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A New High-resolution Late Glacial-Holocene Climatic Record from Eastern Nanling Mountains in South China

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Abstract: A 350-cm-long sediment core sequence from Dahu Swamp situated in the eastern Nanling Mountains was selected for high-resolution paleoclimatic reconstruction since the Late Glacial period. The multi-proxy records of this paper reveal several evidently dry and cold events that may coincide with the Oldest Dryas, the Older Dryas, the Younger Dryas in the late deglacial period. Two relatively wetter and warmer phases occurred in ca. 15,000–14,400 cal yr B.P. and 13,500–12,800 cal yr B.P. respectively may correspond to the Bølling and Allerød warming events. The Younger Dryas event (ca. 12,800–11,500 cal yr B.P.) revealed by multi-proxies was characterized by relatively colder and drier climate. A warmer and wetter climate, occurred in ca. 10,000–6000 cal yr B.P., was consistent with the Holocene Optimum, which coincided with the maximum Northern Hemisphere insolation. The "8.2kyr cool event" and even the "8.8kyr cool event" were indicated as well from our sediment core. A dry mid-Holocene period (ca. 6000–3000 cal yr B.P.) indicated by multi-proxies does not follow the traditional concept of the wet mid-Holocene conditions observed in other regions in China.
Keywords: Late Glacial period; Holocene; climatic record; Dahu Swamp; South China

1 Introduction

One of the most challenging scientific questions in earth sciences is when and how the future climate change will affect the present environment. Of particular interest, with respect to human well-being, is the rate of change which ecosystems undergo in response to climate forcing. However, the behavior of the earth climatology is not well understood at present. Thus, studies addressing the long-term behavior of palaeoclimatology are necessary to describe and quantify the type, duration and intensity of their responses to climatic changes in the past. High-resolution multi-proxy records are very important for palaeoclimatic and palaeoenvironmental investigations, and limnological sediment records are especially important for reconstruction of continental palaeoclimate history. A climatic history with resolution of ca. 240 yr/sample of a core sequence (Dahu site) spanning the last 18,000yr drilled from the Dahu Swamp in the eastern Nanling Mountains in South China has been previously studied by Zhou et al. (2004) and Xiao et al. (2007). Here, we report a new high-resolution palaeoclimatic record (about ca. 45–150yr/sample) covering the last 16,000yr based on a limnological sedimentary sequence derived from the same swamp, aim to strengthen the research of the past climate, and try to obtain some new information on the processes and forcing mechanism of past climatic changes since the last deglaciation in South China.

2 Materials and Methods

2.1 Study area

Dahu Swamp is located in 2km southwest of Dingnan County seat (24º45′40″N, 115º02′27″E) of Jiangxi Province in the eastern Nanling Mountains in South China (Fig. 1). The mean annual precipitation here is about 1600mm and the mean annual temperature is 17.8℃. Granite bed rock formed a near-surface aquiclude that trapped water and established favorable conditions for peat development, and abundant vegetation debris that deposited in the stagnant water body made up thick peat

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accumulation in this swamp. The vegetation in this region has been changed greatly because of human activities (Zhou et al., 2004). Based on the local humidity and temperature indices, the original vegetation are likely dominated by Faguaceae, Theaceae and mid-subtropical evergreen broadleaved forest (China Vegetation Editing Committee, 1980). There is no evident outlet of the carbonate rock stratum in the field investigation.

