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The 'Mediaeval Warm Period' drought recorded in Lake Huguangyan, tropical South China

Guoqiang Chu,[1]* Jiaqi Liu,[1] Qing Sun,[2] Houyuan Lu,[1] Zhaoyan Gu,[1] Wenyuan Wang[3] and Tungsheng Liu[1]

([1]Institute of Geology and Geophysics, Chinese Academy of Science, Beijing 100029, China; [2]The Geological Analysis Center, Beijing, China; [3]The Administrative Center for China's Agenda 21th Century, Beijing, China)

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Abstract: The geochemistry of dated sediment cores from Lake Huguangyan (21°9′N, 110°17′E), tropical South China, reveals distinct stratigraphical patterns in total organic and inorganic carbon (TOC, TIC), biogenic silica (BS) and total nitrogen (TN) over the past 1400 years. In this hydrologically closed lake, TIC variations may reflect changes in the precipitation/evaporation ratio, which controls the evaporative enrichment of carbonate. TOC, BS and TN in the sediment are proxy indicators of lake productivity and nutrient input, which we believe are linked to local precipitation. High TIC content correlates with low concentrations of TOC, BS and TN, and indicates two drought episodes dated to AD 670–760 and AD 880–1260 in the sediments of Lake Huguangyan. Local historical chronicles support these data, suggesting that the climate of tropical South China was dry during the 'Mediaeval Warm Period' (MWP) and wet during the 'Little Ice Age' (LIA). The detected MWP drought is temporally correlated with evidence for lower precipitation on the Guliya (China) and Quelccaya (Peru) ice caps, and with increased salinity in Moon Lake (US Great Plains).

Key words: Palaeoclimate, geochemistry, lacustrine sediments, 'Mediaeval Warm Period', 'Little Ice Age', drought, China.

Introduction

The 'Mediaeval Warm Period' (MWP) (AD 1000–1300) and the 'Little Ice Age' (LIA) (AD1550–1850) (Lamb, 1977), have been recognized at widespread geographic locations (Laird *et al.*, 1996; Keigwin, 1996; Huang *et al.*, 2000), but their timing and intensity appear to vary regionally. Evidence that the MWP was generally a period of drought has been reported from equatorial East Africa (Verschuren *et al.*, 2000), North Africa (Lamb *et al.*, 1995), tropical Peru (Thompson, 1996), the temperate Great Plains and western USA (Laird *et al.*, 1996; Woodhouse and Overpeck, 1998) and Europe (Lamb, 1977). Knowledge of past precipitation variability at the timescale of decades to centuries is important for understanding the behaviour of the Earth's climate system in relation to the global hydrological and energy cycles. Therefore, more regional records are required to explore precipitation variations at various elevations and at widely separated locations.

Here, we use proxy palaeoclimate data (TOC, TIC, TN, TOC/TN and BS) from Lake Huguangyan to reconstruct the climate history of tropical South China during the last 1400 years. We compare these data with historical documents from tropical China, and other natural palaeoclimate archives (ice cores, lake sediments) from distant sites. Our data provide new evidence of MWP drought in tropical South China.

Study site

Lake Huguangyan (21°9′N, 110°17′E) is located on the low-lying Leizhou Peninsula in the tropical region of South China (Figure 1a), and is strongly influenced by the climate regime of the Northwest Pacific Ocean. Climate in the area is strongly seasonal, with 90% of the total mean annual precipitation of 1567 mm falling between April and October, controlled mainly by variation in the position and intensity of the subtropical high in the West Pacific Ocean (Li, 1993). The dry season is from November to March. Annual mean temperature is 23°C with little variation.

Lake Huguangyan is a closed maar lake, its crater basin having been created from basaltic phreatomagmatic eruptions (Liu, 1999). The tephra ring is 10–58 m above the lake surface and consists of pyroclast. The catchment area is 3.5 km^2, while the

*Author for correspondence (e-mail: guoqiangchu@yahoo.com)

