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The wet Little Ice Age recorded by sediments in Huguangyan Lake, tropical South China

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ABSTRACT

Although temperature decreased in a similar trend in many regions around the word during the Little Ice Age (LIA), the reconstructed humidity is remarkably different from region to region. The precipitation history during the LIA is poorly understood as compared to the temperature history in tropical South China. In this study, a sediment core with a length of 117.5 cm was recovered in the central part of Huguangyan Lake in tropical South China. Total organic carbon (TOC), total nitrogen (TN), inorganic carbon (IC) and non-residual strontium (Sr) were analyzed at approximately 1 cm intervals to study the regional precipitation changes during the LIA. Generally, Sr-containing minerals are sensitive to chemical weathering which is dominated by the precipitation in tropical South China. Thus the non-residual Sr in Huguangyan sediments can be used as an indicator of precipitation changes, which is also verified by the downcore variations of TOC, TN and IC in Huguangyan Lake. The non-residual Sr correlated positively with TOC and TN but negatively with IC in the sediment profile. TOC, TN, IC and the non-residual Sr jointly demonstrated a wet period from AD 1500 to 1750, which corresponds to the LIA. Coincidently, both the total solar irradiance (TSI) and Northern Hemisphere temperature have the lowest values between AD 1500 and 1750 over the past millennium. Therefore, the wet LIA in tropical South China was most likely caused by the low solar irradiation. During the LIA, the low solar irradiation likely resulted in the decrease of the Northern Hemisphere temperature, which weakened the intensity of the East Asian summer monsoon (EASM) and synchronously moved the north edge of the Asian summer monsoon southward, leading to an increase in the precipitation in tropical South China.

1. Introduction

Climate change of the past two millennia is one of the focuses of the “Past Global Changes” (PAGES) initiative. Significant progresses have been made in understanding the climate of the past 2000 years since PAGES came into effect (IGBP and WCRP, 1994). Recent studies have focused more on the Little Ice Age (LIA) because it was the latest worldwide typical cold climate event (Schindler, 1998; Bradley, 2000) and had a profound impact on human society (Hsu, 1998). The term “Little Ice Age” was first introduced by Matthes (1939) who documented the glacial regrowth in the Sierra Nevada, California, following the glacial ablation in the early Holocene Hypsithermal. Today, the LIA generally refers to the latest glacier expansion episode between the Mediaeval Warm Period (MWP) and the recent 20th century global warming (Bradley and Jones, 1992; Wang et al., 1998). Many paleoclimatic investigations suggest that the LIA is a global climatic event (Thompson et al., 1986; Keigwin, 1996; Mayewski et al., 2004; Yu et al., 2005). However, the initiation and termination of the LIA are geographically asynchronous (Bradley and Jones, 1993; Wang et al., 1998; Grove, 2001, 2004). A number of records documented significant changes in climate and environment in China during the LIA (Yao et al., 1991; Wang et al., 2003; Ge et al., 2004; Tan et al., 2009). Although temperature decreased globally in a similar trend, the reconstructed humidity varies significantly from region to region and there are no uniform climate change patterns (warm–wet, cold–wet, warm–dry or cold–dry) in China (Wang et al., 2003; Liu et al., 2004; Mayewski et al., 2004; Tan et al., 2009). To better understand the climate changes and its effects on environment during the LIA, more high-resolution records from widely separated locations are needed.

In tropical South China, there are several crater lakes (e.g. Huguangyan Lake, Tianyang Lake, Shuangchi Lake) available for paleoclimate investigation, but the previous studies mostly focused on large time scales (Zheng and Lei, 1999; Liu et al., 2000; Fuhrmann et al., 2003; Mingram et al., 2004; Luo et al., 2006; Yang et al., 2006; Wang et al., 2007). Knowledge of precipitation changes is much poorer than that of temperature during the LIA in tropical

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South China. In this study, Huguangyan Lake, a small closed maar lake with a small catchment, was selected to study the precipitation change because it is a reliable and high-resolution nature archive as indicated by several studies (Chu et al., 2002; Li et al., 2009).

Total organic carbon (TOC) and total nitrogen (TN) in sediments are closely associated with terrestrial and authigenic organic matter and have been widely used to indicate paleoproductivity/paleoclimate changes in the catchment. Authigenic inorganic carbon (IC) is often used as an indicator of hydrological and climatic changes, especially in a closed lake. A previous study preliminarily demonstrated that the non-residual strontium (Sr) content in the lake sediment is controlled by the chemical weathering in the catchment and can potentially reflect the precipitation changes in tropical South China (Zeng et al., 2011). TOC, TN, IC and the non-residual Sr in lake sediments are all controlled by the local climate and environment, and together may provide comprehensive information on the catchment climate and environment, especially in the small closed lake such as Huguangyan Lake. Therefore, TOC, TN, IC and the non-residual Sr in Huguangyan sediments are analyzed in this study for reconstructing the local climatic/environmental changes, with prime emphasis on the precipitation changes during the LIA.

2. Regional setting

Huguangyan Lake (21°9′N, 110°17′E) is located on the low-lying Leizhou Peninsula in the tropical region of South China (Fig. 1), and is strongly influenced by the climate regime of the Northwest Pacific Ocean. The regional climate is strongly seasonal, with 90% of the total mean annual precipitation of 1567 mm between April and October, controlled mainly by variation in the position and intensity of the sub-tropical high in the West Pacific Ocean (Li, 1993; Chu et al., 2002). The dry season is from November to March. Annual mean temperature is 23 °C with limited variations. The lake is meromictic with a sharp temperature gradient (thermocline) between 6 and 13 m depth.

Huguangyan Lake is a closed maar lake and its crater basin was created from basaltic phreatomagmatic eruptions (Liu, 1999; Chu et al., 2002). The tephra ring is 10–58 m above the lake surface and consists of pyroclastics. The lake has a surface area of 2.3 km^2 and a catchment area of 3.5 km^2. The catchment comprises only the inner slopes of the crater rim and is well covered by evergreen sub-tropical forest. The lake has no surface inflow or outflow. The maximum water depth is 22 m. Hydrochemical data of Huguangyan Lake (Mingram et al., 2004) (Table 1) demonstrate its low salinity, which implies a high ratio of direct precipitation into the lake and the inflow of mineralized ground water. The lake water is weakly alkaline with a pH of 7.6. Primary production of the lake is likely limited by the availability of soluble reactive phosphorus (SRP). Chemical precipitation of autochthonous calcite is negligible because of the low Ca concentration in the lake water, and nearly no $CaCO_3$ was observed in Huguangyan Lake (Mingram et al., 2004). Pyroclastics are the main rock type in the catchment, which lacks carbonate. Thus, the catchment is characterized by silicate weathering.

