solar radiation and El Niño - Southern Oscillation (ENSO) activity (Wu et al., 2012; Jia et al., 2015; Wang et al., 2016; Chu et al., 2017; Sheng et al., 2017).

Maar Lakes provide good paleoclimate archives because of their closure, relatively single material source and continuous deposition. Several research studies carried out in Shuangchi Maar Lake, Hainan Province (Bai et al., 2003; Zheng et al., 2003; Luo et al., 2006; Tang et al., 2017; Dodson et al., 2019) have shown that climate change in this area is generally consistent with other records. However, there has been limited research on abrupt climate change. In addition, the topography of east Shuangchi Lake is lower and may be more vulnerable to human activities. Here, we present a multiproxy record of paleoclimatic and paleoenvironmental change from the west Shuangchi Lake, with a hope to disentangle lake and regional climate responses to internal and external forcings.

2 Geological Settings and Methods

2.1 Site description and sediment coring

Hainan Province is located in the southernmost part of China, separated from Leizhou Peninsula by Qiongzhou Strait in the north, facing Beibu Bay in the West and the South China Sea in the East (Fig. 1a). Hainan Island covers an area of about 33,900 km^2, and is generally high in the middle and low-lying on all sides. The climate is mainly influenced by the tropical summer monsoon (the South China Sea Summer Monsoon and the Indian Summer Monsoon), and tropical oceanographic processes

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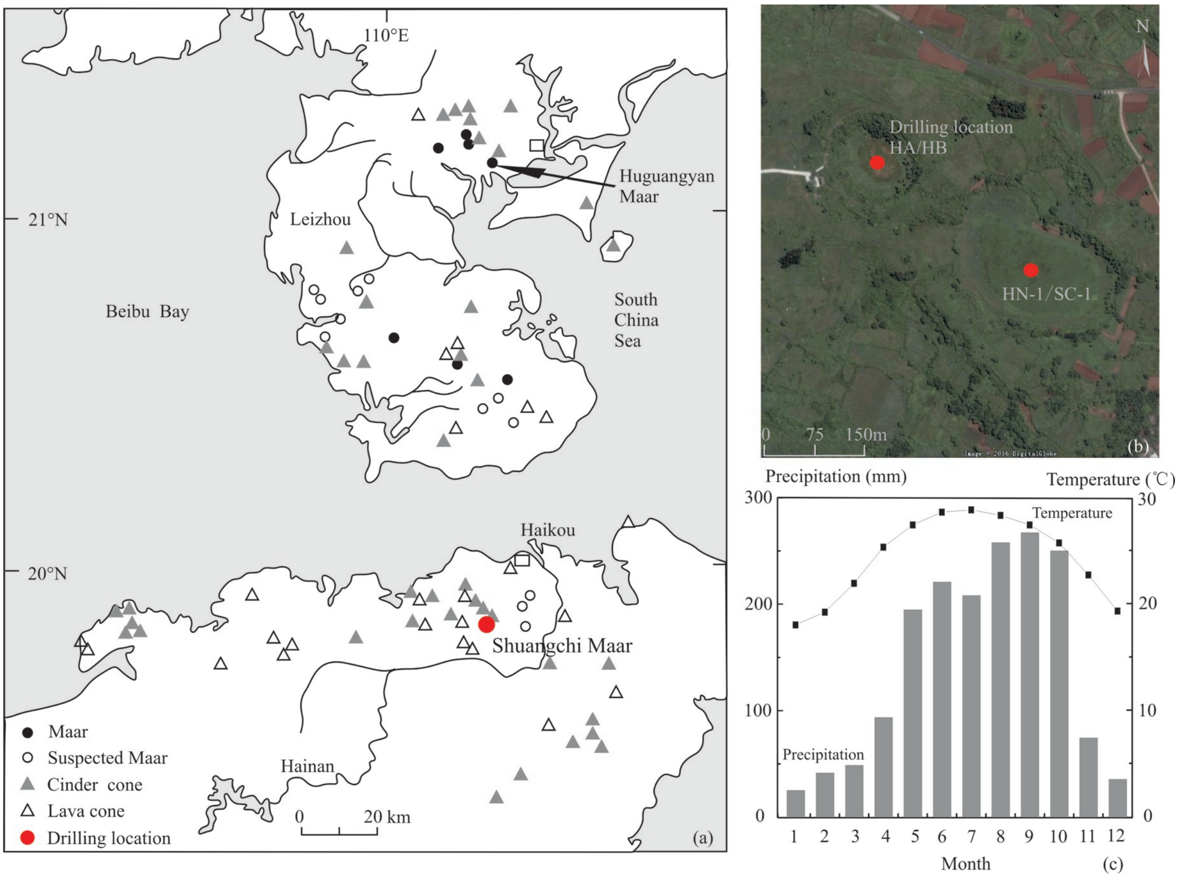