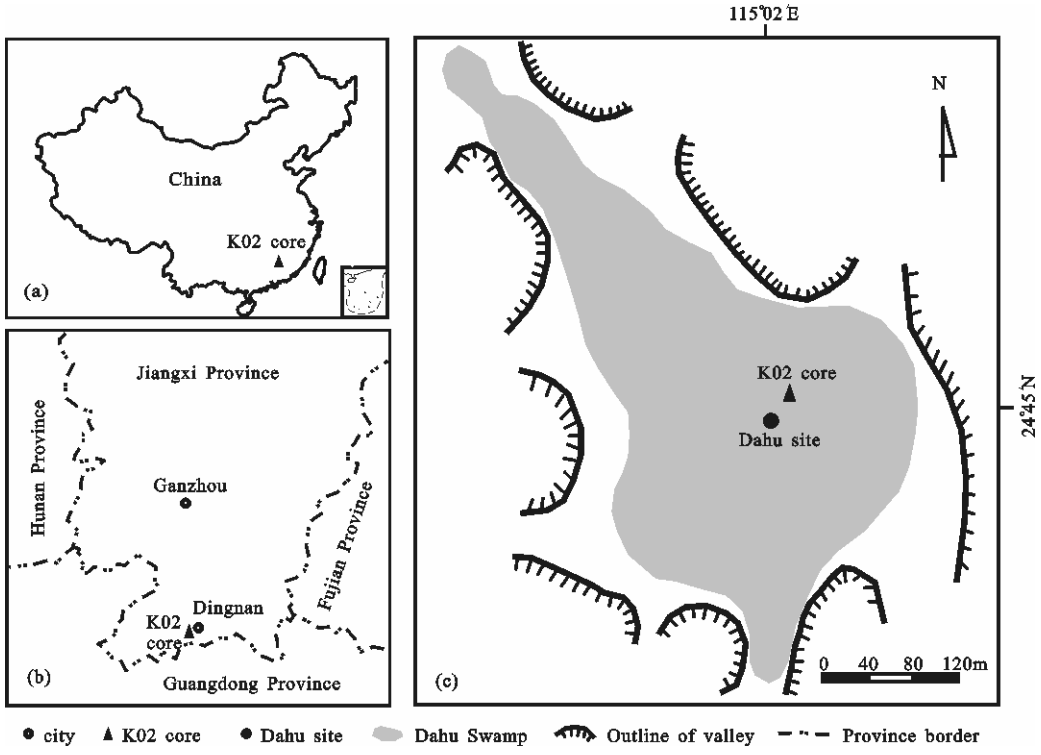


Fig. 1 Study area and locations of K02 core and Dahu site

2.2 Sampling and analytical methods

A 350-cm-long sediment core (K02 core, 24º45′43″N, 115º02′25″E) (Fig. 1) was drilled in Dahu Swamp with an Eijkelkamp sampling core device. The K02 core section was split, photographed, and described on the spot. About 20-cm sediment was estimated to be removed by modern human activities. Core sediment sequence is characterized by the alternation between lacustrine and marshy sediments. Lacustrine sediments primarily consist of grayish green or grayish brown silt or silty clay, while marshy sediments are dominated by brown herb-rich peat and dark gray black organic-rich silt and silty clay (gyttja).

Samples for total organic carbon (TOC) measurement were collected at 1-cm interval using the potassium dichromate-vitriol oxidation titration technique of Walkely (1947) with an uncertainty of 0.2%.

Analyses of organic carbon isotope ($\delta^{13}C$) in sediment samples were taken at about 2-cm intervals using standard analytical methods and procedures. During the pretreatment, the samples were acid-washed with 5% HCl to remove possible trace amounts of carbonate carbon, rinsed with de-ionized water and oven-dried at 50℃. According to organic carbon content, ca. 20mg of each sediment sample was combusted in an excess of oxygen at about 1020℃ by an elemental analyzer. The generated CO_2 was analyzed with a Finnigan MAT-253 Mass Spectrometer. Overall analytical precision for isotope analyses of $\delta^{13}C$ is about 0.1‰, taking sample preparation and mass spectrometer measurement into account. Results are given in the δ notation relative to the international Pee Dee Belemnite (PDB) standard in per mile (‰) (Craig, 1957).

Samples for the determination of dry density (DD, weight of dry mass per volume of fresh sediment) were collected at 2-cm intervals in the sampling field by using a displacement technique to measure the volume (Janssens, 1983). Dry mass was simply determined by oven drying at 40℃ until constant weight was achieved.

3 Results and Analyses

3.1 Chronology

Chronological sequence of K02 core was established based on 12 conventional radiocarbon dates (Table 1, Fig. 2). A half-life of 5568yr was used for the calculation. All ^{14}C dates were converted to the calibrated ages using Calib5.01 program (Stuiver et al., 2005). The age model is based on linear interpolation between each two calibrated ages and the bottom age of K02 core is determined to be about ca. 16,000 cal yr B.P. Based on the sedimentation rate determined from this age model, the mass accumulation rates of the bulk sediment (MAR-BS) were calculated using DD and sedimentation rates.