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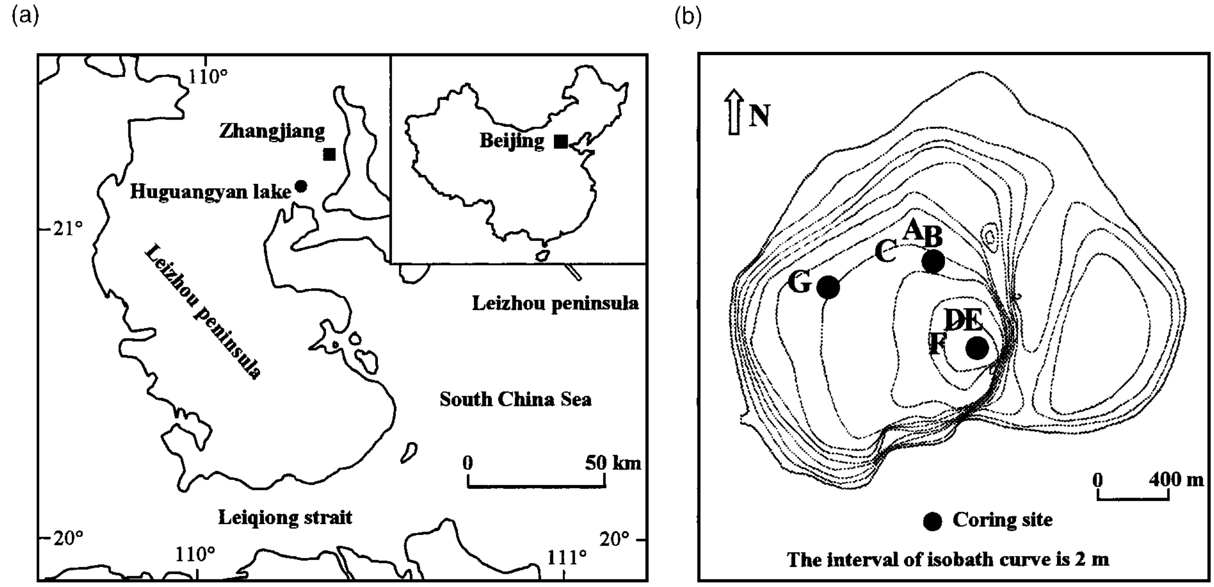

Figure 1 (a) The location of the Huguangyan crater lake in tropical South China, with an indication of the coring sites (b).

lake has a surface area of 2.3 km^2 and a maximum depth of 22 m. The lake is fresh and meromictic, with a sharp temperature gradient (thermocline) between 6 and 13 m depth.

Methods

In 1997 we collected seven sediment cores at three locations between 14 and 22 m depth (Figure 1b) using a modified Livingstone piston corer. The cores were stored in a cooling container until opened. The cores from station A recovered from 14 m water depth (Figure 1b) were chosen for detailed study. Sediments were cut into 0.5 cm discs from 0 to 30 cm and 1 cm discs from 31 to 200 cm, and freeze-dried.

Dating

Age control in the cores is based on ^{137}Cs and AMS ^{14}C data. Measurements of ^{137}Cs activity were carried out by gamma spectrometry at the GeoForschungZentrum Potsdam, Germany, using a low-background well-type germanium detector. Each sample was packed in a 15 mm polyethylene tube and counted for 48 hours.

Radiocarbon dating was done by accelerator mass spectrometry (AMS) on bulk organic matter in gyttja and on hand-picked terrestrial leaves. Five samples were analysed at the Kiel Radiocarbon Laboratory, Germany, and three samples at the Radiocarbon Laboratory of Peking University, China (Table 1). All ^{14}C ages were calibrated to calendar years using the atmospheric decadal data set from the calibration program CALIB 4.0 (Stuiver *et al.*, 1998).

Sediment geochemistry

Total carbon (TC) was determined by burning weighted samples in an oxygen gas stream at 1350°C and infrared spectrometric measurement of the released CO_2. Total nitrogen (TN) was measured simultaneously by a heat conductivity detector (LECO, CNS2000). The coefficient of variation for TC and TN analyses was below 1%. Inorganic carbon (IC) was determined by coulometric titration using a Strölin model coulometer, following evolution of CO_2 from samples using hot phosphorus acid (1:1). Total organic carbon (TOC) was calculated as TC minus TIC.