3. Material and methods

Sediment core F was retrieved from the deepwater part of Huguangyan Lake in December 2004 using a gravitational sediment sampler and a polyethylene tube with a diameter of 59 mm. The sediment core was perfectly preserved. The suspended layer was not disturbed and the interface water was clear. The core with a length of 117.5 cm was sectioned at approximately 1 cm intervals, and 106 samples were collected in total. The samples were put into plastic bags and sealed on site. After being dried in the freeze-drier (FD-IA-50), sediment samples were ground to homogeneous powders (smaller than 124 μm).

Contents of total carbon and nitrogen were measured by the element analyzer (PE2400 SERIES II) with relative errors less than 5%. Chemical volumetric method was used to measure IC with errors less than 10%. TOC was calculated as TC minus IC.

The non-residual Sr in the sediment samples were obtained by extraction with 1M HCl according to the procedure recommended by ASTM D3974-81 Practice B (Snape et al., 2004; Lavilla et al., 2006). This standard practice indicates that the metals released from the sediment upon acid extraction are bound as hydroxides, carbonates, sulphides, oxides and organic materials. The use of lower HCl concentrations, despite being a common practice, may be ineffective since the acidity can be neutralized by carbonates

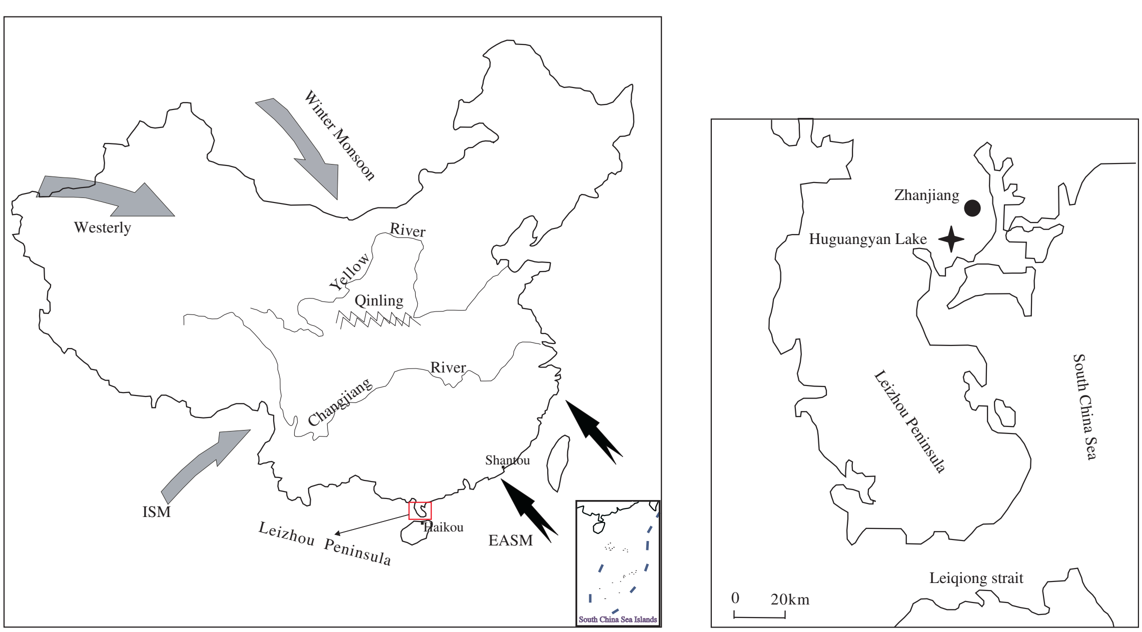

Fig. 1. Location of Huguangyan Lake in tropical South China.

Table 1
Surface water composition of Huguangyan Lake (October 10, 2001) (Mingram et al., 2004).

Cations[a]	Na^+ (mg/l)	K^+ (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Fe^{2+} (mg/l)	Mn^{2+} (mg/l)	Sr^{2+} (mg/l)	Ba^{2+} (mg/l)	Total cations (mequ/l)
	5.8	2.3	6.1	6.1	0.006	0.001	0.047	0.004	1.12
Anions[b]	F^- (mg/l)	Cl^- (mg/l)	NO_3^- (mg/l)	SO_4^{2-} (mg/l)	DIC (mg/l)	Nutrients	Si (mg/l)	SRP (mg/l)	Total anions (mequ/l)
	0.15	7.7	0.7	9.6	8.3		0.5	<0.01	1.13

[a] Membrane filtered sample aliquots (0.45 μm) stabilized by adding of nitric acid (Merck, Suprapur), measurements by ICP-AES.
[b] DIC (total dissolved inorganic carbon) measured by IR-spectrometry, Si by ICP-AES, other components determined by isocratic ion-exchange chromatography, DIC is completely considered as HCO_3^- for the calculation of the anion sum.

present in the sediment (Luoma and Bryan, 1981; Snape et al., 2004). On the other hand, higher HCl concentrations can lead to the attack of residual sediment phases (Luoma and Bryan, 1981; Ying et al., 1992). Extractions were carried out in 50 ml capacity polyethylene tubes using a 0.5 g sample mass and a 20 ml extractant volume. After agitation for 2 h, the extract was separated by centrifugation (4000 rpm, 20 min). The extractions were carried out in triplicate. The three supernatants were merged together and made up to a 100 ml by addition of de-ionized water. The non-residual Sr contents were measured by Inductively Coupled Plasma Mass Spectrometer (ICP-MS) with an average precision of 5% at the Institute of Geochemistry, Chinese Academy of Sciences.

The specific activity of ^{210}Pb was determined using α-spectrometry through its granddaughter ^{210}Po, with ^{208}Po and ^{209}Po added as an internal yield tracer. The specific activity of ^{137}Cs was measured by γ-spectrometry using a Multichannel Analysis System (Canberra S-100) and low-background germanium detector.

Six terrestrial plant macrofossils were picked out from four different sediment samples to carry out radiocarbon dating on the accelerator mass spectrometry (AMS) at the Scottish Universities Environmental Research Centre AMS Facility. The calibrated age was determined from the University of Oxford Radiocarbon Accelerator Unit calibration program (OxCal3).