Fig. 1. Location and cores of Shuangchi Maar Lake, and meteorological information of Hainan Province (modified from Tang et al., 2017).
HA/HB represent the cores in our study, and HN-1/SC-1 represent other cores discussed in this paper (Zheng et al., 2003; Yang et al., 2014).

(El Nino, tropical typhoons, Pacific decadal oscillation, etc.) (Yang et al., 2014). The annual average temperature, precipitation and evaporation of Hainan Island are about 23.8°C, 1800 mm and 1830 mm, respectively (Fig. 1c). The precipitation falls mainly in May to October (accounting for about 80% of the annual precipitation).

Shuangchi Lake (19°56'45"N, 110°11'15"E) is a closed lake surrounded by basalt and tuff (Huang and Cai, 1994). Two overlapping cores (HA, HB) were drilled in the center of the smaller lake basin in the west side (Fig. 1b).

2.2 Radiometric dating

^{210}Pb and ^{137}Cs in the upper 30 cm samples of core were analysed at the Institute of Geology and Geophysics, Chinese Academy of Sciences. AMS^{14}C of plant remains in different depths of the profile was analysed in the laboratory of Poznan University, Poland. The chronological framework of the sediment core from Shuangchi Lake was constructed by combining the data from these two dating methods.

2.3 Geochemical analysis

A total of 804 samples were obtained at 1 cm intervals from the sediment samples of Shuangchi Maar Lake. The contents of organic carbon and nitrogen (TOC, TN), organic carbon isotopes (δ^{13}C) and grain size of the sedimentary samples were analysed at the Institute of Geology, Chinese Academy of Geological Sciences.

Freeze-dried samples were acidified by HCl to remove carbonates. The concentrations of TOC and TN, and δ^{13}C were determined using a CHNS elemental analyzer (Vario PYRO cube) connected to an isotope mass spectrometer (Elementar ISOprime 100). Blank samples and standard sediment samples were used for quality control. The carbon isotope values are reported relative to the VPDB standard. The precision was 3.0%, 1.0%, and 0.1‰ for the measurements of TOC, TN and δ^{13}C, respectively.

Grain-size analyses were performed using a laser grain-size analyzer (Malvern Mastersizer 2000). Prior to grain-size analysis, H_2O_2 was used to remove organic material, HCl was added to remove carbonates, $(NaPO_3)_6$ was added to to disperse particles and the mixture was shaken (following Tian et al., 2017).

3 Results

3.1 Chronology

The sediment profile was divided into two main lithological units: the upper part is mainly gray-black silt, and the lower part is black sapropel (Fig. 2). The ^{137}Cs activity is near zero below the depth of 30 cm, and the highest ^{137}Cs (at a depth of 24 cm) is assumed to correspond to the 1963 maximum emission due to nuclear bomb testing (Fig. 3c). The unsupported $^{210}Pb_{ex}$