Biogenic silica (BS) concentration was measured by flow injection spectrophotometry (molybdenum blue method). Weighted samples were pretreated with H_2O_2 and HCl, to remove organic matter and carbonate, and opal silica was leached with a 2 M

Table 1 Radiocarbon ages in the sediment from the Huguangyan crater lake

Depth (cm)	Sample no.	Material	AMS ^{14}C BP	Calibrated age*
50	HUG A1-o	Gyttja	455 ± 25	AD 1419–1471
97	B1-o-L25	Gyttja	590 ± 110	AD 1223–1487
120	HUG A1-u	Gyttja	550 ± 20	AD 1328–1426
175	B1-u-L100	Gyttja	1340 ± 120	AD 435–977
180	HUG A 2-o	Gyttja	1225 ± 25	AD 692–888
210	B1-u-L151	Gyttja	1560 ± 200	AD 31–890
305	HUG F1-u	Leaf	2295 ± 25	400–259 BC
450	HUG C 3-o	Leaf	3520 ± 60	2025–1996 BC

*Calibrated age based on CALIB 4.0 with the terrestrial calibrated data sets (Stuiver *et al.*, 1998). Uncertainties were calculated at the 2σ probability. Samples labelled HUG were measured at the Kiel Radiocarbon Laboratory, Germany; samples labelled B1 were measured at the Radiocarbon Laboratory of Peking University, China.

NaOH solution at 90°C for five hours (Schettler, unpublished data). The coefficient of variation for repeated SiO_2 measurements was about 1%.

Historical documents

Historical documents are used here to reconstruct and evaluate the history of cold winters and rainfall in relation to the climate-proxy records from Lake Huguangyan.

Considering the great geographical variety of climatic regimes in China, historical data were restricted to the tropical plain south of 21°9′N (Chu, 1999). The most important original source is ‘Natural disasters in historical documents in Guangdong province’ (The Institute of Literary and History, Guangdong Province, unpublished data), which compiles 140 local chronicles and 14 monographs.

Use of historical data in palaeoclimate study is complicated by differences in the abundance and quality of historical data, in their interpretation and quantification (Brázdil, 1996) and in the definition of extreme climatic events (Camuffo and Enzi, 1996).

Records of frozen rivers or presence of snow, sleet and frost in these chronicles are here interpreted as convincing evidence for cold winter conditions in the tropical plain of South China. To distinguish different degrees of increasing cold severity from

Table 2 The coefficients of cold winter

Description of the cold winter event	Related coefficient
Frost	$P_1 = 1$
Sleet	$P_2 = 2$
Snow	$P_3 = 3$
Heavy snow or river frozen	$P_4 = 4$

frost, sleet and snow to frozen rivers (Table 2), we developed an index of cold winter (ICW), defined as:

$$ICW = P_1 \times N_1 + P_2 \times N_2 + P_3 \times N_3 + P_4 \times N_4$$

where P_1–P_4 are the severity coefficients of cold winter events, and N_1–N_4 are the numbers of counties in the region which experienced these events, totalled per decade. Records of flood events in the study region are presented as (1) the number of counties with flood events per decade and (2) the number of years with flood events per decade.

Results and discussion

Historical records

Cold winter events over the past 1000 years in tropical South China are concentrated in three time intervals during the LIA at *c.* AD 1480–1550, 1670–1730 and 1830–1900, alternating with warmer periods (Figure 2, c–e). The temporal distribution of cold winter events shows a good agreement with the result from phenological studies (flowering season of peach, apricot, clove, etc.), in which three cold intervals at AD 1470–1520, 1620–1720 and 1840–1890 (Chu, 1973) are consistent with anomalies in NH surface-temperature patterns over the past six centuries (Mann *et al.*, 1998).

Flood events were more frequent during the LIA than in the MWP (Figure 2, a and b). This suggests that precipitation was greater or more variable in the LIA than in the MWP.

Chu (1973) had earlier suggested that no significant warm MWP-equivalent period was recorded in China. However, recent publications based on the phenological phenomena, distribution patterns of subtropical plants and cold events (Wang and Gong, 2000; Man, 1998; Wu and Dang, 1998; Zhang, 1994) argued for a warm period from the beginning of the tenth century AD to the late thirteenth century AD.

Sediment geochemistry

The ^{137}Cs peak assumed to correlate to the 1963 peak in atomic-bomb testing was detected at 27.5 cm in the core (Figure 3a). Linear sedimentation at site A has averaged about 0.83 cm yr^{-1} since 1963.