4. Results

4.1. Chronology of sediment core F

The cored sediment in Huguangyan Lake consists of homogeneous greenish-grey gyttja without clear lamination. ^{14}C, ^{210}Pb, and ^{137}Cs are used to date the sediment core. Mass depth (gcm^{-2}), instead of depth (cm), is adopted to calculate the sedimentation rate because the sediment is usually compacted in the lower part of the sediment core as confirmed by the decreased sediment porosity with depth (Chen et al., 2005). As shown in Fig. 2a, the unsupported ^{210}Pb activity versus mass depth is well approximated by an exponential equation, indicating a uniform accumulation over the upper 30 cm layer. Thus the Constant Flux and Constant Sedimentation (CFCS) model (Robbins, 1978; Appleby, 2001) can be used and the sedimentation rate of the upper 30 cm layer can be calculated from the slope of the regression line. The result showed that the average sedimentation rate of the upper-layer sediments was approximately 0.06 gcm^{-2} a^{-1}. This is also supported by the distribution characteristics of ^{137}Cs in the sediment core. The peaks of ^{137}Cs occur from 1963 to 1976 (Fig. 2a), which is well-known to be the main fallout period of global ^{137}Cs in the atmosphere. The accordance between the unsupported ^{210}Pb and ^{137}Cs time markers indicates the stable sediment accumulation and good preservation conditions in Huguangyan Lake. The rapid decrease of ^{137}Cs activity in the top sediment layers is mainly attributed to radioactive decay and the dilution of high TOC in the surface sediment. As shown in Fig. 3, the TOC is extremely high in the upper 3 cm sediment layers.

Linear interpolation between radiocarbon measurements from six terrestrial plant macrofossils is used to calculate sediment age by assuming that the sediment accumulation rate between the dated levels was linear (Fig. 2b). The average sedimentation rate in the upper part of the sediment core was 0.066 gcm^{-2} a^{-1} according to the ^{14}C age of the plant macrofossils at the depth of 54.5 cm, 56 cm and 58 cm (Table 2). This is in good agreement with the ^{210}Pb and ^{137}Cs dating results. A lower accumulation rate of 0.036 gcm^{-2} a^{-1} occurred in the lower part of the sediment core possibly as a result of less human influence.

4.2. TOC, TN, IC and non-residual Sr

TOC/TN ratios in the sediments of Huguangyan Lake are low, varying between 7.5 and 12, and most ratios are below 10. The TOC contents range from 0.86% to 5.48%. The TN contents present

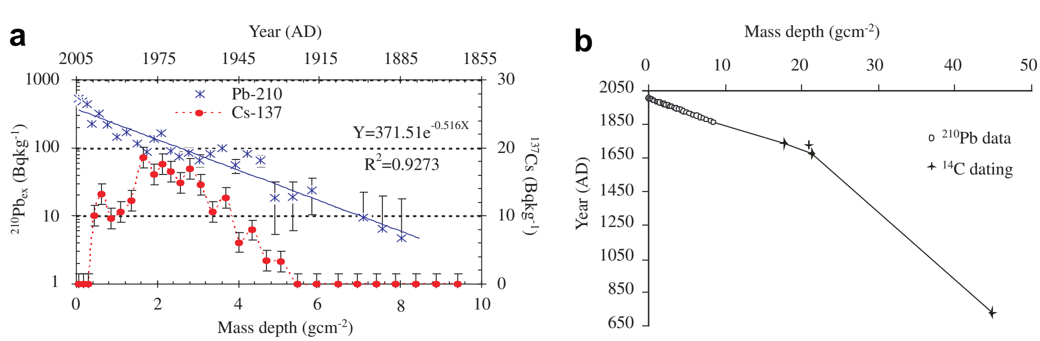

Fig. 2. (a) Variations in specific activities of the unsupported ^{210}Pb and ^{137}Cs in the sediment core of Huguangyan Lake. The oblique solid line is the ^{210}Pb exponential curve. The profile, unsupported ^{210}Pb activity versus mass depth in gcm^{-2}, is well represented by the exponential equation $C = C(0)e^{-\lambda m/r}$, where r denotes the dry mass sedimentation rate (gcm^{-2} a^{-1}), m denotes the mass depth (gcm^{-2}), λ is the ^{210}Pb radioactive decay constant ($0.03114a^{-1}$) and C(0) is the unsupported activity at the surface of the core. The dating method described by Appleby (2001) yielded C(0) = 371.51 $Bgkg^{-1}$, r is 0.06 gcm^{-2} a^{-1} from the regression line. (b) Mass depth versus age in the sediment core in Huguangyan Lake. Six terrestrial plant remains were found in four sediment samples at the depth of 54.5 cm, 56 cm, 58 cm and 116 cm respectively, corresponding to the mass depth of 17.694 gcm^{-2}, 18.738 gcm^{-2}, 21.362 gcm^{-2}, and 45.480 gcm^{-2} respectively.

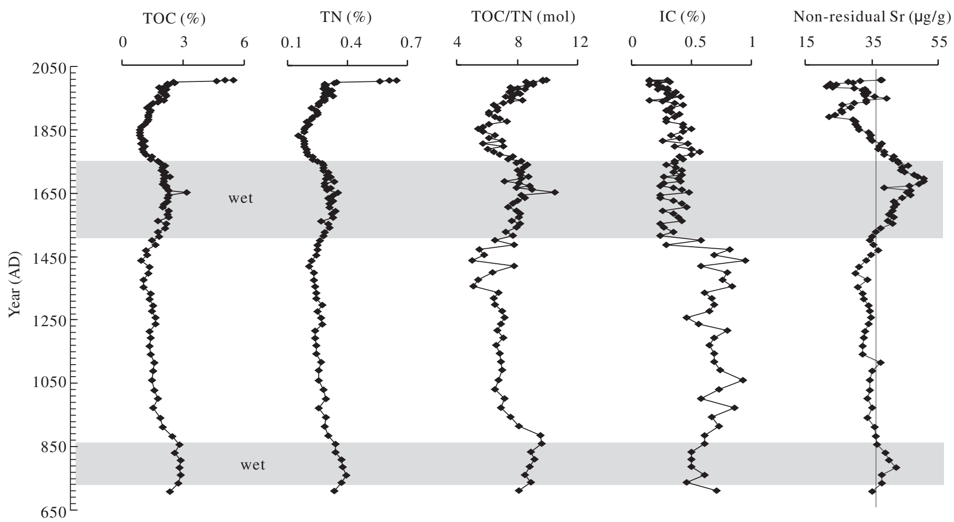

Fig. 3. Variations of TOC, TN, TOC/TN, IC and the non-residual Sr in the sediment core in Huguangyan Lake. Horizontal shaded bars show two wet episodes during the last 1300 years. The vertical line represents the average value of the non-residual Sr content in the sediment core.

a comparable age profile to that of TOC and range from 0.15% to 0.65%. The IC contents show a variation pattern opposite to TOC and TN and range from 0.14% to 0.95%. The non-residual Sr contents vary from 21.5 μg/g to 50.8 μg/g. Before AD 1930, the non-residual Sr correlated positively with TOC ($r = 0.595$, $p < 0.001$) and TN ($r = 0.508$, $p < 0.001$), but negatively with IC ($r = -0.317$, $p < 0.01$). After AD 1930, the correlation disappeared. TOC and TN increased sharply, IC decreased, and the non-residual Sr fluctuated abruptly but maintained low values.