3.2 Organic carbon isotope

Based on the previous work carried out by other researchers (Andreas et al., 2003; Hammarlund, 1992; Sukumar et al., 1993; Zhou et al., 1999), it can be inferred that $\delta^{13}C$ values can reflect the changes of environm-

Table 1 Radiocarbon dating results of K02 core in Dahu Swamp

Laboratory code	Field code	Depth (cm)	Conventional ^{14}C age (yr B.P.)	Calibrated age (cal yr B.P.)	Dating material
07-119	JXDN-01-01	8	1711±64	1420–1815	TOC
07-121	JXDN-01-03	36	4468±80	4874–5307	TOC
07-123	JXDN-01-05	81	6421±76	7174–7466	TOC
07-124	JXDN-01-06	113	7319±89	7972–8329	TOC
07-125	JXDN-01-07	134	7961±106	8544–9113	TOC
07-127	JXDN-01-09	178	8555±122	9621–10112	TOC
07-128	JXDN-01-10	203	9742±102	10746–11387	TOC
07-147	JXDN-01-11	223	10180±108	11348–12352	TOC
07-148	JXDN-01-12	238	11565±109	13225–13672	TOC
07-149	JXDN-01-13	273	12160±91	13780–14259	TOC
07-150	JXDN-01-14	288	12798±126	14642–15568	TOC
07-151	JXDN-01-15	348	13410±155	15386–16477	TOC

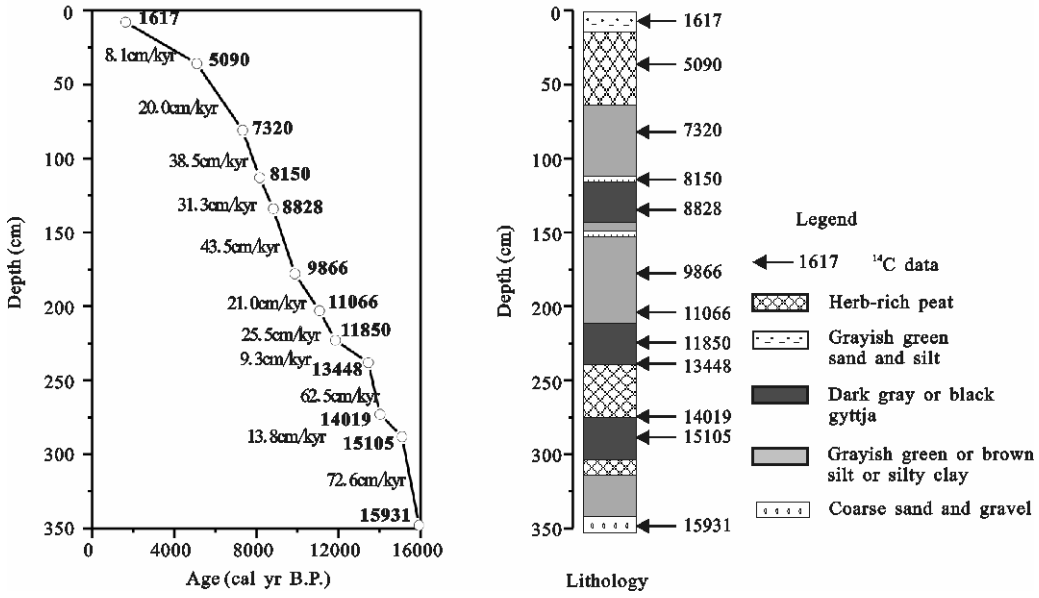
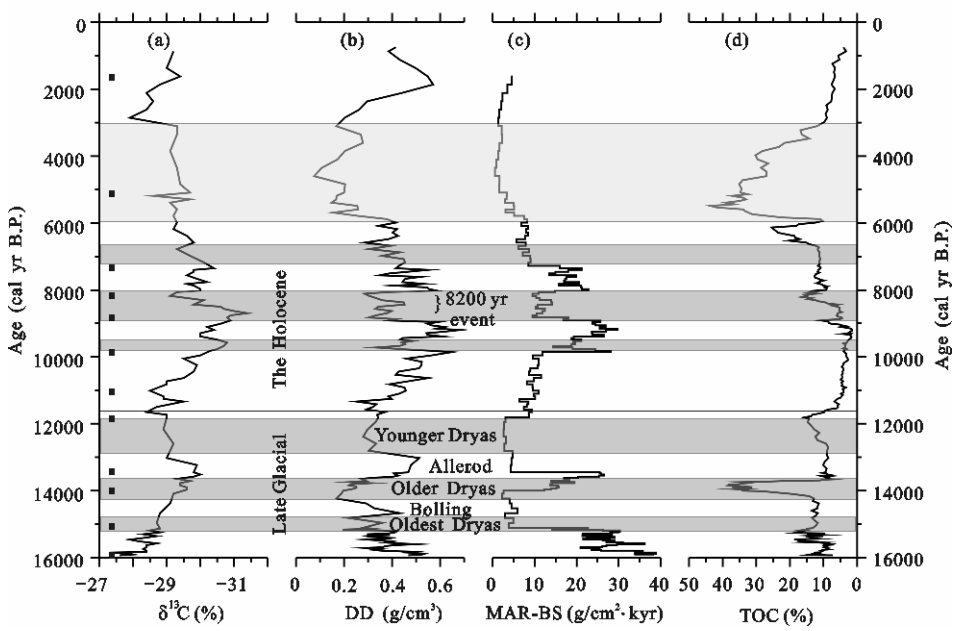