The sedimentation rate below 120 cm is linear, with an average sedimentation rate of 0.103 cm yr^{-1} (Figure 3b). The AMS ^{14}C data at 50 cm and 97 cm appear to be too old for referring to the top sediment rate. Uncertainty associated with the dates in the upper part of the core precludes accurate age assessment. A two-order polynomial regression was used to interpolate the accumulation rate between 27.5 cm and 120 cm, excluding the two data at 50 cm and 97 cm depth (Figure 3b).

Here we discuss palaeoclimate proxy data in the upper 2 m of the core, representing lake history since ~ AD600. TOC and TN are stratigraphically correlated (Figure 4), probably because both elements are bound on organic matter. TOC/N ratios are low, varying between 8 and 12, with a mean near 10. This suggested that the organic matter derives largely from planktonic algae (Tyson, 1995; Dean and Gorham, 1998; Talbot and Laerdal, 2000). 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 growing (Brenner *et al.*, 1991; Rein and Negendank, 1993; Sifeddine *et al.*, 1996). The highest TOC, TN and TOC/N values are in the time intervals of *c.* AD 760–880 and 1340–1720 (Figure 4).

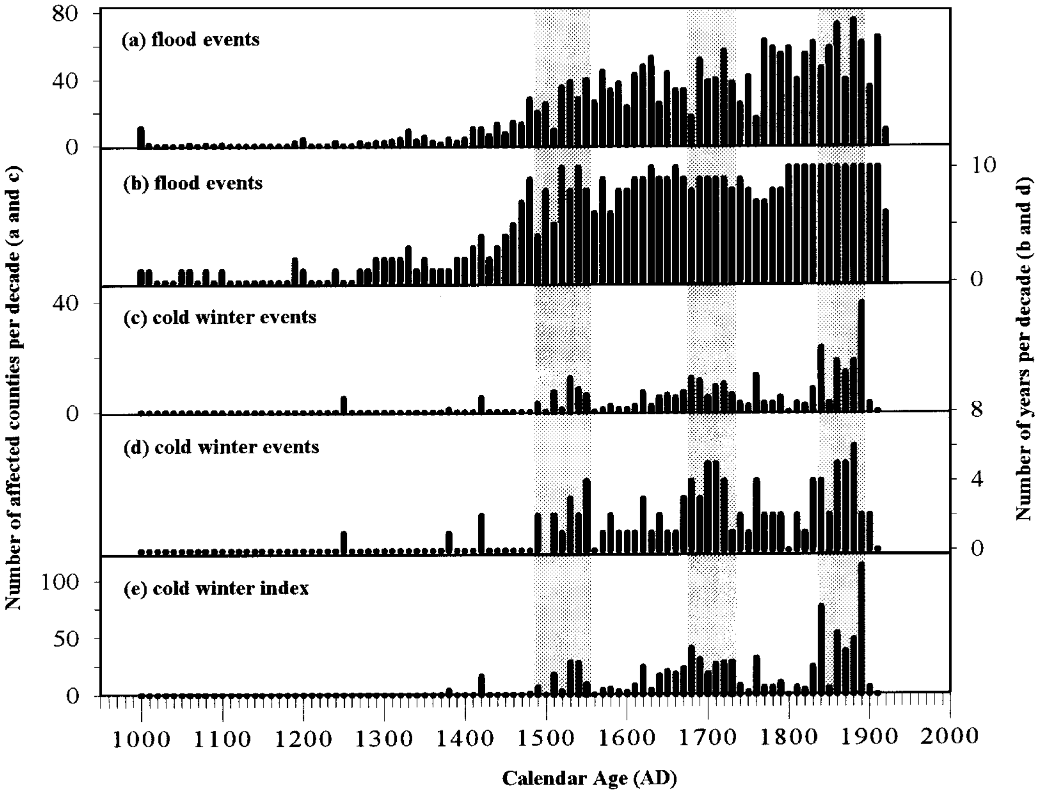

Figure 2 Compilation of historical climate records from tropical South China; vertical shaded bars show major cold episodes.