5. Discussion

5.1. Paleoclimate implications of TOC and TN

Total organic carbon (TOC) and total nitrogen (TN) in lacustrine sediments are indicative of the productivity (Meyers, 1997). The atomic TOC/TN ratio reflects the proportion of allochthonous (terrestrial) vs. autochthonous (algal) organic matter, while the former has a ratio of greater than 20, and the latter is typically 4–10 (Meyers, 1997). TOC/TN ratios in the sediments of Huguangyan Lake are low, varying between 7.5 and 12. This suggests that the organic matter was derived largely from planktonic algae. TOC and TN are stratigraphically correlated, probably because both elements are bound on organic matter. Variations of TOC and TN may reflect changes in temperature or rainfall because warm climate and high nutrients derived by rainfall are favourable for alga growth (Brenner et al., 1991; Rein and Negendank, 1993; Sifeddine et al., 1996).

In this tropical area, the surface-water temperatures are high year-round, and thus temperature is probably a less important factor controlling algal productivity. Therefore, increased rainfall may be responsible for the observed increase in TOC, TN, and TOC/TN.

5.2. Paleoclimate implications of IC

Carbonates are probably of authigenic origin because the catchment of Huguangyan maar consists of non-calcareous rocks (Chu et al., 2002). The only carbonate mineral detectable in Huguangyan sediments by means of X-ray diffraction and Scanning Electron Microscopy-Energy Dispersive Spectroscopy (SEM-EDS) analyses is siderite (Mingram et al., 2004). Primary siderite from iron-meromictic lakes, especially from tropical or sub-tropical climates, has been frequently reported from the Eocene (e.g. Lake Tubutulik, Dickinson, 1988; Eckfeld and Messel maar lakes, Bahrig, 1989; Mingram, 1998) and the Holocene (Lake Kivu, Degens and Stoffers, 1976; Lake Nyos, Bernard and Symonds, 1989). All these lakes, as well as Huguangyan Lake, are surrounded by mafic volcanic rocks and deeply weathered red soils with a high Fe/Ca ratio, which is, among other factors such as high p_{CO2}, reducing conditions and low dissolved sulphur (Bernard and Symonds, 1989), essential for siderite formation (Kelts and Hsu, 1978).

In a lake with a seasonally anoxic hypolimnion, processes in the water column can also influence carbonate precipitation over time (Dean, 1999). If productivity of the lake increases, the rain rate of organic carbon (OC) from the epilimnion increases. Biogenic removal of CO_2 and accompanying increase in pH may also increase the production of carbonate. On the other hand, the decomposition of organic matter in the hypolimnion will decrease the pH of the hypolimnion, causing a greater dissolution of carbonate and therefore a decrease in the rain rate of carbonate to the sediment–water interface. Although TOC and IC show an inverse relationship in the sediments of Huguangyan Lake, the influence of this process on carbonate precipitation can be neglected because of the low TOC through the whole core.

Table 2
Radiocarbon dating results in Huguangyan Lake.

Sample ID	Lab ID	Material	$\delta^{13}C$ (‰PDB)	^{14}C age (BP)	Calibrated age (BP)	Age used for calculation (BP)	Depth (cm)	Mass depth (gcm^{-2})	Sedimentation rate ($gcm^{-2}\ a^{-1}$)
F-55	SUERC-8674	Terrestrial plant	−28.1	290 ± 18	265 ± 35	265	54.5	17.694	0.067
F-57	SUERC-8675	Terrestrial plant	−27.7	303 ± 20	280 ± 35	280	56.0	18.738	0.067
F-58-1	SUERC-8676	Terrestrial plant	−25.0	366 ± 23	370 ± 35	328	58.0	21.362	0.065
F-58-2	SUERC-8677	Terrestrial plant	−27.7	319 ± 20	300 ± 35				
F-58-3	SUERC-8678	Terrestrial plant	−29.2	351 ± 23	315 ± 35				
F-105	SUERC-8679	Terrestrial plant	−25.0	1273 ± 20	1275 ± 35	1275	116.0	45.480	0.036

Changing lake levels may have additional influences on the precipitation of carbonates through altering the relative mixing depth of the water column and thus the relation between epilimnion and hypolimnion in stratified lakes. In thermally stratified lakes, Fe^{2+} is accumulated in the water of relatively low pH below the thermocline. Under such conditions the precipitation of $FeCO_3$ in the water column depends on the diffusive and advective exchanges between the deep and surface water. Siderite precipitation within the water column can therefore be strongly influenced by the fluctuations of the thermocline as it has been proposed for manganosiderites from Lake Kivu (East Africa, Degens and Stoffers, 1976). Low water stands are favorable for the precipitation of carbonate in Huguangyan Lake (Mingram et al., 2004). Thus, IC variations may reflect changes in the lake level and the precipitation/evaporation ratio in Huguangyan Lake, a typically hydrologically-closed maar lake.

5.3. Environmental significances of the non-residual Sr in lake sediments

Under natural conditions, lake sediments have two material sources. One is terrigenous debris, which is directly brought in by physical erosion and exists in the sediments mainly as the residual form. The other is dissolved substances, produced by chemical weathering in the catchment and deposit in lake sediments as the non-residual form through physical adsorption, chemical coprecipitation and biological uptaking. Previous studies have shown that the Rb/Sr ratio in weathering residue increases as the weathering intensity increases due to a higher activity of Sr and a more inert nature of Rb. As the main sink of the transported surface material, lakes receive lots of weathering products of rock and soil in the catchment. Stronger chemical weathering leads to more dissolved Sr^{2+} being transported into the lake. The Rb/Sr ratios of the bulk sediments of Lake Daihai were interpreted to be the direct result of changes in fluxes of dissolved materials controlled by climatic change within a single catchment (Jin et al., 2006). Essentially, most discussion on Rb/Sr ratios as an indicator of chemical weathering in watershed only focused on the non-residual Sr. The study in Cuoe Lake (Wu et al., 2006) also showed that Sr and TOC had almost the same variation pattern, indicating that the high Sr as well as high TOC represented the enhanced macrophyte and stronger chemical weathering due to warmer and wetter climate. The increase of Sr in sediments was usually considered to be the contribution of more dissolved Sr inputs.

Strontium acts as an analog to Ca because both are alkaline earth elements with similar ionic radius and the same valence (Bailey et al., 1996). However, in Huguangyan Lake, almost no $CaCO_3$ was observed and Ca exists mainly in detritus minerals. The authors' unpublished data shows that about 75% of the non-residual Sr exists in the fractions of hydroxides and Fe–Mn oxides dominated by in-lake processes including absorption and/or coprecipitation. Thus, Ca and the non-residual Sr are respectively controlled by two distinct processes in Huguangyan Lake. The content of the non-residual Sr in the lake sediment is mainly determined by Sr^{2+} concentration in the lake water which is controlled by the chemical weathering.