Fig. 2 Lithology and relationship between depth and age of K02 core in Dahu Swamp

ental conditions and can be used as a valuable palaeoclimatic proxy indicator, i.e., more negative $\delta^{13}C$ values indicate an increase in tree-grass ratio in vegetation types, hence increase precipitation or humidity, while more positive $\delta^{13}C$ values indicate cold and dry conditions, decrease in vegetation cover and predominance of C4 grasses. Thus we employ the $\delta^{13}C$ record from K02 core as a proxy to indicate palaeoclimatic changes. The $\delta^{13}C$ values since the Late Glacial period in K02 core varied between –27.3‰ and –31.1‰, and the average value was –29.4‰ (Fig. 3). The highest $\delta^{13}C$ value (–27.3‰) was observed at ca. 15,800 cal yr B.P., subsequently, more than 3‰ decrease in $\delta^{13}C$ value covered the next two thousand years, suggesting a climatic change toward slightly warmer and wetter conditions. During the Allerød epoch, the $\delta^{13}C$ reached to about –30‰, and then the $\delta^{13}C$ increased slightly to about –28.9‰ in the Younger Dryas (YD), indicating a relatively colder and drier condition. At the end of the YD (ca. 11,500 cal yr B.P.), the $\delta^{13}C$ values decreased sharply, implying the germination of the Holocene period. At the beginning of the Holocene, stepwise decreases in the $\delta^{13}C$ indicate that climate changed towards warmer and wetter conditions. We can observe in Fig. 3, from ca. 10,500 to ca. 6500 cal yr B.P., the $\delta^{13}C$ values showed two sudden declines at ca. 9300 cal yr B.P. and 8100 cal yr B.P. respectively, indicating two rapid shifts to colder and drier conditions. After ca. 5000 cal yr B.P., the $\delta^{13}C$ values increased slightly, implying a colder and drier condition, but after ca. 2850 cal yr B.P., the $\delta^{13}C$ values decreased again.



DD: dry density; MAR-BS: mass accumulation rates of bulk sediment

The black squares in the left are ^{14}C dating samples

Fig. 3 Variations of palaeoclimatic proxy indicators of K02 core since Late Glacial period

3.3 Total organic carbon

The TOC proxy has been proved to be sensitive to the hydrologic shifts from stagnant swamp to lacustrine environment. But for the lacustrine or marshy sedimentary sequence, the TOC may have different climatic implication. Zhou et al. (2004) have indicated that higher TOC suggests relatively drier marshy (peat-forming) conditions in Dahu Swamp profile, while lower TOC implies relatively wetter conditions, which was supported by the pollen results. From the TOC curve of the K02 profile (Fig. 3), it can be seen that variations in TOC concentration demonstrate two relatively drier epochs, i.e., 14,250–13,600 cal yr B.P. and 6500–3000 cal yr B.P., which are characterized by higher TOC values. From ca. 11,500 to 6500 cal yr B.P., lower and gentle fluctuation of the TOC concentration represents a wetter condition that coincides with the climatic changes reflected by the pollen assemblages (Zhou et al., 2004). From ca. 13,600 to 11,600 cal yr B.P., the TOC values were higher than that during the above epoch (ca. 11,500–6500 cal yr

B.P.), showing a drier climatic condition.