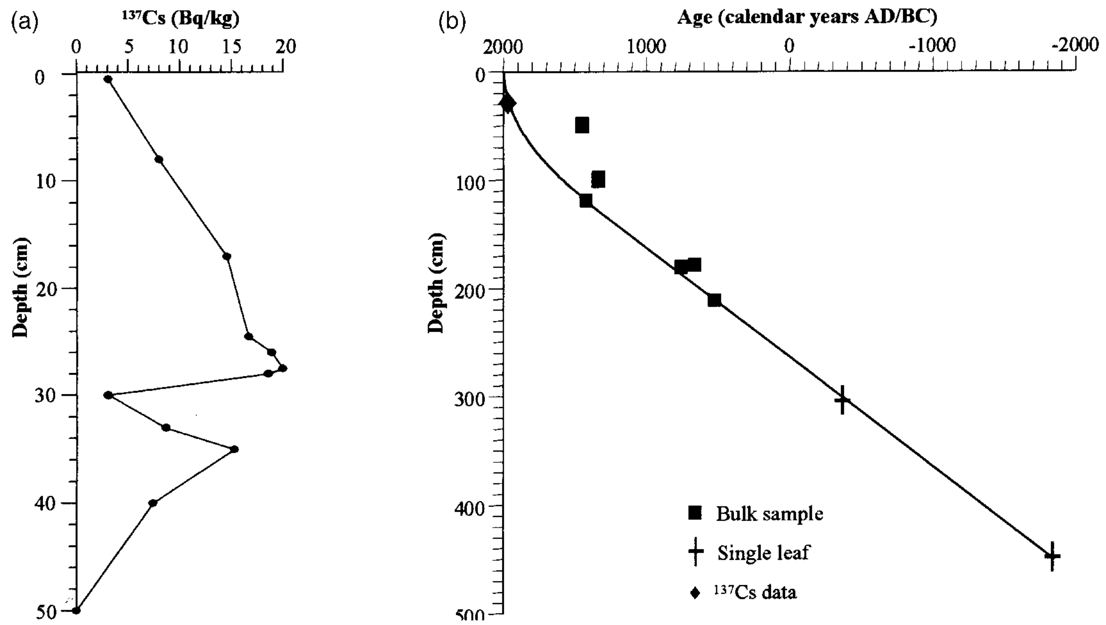

Figure 3 (a) ^{137}Cs activity versus depth in core A. (b) Depth versus age in core A. A two-order polynomial regression ($Y = -0.0399 \times X^2 - 0.1397 \times X + 1997$, X: depth (cm), Y: age (AD)) was used to interpolate the accumulation rate between 27.5 cm and 120 cm. The data used in the two-order polynomial regression are 0 cm, 27.5 cm and 120 cm.