As discussed above, the non-residual Sr in lake sediments can thus be used as an indicator of chemical weathering. Chemical weathering is sensitive to changes in temperature and humidity. Under cold and dry climate conditions, the dissolved Sr content is mainly controlled by temperature and decreases with decreasing temperature. Under warm and wet conditions, precipitation is more important and increasing precipitation brings more dissolved Sr into the lake sediment (Chen et al., 1999; Jin et al., 2001).

5.4. Precipitation changes during the past millennium

There are two periods with high non-residual Sr contents in the sediment core of Huguangyan Lake in the past 1300 years, AD 1500 ∼ 1750 and AD 740 ∼ 860 respectively, implying strong chemical weathering in these two periods (Fig. 3). Although there are disputable views about the initiation and termination of the LIA in tropical South China, all the evidence indicates that the LIA occurred during AD 1500 ∼ 1900. Therefore, it was cold, and temperature could not enhance the degree of chemical weathering during the LIA. Accordingly, it is the increase of precipitation/humidity that led to enhanced chemical weathering in the basin. This is mirrored by low IC and high TOC and TN. As discussed previously, TOC, TN and IC reflect rainfall changes in the catchment of Huguangyan Lake. Higher TOC and TN and lower IC imply the increased precipitation. The result suggests that the humid climate caused a significant enhancement of chemical weathering and a gradual increase of planktonic algae. Before AD 1930, the non-residual Sr correlated positively with TOC and TN, but negatively with IC. This may imply that chemical weathering intensity in tropical South China is predominantly controlled by precipitation, whereas the influence of temperature is not significant. Therefore, the non-residual Sr may be used as an indicator of paleoprecipitation in tropical South China. This is verified by the comparison of the non-residual Sr and Drought/Flood (D/F) index of Haikou city and Shantou city, both of which are located near Huguangyan Lake. D/F index is an indicator of variations of effective moisture. Overall, D/F index and the non-residual Sr contents displayed similar changes (Fig. 4), although their resolutions are different.

The non-residual Sr, in combination with TOC, TN and IC, suggests that the rather wet periods at Huguangyan Lake occurred from AD 1500 to 1750 and from AD 740 to 860, and the wettest period was from AD 1600 to 1700, during the last 1300 years (Fig. 3). This implies that the climate in tropical South China was dry during the Mediaeval Warm Period (MWP) and wet during the Little Ice Age (LIA).

After AD 1930, TOC and TN increased sharply as a result of the impact of human activities while IC decreased due to the acid deposition. The non-residual Sr contents fluctuated strongly, but maintained low values, which implies that the climate was relatively dry.

5.5. Precipitation changes during the LIA in tropical South China and possible mechanism

The precipitation in Huguangyan Lake is mainly influenced by the East Asian summer monsoon (EASM) (Fig. 1). The East Asian summer monsoon precipitation in China is controlled by the interaction of the frontal systems between cold-dry air mass from high-latitude continents and warm-wet air mass from tropical oceans (Guo, 1985). At present, the precipitation zone is located in south of Nanling in late spring and early summer, and then moves to the middle and lower Yangtze River valley and forms a continuous rain (the so-called plum rains). In July and August, it stays in north China, northeast China and the eastern region of northwest China, and makes the monsoon region of northern China the rainy season. The East Asian summer monsoon front advances, retreats or persists with seasonal changes in solar radiation in the central and eastern China. The solar radiation which is caused by the orbital changes influenced the East Asian summer monsoon on central/decadal scales over the past 12,000 years, is similar to that in modern China. Tan et al. (2008) argued that solar activity controlled the motion of the north edge of the Asian summer monsoon by affecting the Asia summer monsoon intensity, the East Asian winter monsoon intensity, and the locations of westerlies. When solar activity increases, the temperature of land increases quickly. The Asian summer monsoon is strengthened and

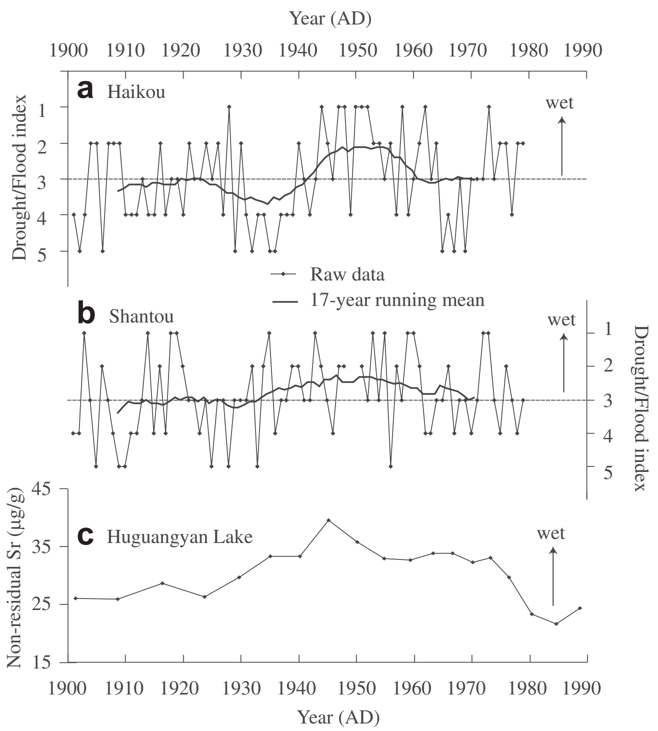

Fig. 4. Comparison of variation of the non-residual Sr and the Drought/Flood index of Haikou city and Shantou city. (a) the D/F index of Haikou between AD 1901 and 1979; (b) the D/F index of Shantou between AD 1901 and 1979; (c) the non-residual Sr in the sediments in Huguangyan Lake. The bold black lines in (a) and (b) show the 17-year running mean of D/F index.