3.4 Dry density

Sediment dry density (DD) has been applied successfully to interpreting the palaeoclimatic changes based on oceans and lakes sediments. However there are kinds of factors influencing the DD of lake sediments, and the climatic implication of sediment dry density in different lakes may be different (Zolitschka and Negendank, 1996; Achim et al., 2000; Liu et al., 2000). It is the most effective way to contrast the other proxy-data with clear climatic implication to DD of the same profile, and to determine the environmental implication of DD. The TOC record has been proved effective to reflect the climate changes in Dahu Swamp. In general, higher TOC values in the Dahu profile reflect the peat-forming environmental conditions (drier marshy conditions), while lower TOC values indicate wetter conditions with stream deposition (precipitation in this period may be higher). Hence, in contrast to TOC in K02 core, the DD would provide information on the ratio between organic and minerogenic detritus, which is an expression of the relation between autochthonous and allochthonous deposition with lower DD dominated by lacustrine organic components reflecting drier marshy conditions and higher DD values typical for dominance of terrigenous detritus resulting from stream deposition. Corroborating this hypothesis is the negative correlation of DD with TOC (Fig. 4). The negative correlation of DD with TOC suggests that DD proxy may have contrary implication compared to the TOC for the past climate. Hence, the variations of DD directly reflect the process of the climate change, higher DD values indicate wetter conditions and lower DD values indicate drier conditions.

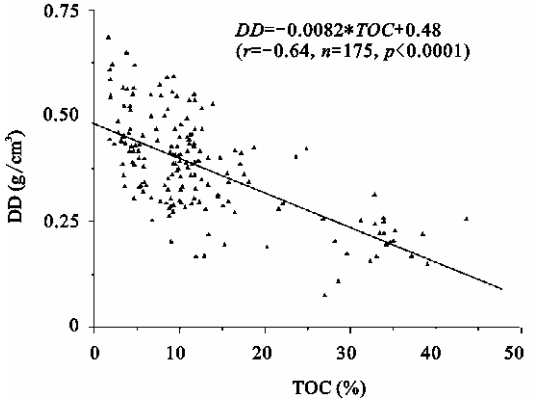


Fig. 4 DD data plotted against TOC of K02 core in Dahu Swamp

DD gives a first impression about the input of clastic material into the lake, clearly revealing the enhanced input during the early and middle Holocene (ca. 11,800–6000 cal yr B.P.), and reflecting a general trend towards warmer and wetter climate. Four drier and cooler intervals centered at ca. 9800–9400 cal yr B.P., 8800–8000 cal yr B.P., 7000–6400 cal yr B.P. and 6000–3000 cal yr B.P. respectively are revealed by lower DD values. Two notable drier and colder events known as the Younger Dryas and the "8.2kyr cold event" were also demonstrated by the DD proxy in K02 core.

3.5 Mass accumulation rates of bulk sediment

As mentioned above, MAR-BS was calculated using DD and sedimentation rates, which indicates the amounts of terrigenous inputs transported by streams. Hence, higher MAR-BS values would suggest enhanced water flows leading more terrigenous detritus transported to the lake, while lower MAR-BS values would reflect reduced precipitation in this region, indicating drier conditions. From the MAR-BS curve of the K02 profile (Fig. 3), we can find that an evident transition from drier conditions towards wetter conditions occurred at the origination of the Holocene epoch (ca. 11,800 cal yr B.P.). During the Holocene, two relatively wetter epochs were revealed by the MAR-BS proxy that was characterized by higher values at ca. 10,000–8800 cal yr B.P. and ca. 8000–7200 cal yr B.P. During the period of ca. 8800–8000 cal yr B.P., the MAR-BS values decreased sharply, indicating a drier and colder condition in this epoch. Lower MAR-BS values revealed relatively drier conditions in the Dahu Swamp region during the mid- to late-Holocene (especially from ca. 6000–3000 cal yr B.P.).