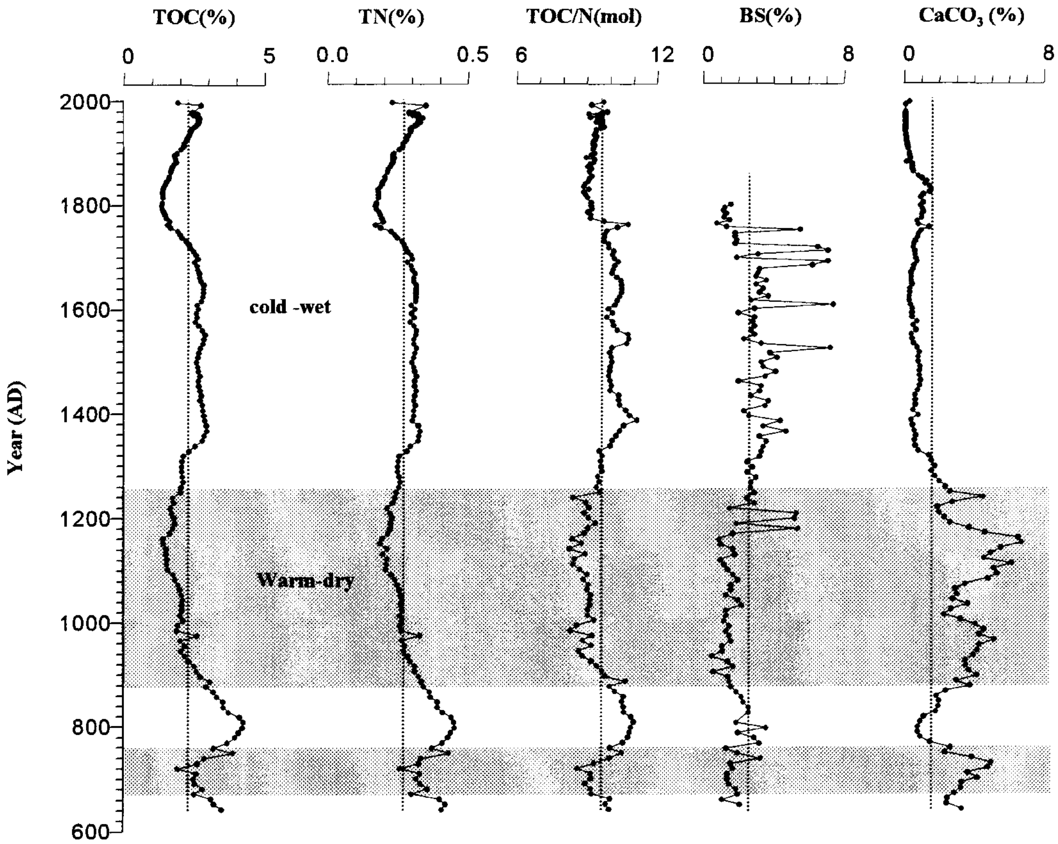

Figure 4 Variations of BS, TOC/N, TN, TOC and TIC in Lake Huguangyan core A relative to their mean values (dashed lines); horizontal shaded bars show episodes interpreted to have been warm and dry.

Variations of BS reveal a similar pattern with the changes of TOC, TN and TOC/N. Diatom productivity is controlled mainly by the surface-water temperature and trophic state of the lake. Because dissolved materials from the watershed are an important source of nutrients to the lake, increases in rainfall and soil erosion may result in an increase in nutrient loading to the lake (Colman *et al.*, 1995; Xiao *et al.*, 1997). The increase of nutrients would enhance diatom productivity.

In this tropical area, where surface-water temperatures are high year-round, temperature is probably a less important factor controlling algal productivity. Therefore, increased rainfall may be responsible for the observed increase in TOC, TN, TOC/N and BS. This interpretation is also supported by the independent data of carbonate content calculated as 8.33 × TIC. Carbonate concentrations in the sediments show distinct fluctuations, and reveal a negative correlation with temporal variations of TOC, TN, TOC/N and BS. Carbonates are probably of authigenic origin, because the catchment of Huguangyan maar is formed of non-calcareous rocks. Carbonates in the sediments possess authigenic characteristics. They are hypidiomorphic-granular or aggregate, and $< 20\ \mu m$ by determination in thin sections. There are two possible interpretations for the changes in sediment carbonate content. First, total carbonate content may reflect temperature changes (Mullins, 1998). Colder summer temperatures can cause a reduction in bioinduced calcite precipitation in temperate lakes because seasonal thermal stratification is delayed, resulting in a decreased length and intensity of the summer photosynthetic period (Hodell *et al.*, 1998; Thompson *et al.*, 1997). Second, total carbonate content may be mediated by groundwater and hydrological mass-balance (Lamb *et al.*, 1995) or precipitation/evaporation levels in closed lakes (Beierle and Smith, 1998). We suggest that the stratigraphic changes of sedimentary IC in the tropical, closed Lake Huguangyan were controlled mainly by evaporative enrichment of carbonate.

High carbonate content suggests that severe drought periods at Lake Huguangyan occurred from AD 880 to 1260 and from AD670 to 760. The moisture index in eastern China (Gong and Hameed, 1991) and lake-level variations for all of China (Fang, 1993) also indicate significant drought during the MWP. This drought period coincides with reduced net accumulation data from the ice core in Guliya, China, and in Quelccaya, Peru (Thompson, 1996), and increased diatom-inferred salinity in Moon Lake, northern Great Plains, USA (Laird *et al.*, 1996) (Figure 5).

Conclusions

The proxy data (TOC, TN, TOC/N, BS and carbonate content) and historical documents from Lake Huguangyan indicate a distinct drought episode during the MWP in tropical South China. Identification of comparable events in other climate archives suggests that a dry MWP was a global phenomenon.