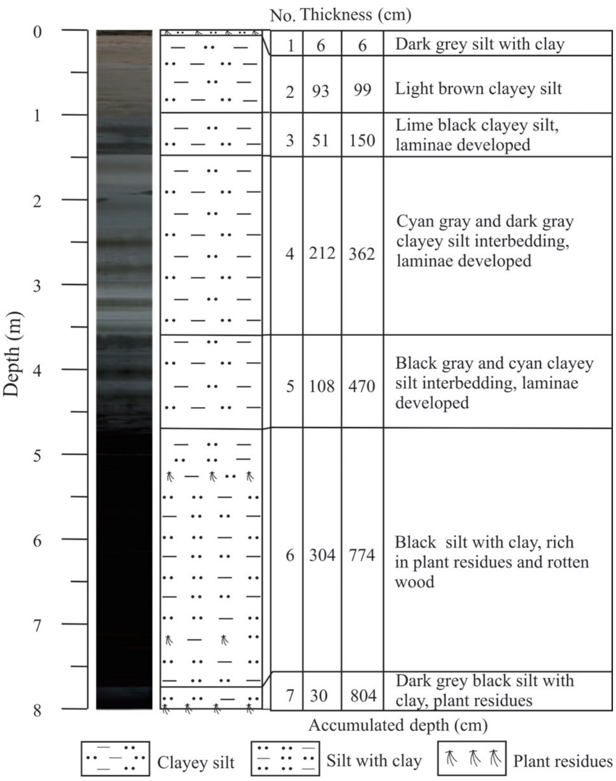

Fig. 2. The lithology of the sediment core from Shuangchi Lake.

(subtracting ^{226}Ra) declines exponentially with depth, dropping to near zero below 30 cm (Fig. 3b). The AMS^{14}C ages were corrected using the OxCal 4.2 software and the IntCal 13 calibration curve (Table 1, Reimer et al., 2013). In view of the results of ^{137}Cs and ^{210}Pb, the carbon effect of Shuangchi Lake is not significant. Sediment ages were calculated by a polynomial fitting ($Y=10^{-4}x^2+0.4102x+29.074$, $R^2=0.9994$) for 0 to 2.4 m. In the lower part of the profile (2.4 to 8.0 m), the age-depth relationship was constructed using the linearization method based on the cram package of the R language (Blaauw and Christen, 2011) (Fig. 3a). The sedimentation rate was relatively high in the upper part of the profile (0.32 cm/a above 5.0 m), but low in the lower part (0.05 cm/a below 5.0 m).

3.2 Multiproxy record

Organic geochemical indexes such as TOC, TN, ratio of carbon and nitrogen content (C/N) and $\delta^{13}C$ are widely used in paleoclimatic and environmental reconstruction (Zhang et al., 2012). In addition, the grain-size index has been widely used in loess, ocean and lake research, as an important paleoclimate index.

TOC and TN contents of Shuangchi Lake sediments range from 1.6 to 58.4% and 0.2 to 2.4%, respectively, with average contents of 20.0% and 0.8%, respectively (Fig. 4). The average contents of TOC and TN below 5.0 m (7.0 to 1.4 kaBP) and above 5.0 m (1.4 to 0 kaBP) is 45.7%, 1.7% and 2.8%, 0.3%. This marks a lithological change from black sapropel to silt around 1.4 kaBP.

Table 1 Radiocarbon ages of the sediment in the core

Lab No.	Depth (cm)	AMS^{14}C Age (yr BP)	Error (a)	Material	Corrected AMS^{14}C age (yr BP) (2σ)
Poz-58735	107	410	70	Plant residue	308–538
Poz-58736	163	600	80	Plant residue	509–680
Poz-58737	220	590	80	Plant residue	505–678
Poz-58743	240	610	70	Plant residue	520–675
Poz-58738	382	670	90	Plant residue	517–763
Poz-58744	467	1220	30	Plant residue	1063–1188
Poz-58745	492	1175	30	Plant residue	1048–1180
Poz-58747	565	2045	30	Plant residue	1926–2114
Poz-58748	639	3230	30	Plant residue	3381–3511
Poz-58749	716	5275	35	Plant residue	5982–6130
Poz-58751	796	6090	35	Plant residue	6850–7030