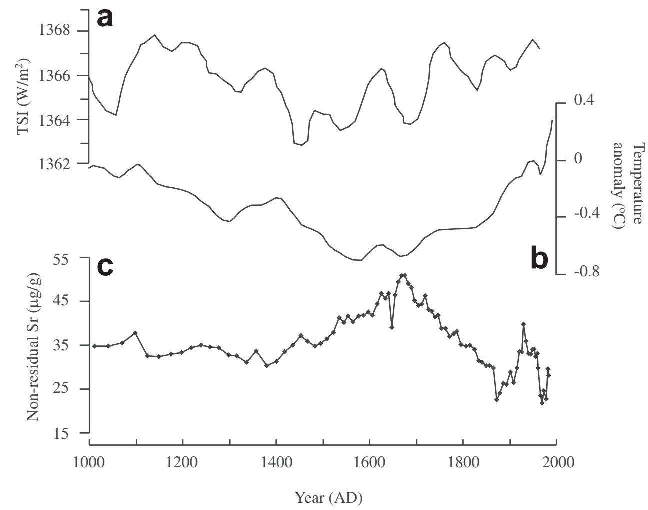

Fig. 5. Comparison of the non-residual Sr, TSI and Northern Hemisphere temperature. (a) TSI (total solar irradiance) reconstructed based on the smoothed cosmonuclides production record (Bard et al., 2000); (b) Northern Hemisphere temperature reconstructed through combining low-resolution proxies with tree-ring data and using a wavelet transform technique to achieve timescale-dependent processing of the data (Moberg et al., 2005).

the East Asian winter monsoon is weakened, which results in the northward moving of the north edge of the Asian summer monsoon. At the same time, the increase of solar activity forces the westerlies to move northward (Haigh, 1996), so that the Asian summer monsoon will move northward into the northwest inner land and bring rainfall there. In contrast, when solar activity weakens, the temperature of land decreases quickly, the winter monsoon is strengthened (Xiao et al., 2006), the summer monsoon is weakened, and the north edge of the Asian summer monsoon and westerlies move southward synchronously. Daihai Lake (Zhang, 1984), Dali Lake (Xiao et al., 2008), Qinghai Lake (Henderson et al., 2010), Longxi area (Tan et al., 2008) and Wanxiang cave (Zhang et al., 2008), all of which are located near the north limit of the Asian summer monsoon, had less precipitation, while it was wet in the middle and lower Yangtze River valley during the LIA (Zheng et al., 2006).

It has been widely accepted that the variability of the Asian monsoon system is driven directly by solar forcing (Hong et al., 2000; Agnihotri et al., 2002; Fleitmann et al., 2004; Tan et al., 2004). ^{14}C and ^{10}Be records are considered as the most reliable proxies of changes in solar activity (Hoyt and Schatten, 1997; Magny, 2004; Muscheler et al., 2007), although cosmogenic radionuclide records are also influenced by both the geomagnetic field and climate (Renssen et al., 2000; Muscheler et al., 2007). As shown in Fig. 5, the total solar irradiance (TSI), reconstructed based on the smoothed cosmonuclide production records, was significantly reduced between AD 1450 and 1750 (Bard et al., 2000). The reconstruction of Northern Hemisphere temperatures for the past 2000 years, by combining low-resolution proxies with tree-ring data and using a wavelet transform technique to achieve timescale-dependent processing of the data, demonstrated the coldest period in the past 2000 years occurred between AD 1500 and 1750 (Moberg et al., 2005). Thus, it can be argued that the low solar irradiance is the main factor which contributed to the wet climate between AD 1500 and 1750 in tropical South China, although tropical storms and typhoons also influenced precipitation. Low solar irradiation caused the decrease in Northern Hemisphere temperature, which weakened the intensity of EASM, moved the north edge of the Asian summer monsoon southward synchronously, and caused an increase in precipitation in tropical South China. This inference was also supported by the paleoclimate simulation of the Little Ice Age. The simulation (Liu et al., 2004) reflected that the composite effect of the decrease of solar radiation and the increase of volcanic dust caused the summer monsoon precipitation increase in East China and decrease in South Asia during the LIA.

6. Conclusions

The non-residual Sr in the lake sediment can serve as a reliable proxy for chemical weathering in the catchment. In tropical South China, the chemical weathering is mainly controlled by the precipitation. Thus the non-residual Sr may reflect precipitation changes, which is verified by the downcore variations of TOC, TN and IC in Huguangyan Lake. The non-residual Sr, in combination with TOC, TN and IC, suggests that the rather wet periods in Huguangyan Lake occurred from AD 1500 to 1750 and from AD 740 to 860 during the past 1300 years. The wet period from AD 1500 to 1750 corresponds to the lowest values of TSI and Northern Hemisphere temperature, implying that the low solar irradiance may be the main factor contributing to the wet climate during the LIA in tropical South China. There was more precipitation in tropical South China when the intensity of EASM was weak, which was caused by relatively low solar irradiation, and *vice versa*. The relationship between solar radiation and the precipitation of EASM in tropical South China is opposite to that in the region near the north limit of the Asian summer monsoon, which indicates that Huguangyan Lake is an ideal place to study EASM activity.