A low-frequency teleconnection of drought and wetness during the past 2000 years was revealed between the tropical Peruvian Quelccaya ice cap and the temperate Chinese Guliya ice cap (Thompson, 1996). Contemporaneous variations in ice accumulation at these distant sites suggest that the thermal state of the Pacific can regulate continental moisture availability by inducing perturbations in patterns of atmospheric circulation and moisture transport (Woodhouse and Overpeck, 1998). General circulation models (GCMs) have simulated impacts of the thermal state of the tropical Pacific Ocean on Asian summer monsoon. GCMs suggest that, when warm sea water accumulates in the western Pacific Warm Pool, the convective activities are intensified from the Indo-China Peninsula to the area around the Philippines. Thus, the western Pacific subtropical high shifts northward, and East Asian summer monsoon rainfall is below normal (Huang and Sun, 1992). Drought and rainfall in certain regions of the tropics are strongly determined by the temperature of the underlying sea surface (Shukla, 1998). Rainfall in our research area is controlled mainly by the position and intensity of the subtropical high in the West Pacific Ocean. Assuming that global warming continues in the future, a return to drought conditions like those that prevailed during the MWP would be expected.

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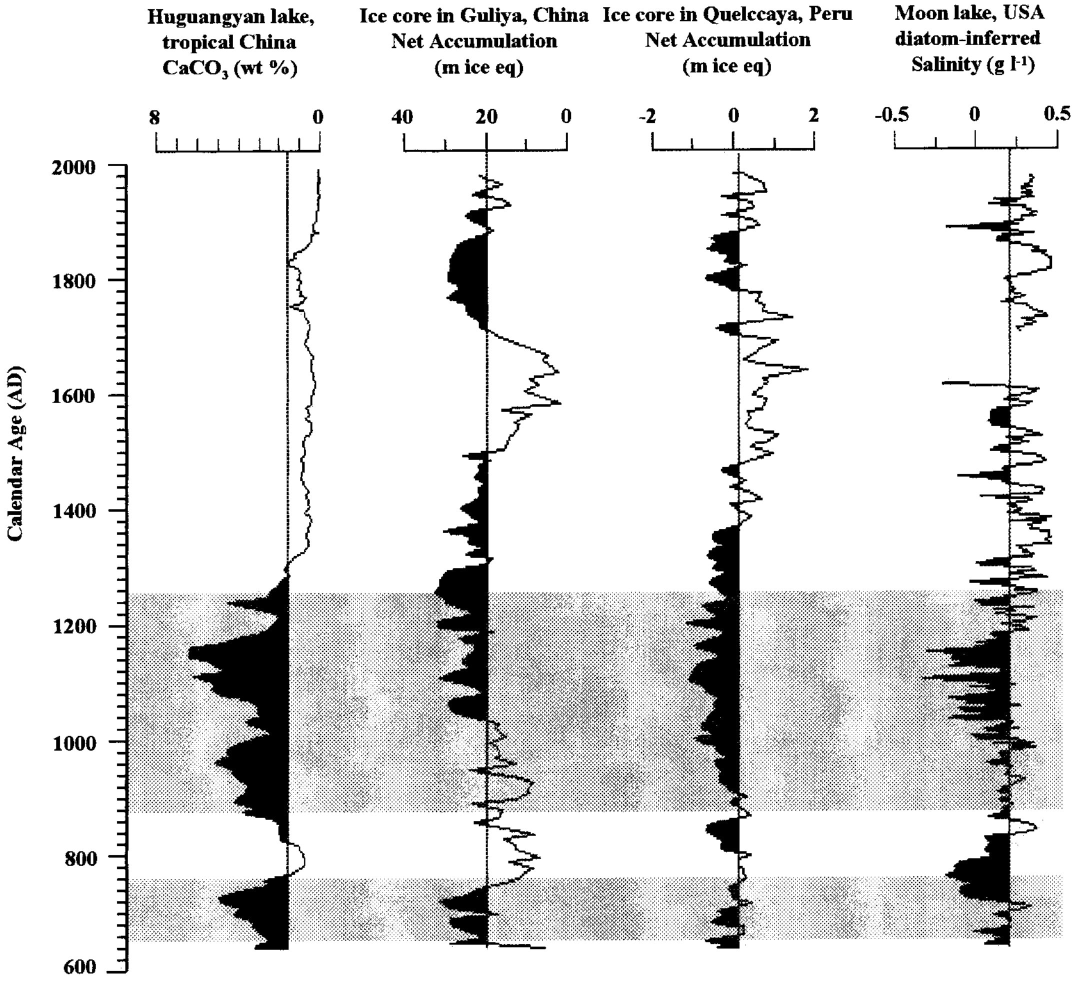

Figure 5 Comparative diagram of palaeoclimatic changes in tropical South China and elsewhere (relative drought in black); (a) this study; (b, c) Thompson, 1996; (d) Laird *et al.*, 1996.

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