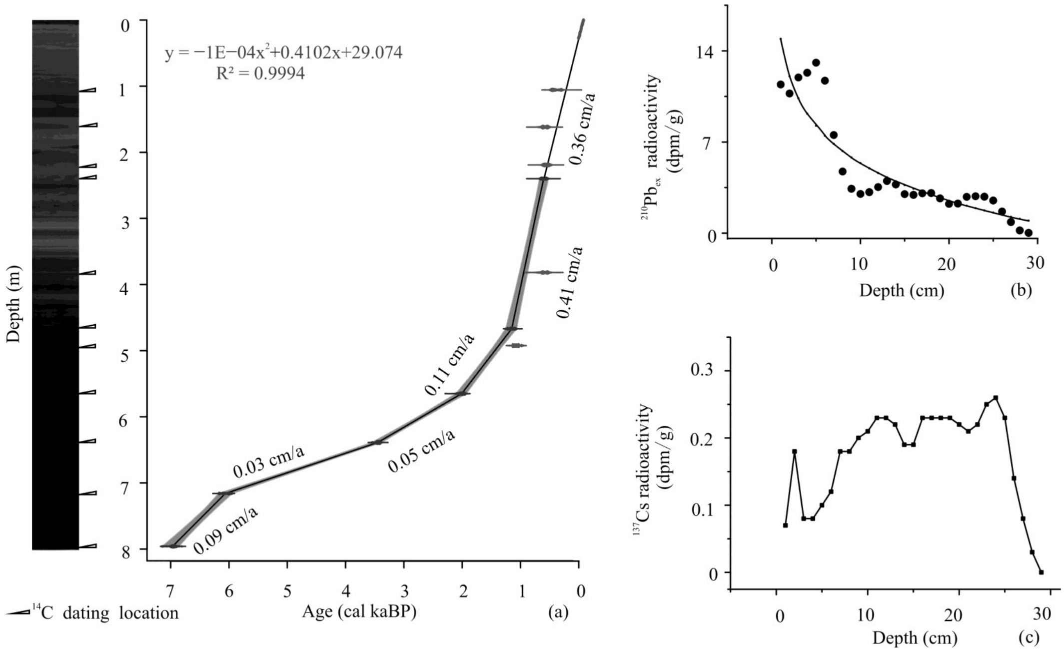

Fig. 3. Age-depth profile based on ^{210}Pb, ^{137}Cs and AMS ^{14}C dates from the sediment core of Shuangchi Lake (modified from Tang et al., 2017).