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References

Agnihotri, R., Dutta, K., Bhushan, R., Somayajulu, B.L.K., 2002. Evidence for solar forcing on the Indian monsoon during the last millennium. Earth and Planetary Science Letters 198, 521–527.
Appleby, P.G., 2001. Chronostratigraphic techniques in recent sediments. In: Last, W.M., Smol, J.P. (Eds.), Tracking Environmental Changes Using Lake Sediments. Basin Analysis, Coring, and Chronological Techniques, vol. 1. Kluwer Academic Publishers, Dordrecht, pp. 171–203.
Bahrig, B., 1989. Stable isotope composition of siderite as an indicator of the paleoenvironmental history of oil shale lakes. Palaeogeography, Palaeoclimatology, Palaeoecology 70, 139–151.
Bailey, S.W., Hornbeck, J.W., Driscoll, C.T., Gaudette, H.E., 1996. Calcium inputs and transport in a base-poor forest ecosystem as interpreted by Sr isotopes. Water Resources Research 32, 707–719.
Bard, E., Raisbeck, G., Yiou, F., Jouzel, J., 2000. Solar irradiance during the last 1200 years based on cosmogenic nuclides. Tellus Series B-Chemical and Physical Meteorology 52, 985–992.
Bernard, A., Symonds, R.B., 1989. The significance of siderite in the sediments from Lake Nyos, Cameroon. Journal of Volcanology and Geothermal Research 39, 187–194.
Bradley, R.S., Jones, P.D., 1992. Climate since AD 1500. Routledge, London.
Bradley, R.S., Jones, P.D., 1993. Little Ice Age's summer temperature variations: their nature and relevance to recent global warming trends. Holocene 3, 367–376.
Bradley, R.S., 2000. Climate paradigms for the last millennium. Pages Newsletter 8, 2–3.
Brenner, M., Dorsey, K., Song, X.L., Wang, Z.G., Ruihua, L., Binford, M.W., Whitmore, T.J., Moore, A.M., 1991. Paleolimnology of Qilu-Hu, Yunnan Province, China. Hydrobiologia 214, 333–340.
Chen, J., An, Z.S., Head, J., 1999. Variation of Rb/Sr ratios in the loess-paleosol sequences of central China during the last 130,000 years and their implications for monsoon paleoclimatology. Quaternary Research 51, 215–219.
Chen, J.A., Wan, G.J., Zhang, D.D., Chen, Z.L., Xu, J.Y., Xiao, T.F., Huang, R.G., 2005. The 'Little Ice Age' recorded by sediment chemistry in Lake Erhai, southwest China. Holocene 15, 925–931.
Chu, G.Q., Liu, J.Q., Sun, Q., Lu, H.Y., Gu, Z.Y., Wang, W.Y., Liu, T.S., 2002. The 'Mediaeval warm period' drought recorded in Lake Huguangyan, tropical South China. Holocene 12, 511–516.
Dean, W.E., 1999. The carbon cycle and biogeochemical dynamics in lake sediments. Journal of Paleolimnology 21, 375–393.
Degens, E.T., Stoffers, P., 1976. Stratified waters as a key to the past. Nature 263, 22–27.
Dickinson, K.A., 1988. Paleolimnology of Lake Tubutulik, an ironmeromictic Eocene Lake, eastern Seward Peninsula, Alaska. Sedimentary Geology 54, 303–320.
Fleitmann, D., Burns, S.J., Neff, U., Mudelsee, M., Mangini, A., Matter, A., 2004. Palaeoclimatic interpretation of high-resolution oxygen isotope profiles derived from annually laminated speleothems from Southern Oman. Quaternary Science Reviews 23, 935–945.
Fuhrmann, A., Mingram, J., Lucke, A., Lu, H.Y., Horsfield, B., Liu, J.Q., Negendank, J., Schleser, G.H., Wilkes, H., 2003. Variations in organic matter composition in sediments from Lake Huguang Maar (Huguangyan), South China during the last 68 ka: implications for environmental and climatic change. Organic Geochemistry 34, 1497–1515.
Ge, Q.S., Zheng, J.Y., Man, Z.M., Fang, X.Q., Zhang, P.Y., 2004. Key points on temperature change of the past 2000 years in China. Progress in Natural Science 14, 730–737.
Grove, J.M., 2001. The initiation of the "Little Ice Age" in regions round the North Atlantic. Climatic Change 48, 53–82.
Grove, J.M., 2004. Little Ice Ages: Ancient and Modern. Routledge, London.
Guo, Q.Y., 1985. The variations of summer monsoon in East Asia and the rainfall over China. Journal of Tropical Meteorology 1, 44–52 (in Chinese, with English Abstract).
Haigh, J.D., 1996. The impact of solar variability on climate. Science 272, 981–984.
Henderson, A.C.G., Holmes, J.A., Leng, M.J., 2010. Late Holocene isotope hydrology of Lake Qinghai, NE Tibetan Plateau: effective moisture variability and atmospheric circulation changes. Quaternary Science Reviews 29, 2215–2223.
Hong, Y.T., Jiang, H.B., Liu, T.S., Zhou, L.P., Beer, J., Li, H.D., Leng, X.T., Hong, B., Qin, X.G., 2000. Response of climate to solar forcing recorded in a 6000-year delta O-18 time-series of Chinese peat cellulose. Holocene 10, 1–7.
Hoyt, D.V., Schatten, K.H., 1997. The Role of the Sun in Climate Change. Oxford University Press, Oxford, 1–279 pp.
Hsu, J.K., 1998. Sun, climate, hunger, and mass migration. Science in China (Series D) 41, 449–472.
IGBP, P., WCRP, C., 1994. The PAGES/VLIVAR Intersection Report of a Joint IGBP-WCRP Workshop. Venice, Italy.
Jin, Z.D., Wang, S.M., Shen, J., Zhang, E.L., Li, F.C., Ji, J.F., Lu, X.W., 2001. Chemical weathering since the Little Ice Age recorded in lake sediments: a high-resolution proxy of past climate. Earth Surface Processes and Landforms 26, 775–782.
Jin, Z.D., Cao, J.J., Wu, J.L., Wang, S.M., 2006. A Rb/Sr record of catchment weathering response to Holocene climate change in inner Mongolia. Earth Surface Processes and Landforms 31, 285–291.
Keigwin, L.D., 1996. The Little Ice Age and medieval warm period in the Sargasso Sea. Science 274, 1503–1508.
Kelts, K., Hsu, K.J., 1978. In: Lerman, A. (Ed.), Freshwater Carbonate Sedimentation. Lakes. Springer, New York, Heidelberg, Berlin, pp. 295–323.
Lavilla, I., Filgueiras, A.V., Valverde, F., Millos, J., Palanca, A., Bendicho, C., 2006. Depth profile of trace elements in a sediment core of a high-altitude lake deposit at the Pyrenees, Spain. Water Air and Soil Pollution 172, 273–293.
Li, J., Zhang, W., Tian, S.H., Chen, J.A., 2009. Silicon isotope compositions of diatoms as indicators of environmental change in the sediment of Maar Lake Huguangyan, Guangdong Province, China. Acta Mineralogica Sinica 29, 530–535 (in Chinese, with English Abstract).
Li, K.R., 1993. The Climate in Western Pacific Ocean and China. Marine Press, Beijing (in Chinese).
Liu, J.Q., 1999. Volcanoes in China. Science Press of China, Beijing (in Chinese).
Liu, J.Q., Lu, H.Y., Negendank, J., Mingram, J., Luo, X.J., Wang, W.Y., Chu, G.Q., 2000. Periodicity of Holocene climatic variations in the Huguangyan Maar Lake. Chinese Science Bulletin 45, 1712–1717.
Liu, J., Chen, X., Wang, S.M., Zheng, Y.Q., 2004. Palaeoclimate simulation of Little Ice Age. Progress in Natural Science 14, 716–724.
Luo, P., Zheng, Z., Yang, X.Q., 2006. Holocene magnetic susceptibility from Shuangchi Maar Lake, Hailan Island and its environmental significance. Tropical Geography 26, 211–217 (in Chinese, with English Abstract).
Luoma, S.N., Bryan, G.W., 1981. A statistical assessment of the form of trace-metals in oxidized estuarine sediments employing chemical extractants. Science of the Total Environment 17, 165–196.
Magny, M., 2004. Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements. Quaternary International 113, 65–79.
Matthes, F.E., 1939. Report of the committee on glaciers, April 1939. Transactions of the American Geophysical Union 20, 518–523.
Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlen, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R., Steig, E.J., 2004. Holocene climate variability. Quaternary Research 62, 243–255.
Meyers, P.A., 1997. Organic geochemical proxies of paleoceanographic, paleolimnologic, and paleoclimatic processes. Organic Geochemistry 27, 213–250.
Mingram, J., 1998. Laminated Eocene maar-lake sediments from Eckfeld (Eifel region, Germany) and their short-term periodicities. Palaeogeography, Palaeoclimatology, Palaeoecology 140, 289–305.
Mingram, J., Schettler, G., Nowaczyk, N., Luo, X., Lu, H., Liu, J., Negendank, J.F.W., 2004. The Huguang Maar Lake-a high-resolution record of palaeoenvironmental and palaeoclimatic changes over the last 78,000 years from South China. Quaternary International 122, 85–107.
Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., Karlen, W., 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. Nature 433, 613–617.
Muscheler, R., Joos, F., Beer, J., Muller, S.A., Vonmoos, M., Snowball, I., 2007. Solar activity during the last 1000 yr inferred from radionuclide records. Quaternary Science Reviews 26, 82–97.
Rein, B., Negendank, J.F.W., 1993. Organic carbon contents of sediments from Lake Schalkenmehrener Maar: a palaeoclimate indicator. In: Negendank, J.F.W., Zolitschka, B. (Eds.), Paleolimnology of European Maar Lakes. Springer-Verlag, Berlin, pp. 163–172.
Renssen, H., van Geel, B., van der Plicht, J., Magny, M., 2000. Reduced solar activity as a trigger for the start of the Younger Dryas? Quaternary International 68, 373–383.
Robbins, J.A., 1978. Geochemical and geophysical applications of radioactive lead isotopes. In: Nriago, J.P. (Ed.), Biogeochemistry of Lead. Elsevier, North Holland, pp. 285–393.
Schindler, D.W., 1998. Another look at the Little Ice Age – response. Bioscience 48, 884–885.
Sifeddine, A., Bertrand, P., Lallier Verges, E., Patience, A.J., 1996. Lacustrine organic fluxes and palaeoclimatic variations during the last 15 ka: Lac du Bouchet (Massif Central, France). Quaternary Science Reviews 15, 203–211.
Snape, I., Scouller, R.C., Stark, S.C., Stark, J., Riddle, M.J., Gore, D.B., 2004. Characterisation of the dilute HCl extraction method for the identification of metal contamination in Antarctic marine sediments. Chemosphere 57, 491–504.
Tan, L.C., Cai, Y.J., Yi, L., An, Z.S., Ai, L., 2008. Precipitation variations of Longxi, northeast margin of Tibetan Plateau since AD 960 and their relationship with solar activity. Climate of the Past 4, 19–28.
Tan, L.C., Cai, Y.J., Cheng, H., An, Z.S., Edwards, R.L., 2009. Summer monsoon precipitation variations in central China over the past 750 years derived from a high-resolution absolute-dated stalagmite. Palaeogeography, Palaeoclimatology, Palaeoecology 280, 432–439.
Tan, M., Hou, J.Z., Liu, T.S., 2004. Sun-coupled climate connection between eastern Asia and northern Atlantic. Geophysical Research Letters 31, L07207. doi:10.1029/2003GL019085.
Thompson, L.G., Mosleythompson, E., Dansgaard, W., Grootes, P.M., 1986. The little ice-age as recorded in the stratigraphy of the tropical quelccaya ice cap. Science 234, 361–364.
Wang, S.M., Liu, J., Zhou, J., 2003. The Little Ice Age maximum in China. Journal of Lake Sciences 15, 369–376 (in Chinese, with English Abstract).