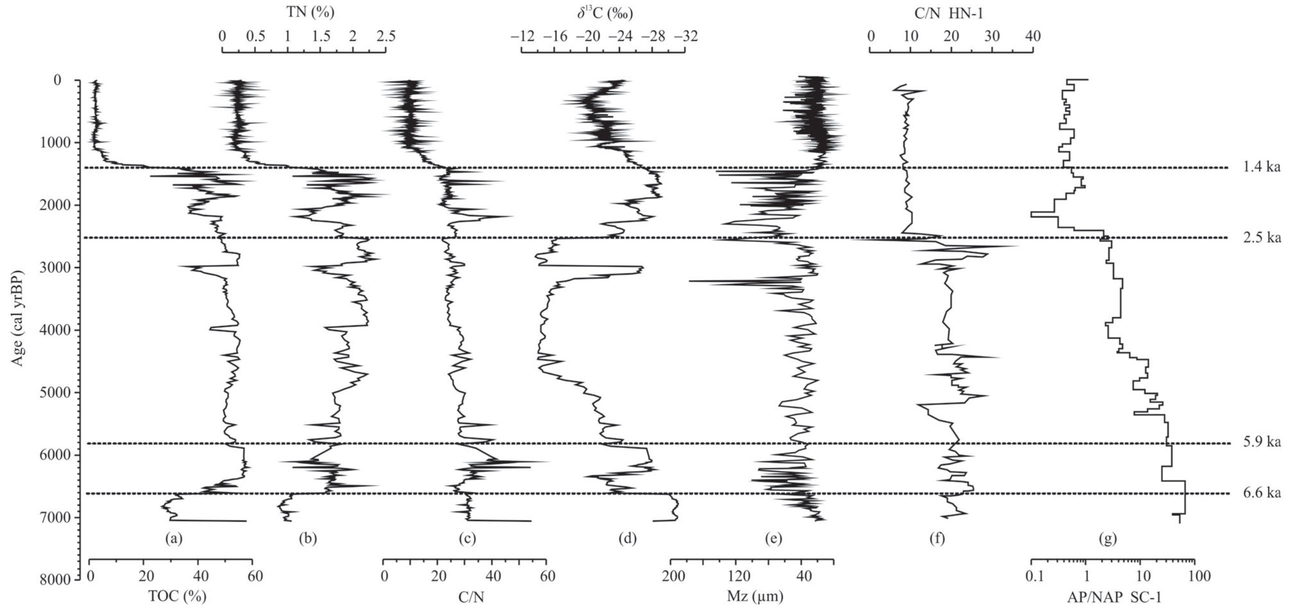

Fig. 4. Time series of geochemical records from Lake Shuangchi.
(a) TOC concentration, (b) TN concentration, (c) C/N ratio, (d) $\delta^{13}C$, and (e) mean grain-size of Lake Shuangchi sediments in this study; (f) C/N ratio in HN-1 sediment core of Lake Shuangchi (Yang et al., 2014); (g) AP/NAP ratio in SC-1 sediment core of Lake Shuangchi (Zheng et al., 2003).

C/N ratios range between 7.3 and 54.6, with an average of 17.4. The average C/N value is 27.8 between 7.0 kaBP and 1.4 kaBP, and 10.5 after 1.4 kaBP. C/N is commonly used to identify the source of organic matter in lake sediments. Generally, the C/N values of lower aquatic non-vascular plants are relatively small, typically 4 to 10; the cellulose contents of higher, vascular terrestrial plants are higher, and their C/N ratios may exceed 20 (Meyers et al., 2003). Therefore, it can be inferred that the organic matter of Shuangchi Lake between 7.0–1.4 kaBP mainly came from terrestrial vascular plants, but from aquatic plants (mainly algae) after 1.4 kaBP.

$\delta^{13}C$ of the Shuangchi Lake sediments varies from −31.2‰ to −13.7‰, with an average of −22.9‰. The mean grain size shows obvious fluctuations, with higher values at 6.6 to 5.9, 3.2, and 2.5 to 1.4 kaBP (Fig. 4e). Previous studies suggested that an increase of fine particles in the sedimentary records indicates enhanced precipitation intensity in the basin. These periods with coarser grain size might suggest more frequent flood events (Chen et al., 2003).

4 Discussion

4.1 Environmental and climate change of Shuangchi Maar Lake

Multiproxy studies provide a useful approach to disentangle different proxies in response to complex lake systems, and to interpret climate and environmental changes. For example, the TOC content can reflect a change in lake productivity or climate change in the sedimentary period (Shen et al., 2001). The organic $\delta^{13}C$ is affected by the source of organic matter and various climatic and environmental factors. If the organic matter of the lake sediment mainly comes from terrestrial plants, a change in $\delta^{13}C$ can reflect changes in the relative biomass contributions from terrestrial vegetation, such as C_3 and C_4 plants. For Shuangchi Lake, the impact of plants using crassulacean acid metabolism (CAM), which are mainly distributed in extremely arid areas, can be ignored (Liu et al., 2005). Due to their different carbon sequestration processes, the ecological habits and carbon isotope compositions of C_3 and C_4 plants are different. The carbon isotope composition of C_3 plants is in the range −22‰ to −34‰, with an average of −27‰, while the respective range for C_4 plants is −9 ‰ to −19‰, with an average of −13‰ (Smith and Epstein, 1971). With an increasing relative biomass of C_3/C_4 plants, the $\delta^{13}C$ value tends to become more negative. The study in Huguangyan Lake shows that changing aridity is probably the main reason for the variation of the relative biomass of C_3/C_4 plants (Liu et al., 2005). A significant decrease of effective precipitation favours C_4 herbaceous plants, because they are more drought tolerant, which results in heavier $\delta^{13}C$ values.

In order to determine the interrelation between the indices, the Pearson correlations between the indices were calculated using SPSS software. The results show good correlation between the multi-indices of Shuangchi Maar Lake. For instance, TOC is positively related with TN and C/N, but negatively correlated with mean grain size (Mz) (correlation coefficients are shown in Table 2). These indices can complement and verify each other, thus providing more reliable climate and environmental information.

Based on the multi-proxy analyses, this record can be divided into six paleoclimatic intervals. During 7.0 to 6.6 kaBP (core: 8.0 to 7.7m), TOC and TN are high, indicating that Shuangchi Lake was rich in organic matter. C/N values are more than 30, which indicates that the source of organic matter was mainly terrestrial vascular plants. The obviously negative $\delta^{13}C$ values (−31.2‰ to −22.8‰) are characteristic of the carbon isotope composition of terrestrial C_3 plants, suggesting a humid climate. Low mean grain-size values also indicate that precipitation was abundant in this period. Based on this

Table 2 Correlation analyses of environmental proxies from the core

	TOC	TN	C/N	$\delta^{13}C$
Mz	−0.60**	−0.61**	−0.52**	0.03
TOC		0.98**	0.84**	−0.05
TN			0.92**	−0.11**
C/N				−0.35**

Notes: **: Significant correlation at 0.01 level (bilateral); N = 682.

evidence, it can be concluded that the vegetation type of the Shuangchi area in this period was a tropical-subtropical forest dominated by C_3 plants.

During 6.6 to 1.4 kaBP (core: 7.7 to 5.0 m), the C/N values fluctuated frequently but were generally greater than 20, implying that the source of organic matter was still mainly terrigenous. The increases of mean grain-size and $\delta^{13}C$ indicate that the water level of the lake might have decreased. In addition, this portion of the core is loose and porous, with a lot of plant residues mixed into the sediment, and a high TOC. We speculate that Shuangchi was a typical peat bog in this period. It can be divided into three sub stages:

a: 6.6 to 5.9 kaBP. The mean grain-size was getting coarser, indicating that the water level of the basin was decreasing and that hydrodynamic forces were increasing. The rapid fluctuation of grain size may be related to flood events. It is worth noting that $\delta^{13}C$, mean grain-size and C/N ratio all reached a clear peak at ~6.1 kaBP, which may be correlated to an event that the climate was suddenly wet. The $\delta^{13}C$ values indicate that C_3 plants were still the main vegetation type at this time.

b: 5.9 to 2.5 kaBP. The rather high TOC values and plant residues indicate that Shuangchi was still a peat bog. The higher $\delta^{13}C$ values during 5.9 to 3.2 and 3.0 to 2.5 kaBP indicate that C_4 plants were relatively prosperous, due to the increase of aridity. It is worth mentioning that there is an obvious change in several indices around 3.0 kaBP, such as the sudden negative bias of $\delta^{13}C$ and the decrease in TOC and TN contents, which indicates the increasing precipitation around 3.0 kaBP. The grain size record shows a sudden increase at about 3.2 kaBP, which might be related to strong flood events.

c: 2.5 to 1.4 kaBP. The $\delta^{13}C$ values became relatively negative compared to the previous stage, which indicates an increase of C_3 plants and effective precipitation. The mean grain size shows obvious fluctuations during this period, which might suggest more frequent flood events. Overall, this stage was wetter than stage-b.

Since 1.4 kaBP (core: 5.0 to 0 m), the large and significant changes of all indices indicate that the sedimentary environment of the lake basin has changed greatly compared with the previous stages. The C/N ratio decreased rapidly and remained in a stable low range of about 10, indicating that the proportion of aquatic plants in the organic matter sources increased rapidly. The mean grain size decreased in this period, which indicates an increase in rainfall. There is almost no plant residue in the sediment of this interval. Combined with the sharp decrease of organic matter, we therefore suggest that Shuangchi turned from a peat bog to a modern lake after 1.4 kaBP. $\delta^{13}C$ became heavier due to the influences of aquatic plants in the lake.