Wang, S.W., Ye, J.L., Gong, D.Y., 1998. Climate in China during Little Ice Age. Quaternary Sciences, 54–64 (in Chinese, with English Abstract).

Wang, S.Y., Lu, H.Y., Liu, J.Q., Negendank, J.F.W., 2007. The early Holocene optimum inferred from a high-resolution pollen record of Huguangyan Maar Lake in southern China. Chinese Science Bulletin 52, 2829–2836.

Wu, Y.H., Lücke, A., Jin, Z.D., Wang, S.M., Schleser, G.H., Battarbee, R.W., Xia, W.L., 2006. Holocene climate development on the central Tibetan Plateau: a sedimentary record from Cuoe Lake. Palaeogeography, Palaeoclimatology, Palaeoecology 234, 328–340.

Xiao, J.L., Si, B., Zhai, D.Y., Itoh, S., Lomtatidze, Z., 2008. Hydrology of Dali Lake in central-eastern inner Mongolia and Holocene East Asian monsoon variability. Journal of Paleolimnology 40, 519–528.

Xiao, S.B., Li, A.C., Liu, J.P., Chen, M.H., Xie, Q., Jiang, F.Q., Li, T.G., Xiang, R., Chen, Z., 2006. Coherence between solar activity and the East Asian winter monsoon variability in the past 8000 years from Yangtze River-derived mud in the East China Sea. Palaeogeography Palaeoclimatology Palaeoecology 237, 293–304.

Yang, M.Z., Xie, X.C., Chen, J.R., 2006. Wetland depositional records and paleoenvironment significance of Tianyang Maar Lake in the Leozhou Peninsula. Marine Geology Letters 22, 26–29 (in Chinese, with English Abstract).

Yao, T.D., Xie, Z.C., Wu, X.L., Thompson, L.G., 1991. Climatic-change since little ice-age recorded by Dunde ice cap. Science in China (Series B) 34, 760–767.

Ying, W.M., Batley, G.E., Ahsanullah, M., 1992. The ability of sediment extractants to measure the bioavailability of metals to 3 marine-invertebrates. Science of the Total Environment 125, 67–84.

Yu, K.F., Zhao, J.X., Wei, G.J., Cheng, X.R., Chen, T.G., Felis, T., Wang, P.X., Liu, T.S., 2005. $\delta^{18}O$, Sr/Ca and Mg/Ca records of Porites lutea corals from Leizhou Peninsula, northern South China Sea, and their applicability as paleoclimatic indicators. Palaeogeography Palaeoclimatology Palaeoecology 218, 57–73.

Zeng, Y., Chen, J.A., Zhang, W., Zhu, Z.J., Li, J., 2011. The non-residual Rb/Sr ratio of the Huguangyan Maar Lake and its implications for paleoclimate change. Geochimica 40, 249–257 (in Chinese, with English Abstract).

Zhang, D., 1984. Synoptic-climatic studies of dust fall in China since historic time. Scientia Sinica (Scientia B) 27, 825–836.

Zhang, P.Z., Cheng, H., Edwards, R.L., Chen, F., Wang, Y.J., Yang, X., Liu, J., Tan, M., Wang, X.F., Liu, J.H., An, C., Dai, Z., Zhou, J., Zhang, D., Jia, J., Jin, L., Johnson, K.R., 2008. A test of climate, sun, and culture relationships from an 1810-year Chinese cave record. Science 322, 940–942.

Zheng, J.Y., Wang, W.C., Ge, Q.S., Man, Z.M., Zhang, P.Y., 2006. Precipitation variability and extreme events in eastern China during the past 1500 years. Terrestrial Atmospheric and Oceanic Sciences 17, 579–592.

Zheng, Z., Lei, Z.Q., 1999. A 400,000 year record of vegetational and climatic changes from a volcanic basin, Leizhou Peninsula, southern China. Palaeogeography Palaeoclimatology Palaeoecology 145, 339–362.