4.2 Comparison of regional paleoclimatic records and dynamic links

The multiproxy data in Lake Shuangchi indicate several significant changes at 6.6 ka, 6.1 ka, 5.9 ka, 3.0 ka, 2.5 ka, and 1.4 kaBP. We compare the data in this study with multiple records derived from different proxies in the same lake and neighboring sites. For example, the pollen analysis of SC-1 core in Shuangchi Lake indicates that the temperature decreased, a large number of woody plants disappeared, and herbaceous plants were prosperous at about 2.7 to 2.5 kaBP (Fig. 4g, Zheng et al., 2003). The carbon and nitrogen indices of HN-1 core (also from Shuangchi Lake) show that the water level rose and aquatic plants flourished at about 3.0 kaBP; Yang et al. (2014) considered this event to be related to ENSO (Fig. 4f). Wang et al. (2016) and Sheng et al. (2017) reported a dramatic decrease in the magnetic susceptibility, and percentages of tropical and subtropical plants at 6.6 kaBP in Lake Huguangyan, and correlated this event with the melting-related freshwater fluxes into the North Atlantic and the resulting slowdown in the Atlantic Meridional Overturning Circulation and southward shifts of the Inter Tropical Convergence Zone (ITCZ) (Fig. 5 c, d). These climatic events are all visible in our record.

There are also some differences between our record and previous studies. The most remarkable climatic and environmental shift occurred at about 1.4 kaBP based on our study, when the sedimentary environment of Shuangchi switched from peat bog to lacustrine deposition. However, the east lake basin showed the major change at about 2.5 kaBP (Zheng et al., 2003; Yang et al., 2014). This may be due to dating errors of different cores, or differences in the local sedimentary environment. For example, lake water leakage through the older strata will affect transformation between swamp facies and lake facies, thus influencing the magnitude and time-scale of the local environmental response to climate. There are few reports of the 1.4 kaBP event, although Bond et al. (1997) and Wang et al. (2009) have reported it, and linked it to the North Atlantic's thermohaline circulation. The marine record of Beibu Bay in the South China Sea also showed significant increases in the median particle size and $\delta^{13}C$, and decreases in the Al/Ti ratio and Quercus pollen content at 1.4 kaBP (Lu et al., 2011). Based on a large number of historical records in China, Zhu et al. (1973) believed that the climate in China was quite cold during the period 1.8–1.4 kaBP, which is known as the Wei Jin Southern and Northern Dynasty Cold event. During this period, the political regime changed frequently, likely related to the deterioration of the living environment caused by the cold climate.

During 7.0 to 2.5 kaBP, the precipitation at Shuangchi Lake gradually decreased and the climate became drier, consistent with changes in the Asian monsoon as indicated by the oxygen isotope records of Chinese stalagmites (Wang et al., 2005) (Fig. 5). Because the Shuangchi Lake area is affected by the tropical summer monsoon, the changes in $\delta^{13}C$ and grain size indices of Lake Shuangchi reflect the change of precipitation in this area, which in turn indicates the variations in summer monsoon intensity.

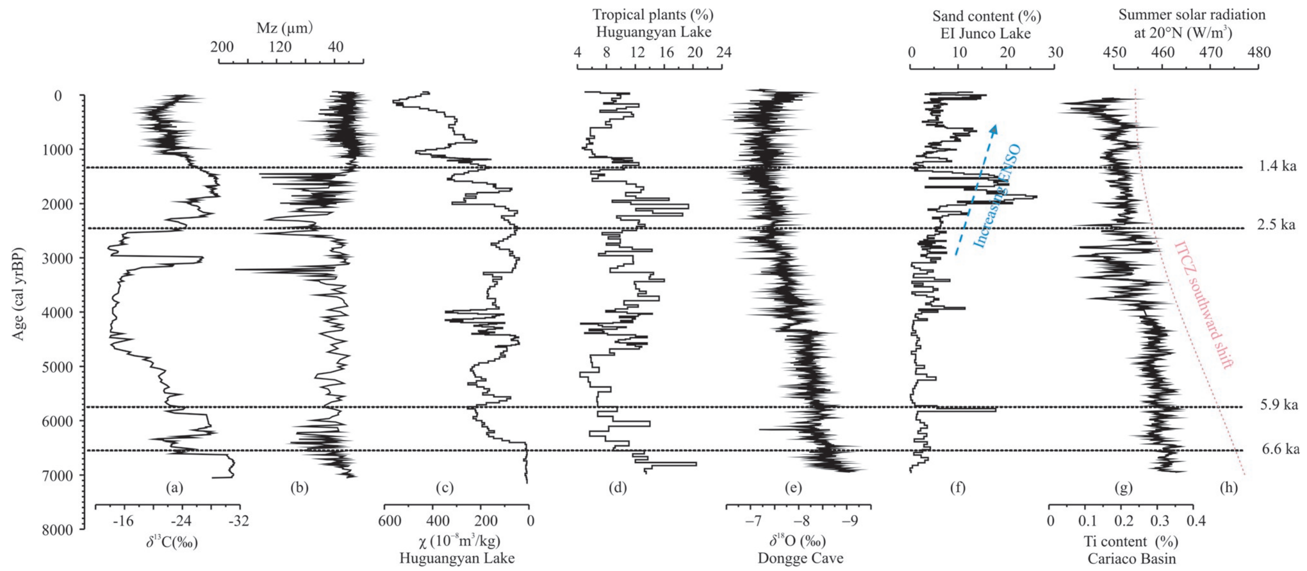

Fig. 5. Time series of geochemical records from Lake Shuangchi, with selected regional paleoclimatic records shown for comparison.

(a) δ^{13}C record and (b) mean grain-size of Lake Shuangchi sediments in the present study; (c) magnetic susceptibility (Wang et al., 2016) and (d) percentage of tropical plants in Lake Huguangyan (Sheng et al., 2017); (e) stalagmite δ^{18}O of Dongge Cave (Wang et al., 2005); (f) sand content of EI Junco Lake sediments (Conroy et al., 2008); (g) Ti content of Cariaco Basin sediments (Haug et al., 2001); (h) 20°N summer solar radiation (Laskar et al., 2004).

As insolation decreased, the ITCZ moved southward, and the intensity of the Asian Summer Monsoon also decreased during this period (Fig. 5, Haug et al., 2001; Laskar et al., 2004; Wang et al., 2005). In addition, previous research showed that the frequency and intensity of ENSO activity have increased obviously in the Holocene, especially after about 7.0 kaBP (Conroy et al., 2008). Since 2.5 kaBP, the change of effective precipitation at Shuangchi, as indicated by δ^{13}C and mean grain-size indices, is consistent with the ENSO activity reconstructed from the sand content of EI Junco Lake (Fig. 5f). Higher ENSO activity corresponds to more precipitation in the lake area.

Overall, the paleoclimate record of Shuangchi Lake in the mid- to late- Holocene reflects the history of the Asian Summer Monsoon, which was controlled by solar radiation, ITCZ and also significantly affected by short time-scale, high latitude events. When rainfall or effective humidity increases, the Summer Monsoon is stronger. Therefore, the climate events we report include two weak monsoon events (6.6 and 5.9 kaBP) and four strong monsoon events (6.1, 3.0, 2.5 and 1.4 kaBP). In addition, several flood events (6.6 to 5.9, 3.2, and 2.5 to 1.4 kaBP) are also revealed. The climate of Shuangchi Lake was mainly affected by the migration of the ITCZ and ENSO since 7.0 kaBP, with ENSO activity likely playing the dominant role after 2.5 kaBP.

5 Conclusions

We present a multi-proxy analysis (TOC, TN, C/N, δ^{13}C and grain-size) of Shuangchi Maar Lake sediments from Hainan, southern China. We conclude the following:

(1) Shuangchi turned from a peat bog into a lake at 1.4 kaBP. At this time, TOC and TN decreased sharply, and the source of organic matter changed from terrestrial plants to algaes. The C_3 plants were dominant during 7.0 to 5.9 and 2.5 to 1.4 kaBP, and C_4 plants were the main vegetation type at 5.9 to 3.2 and 3.0 to 2.5 kaBP.

(2) The higher values of mean grain size at 6.6 to 5.9, 3.2, and 2.5 to 1.4 kaBP might be linked to flood events.

(3) Several climate events (6.6 ka, 6.1 ka, 5.9 ka, 3.0 ka, 2.5 ka and 1.4 kaBP) in tropical South China, may be related to the migration of the ITCZ and ENSO. ENSO activity might play a primary role after 2.5 kaBP.

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