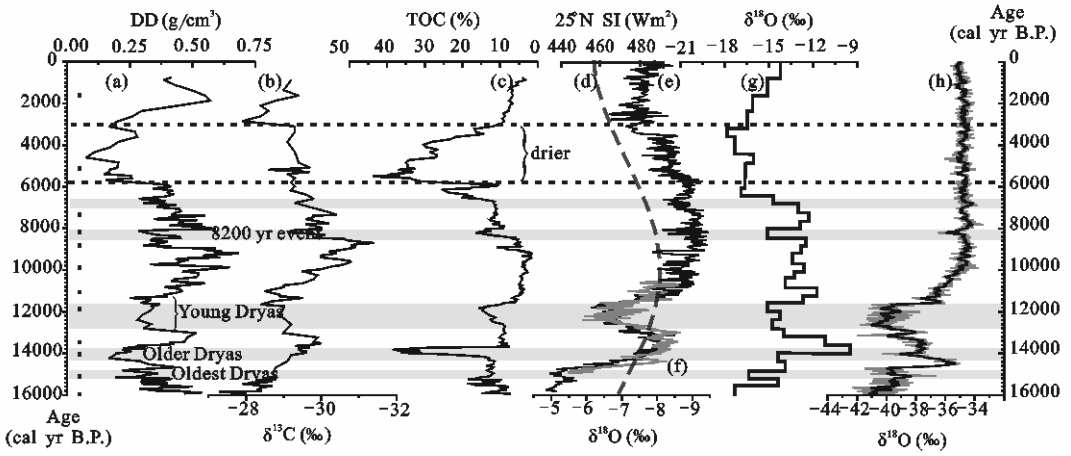
4 Discussion

As explained above, the multi-proxy records of TOC, $\delta^{13}C$ and DD vary dramatically in K02 core. Higher TOC and $\delta^{13}C$ and lower DD values would suggest drier marshy (peatforming) conditions, while lower TOC and $\delta^{13}C$, higher DD may indicate wetter climate. Based on the above analysis, we can propose a multi-proxies record of the past climatic changes during the last ca. 16,000yr in South China.

4.1 Late Glacial climate change

Climate variations in northern high latitude region dur-

ing the last ca. 16,000yr have been well reconstructed by a number of ice cores from Greenland, which have been summarized by Stuiver et al. (1995). The climate derived from those cores defined a number of cold and warm periods during the last deglaciation including the Bølling and Allerød warm events and the Oldest, Older and Younger Dryas cold events. By correlating the multi-proxy records from K02 core with the $\delta^{18}O$ from Greenland ice cores, it was found that those aforementioned well-known short-term climate events were demonstrated in the Dahu record as well (Fig. 5).



(a), (b) and (c) in Dahu Swamp (this paper), (d) and (e) in Dongge Cave stalagmite (Dykoski et al., 2005), (f) in Hulu Cave stalagmite (Wang et al., 2005), (g) in Guliya ice core (Thompson et al., 1998), (h) in GISP2 ice core (Grootes et al., 1993).
DD: dry density; SI: solar insolation

Fig. 5 Comparison of K02 core sediment records from Dahu Swamp with regional and global climate proxy data

Three relatively drier (and colder) phases occurred in ca. 16,000–15,000 cal yr B.P., 14,000–13,500 cal yr B.P. and 12,800–11,500 cal yr B.P. at Dahu Swamp region, respectively, possibly correlated with the Oldest Dryas, Older Dryas and Younger Dryas cold events discovered in the northern high latitude region. Sediments associated with those three short drier events were characterized by brown herb-rich peat or dark gray gyttja (Fig.2). Following the end of the Older Dryas, a warming phase which probably coincided with the Allerød period revealed in the Greenland ice core, is suggested by an increase in the DD and decrease in the $\delta^{13}C$ record. In GISP2 ice core, the $\delta^{18}O$ record suggests that the Allerød period was characterized by lower temperature than the Bølling period (Stuiver et al., 1995). However, our records show high values of the dry density (indicating warmer and wetter conditions) in the Allerød period compared to the Bølling period, coinciding with the $\delta^{18}O$ records of the Dongge Cave (Dykoski et al., 2005) and Hulu Cave stalagmites (Wang et al., 2001) (Fig. 5). Does this imply that the Bølling and Allerød periods had dissimilar responses to the climate change in different regions across the world? However, whether it was caused by the local environmental condition awaits further studies. Our records indicate that the onset of the Younger Dryas is characterized by a sudden decrease in the DD and its duration is about 1000yr (12,500–115,00 cal yr B.P.), that is in good agreement with that estimated in the oxygen isotope records of the GISP2 ice core (12,880–11,640 cal yr B.P.), Hulu Cave stalagmite (12,823–11,473 cal yr B.P.) and Dongge Cave D4 stalagmite (12,800–11,580 cal yr B.P.). Based on the analysis of the pollen assemblages and other palaeoclimatic proxies of the Dahu site, Zhou et al. (2004; 2005) demonstrated cool and wet YD conditions in the Dahu Swamp, significantly different from other manifestation of the YD across other regions in China, typically characterized as cold and dry conditions. Inconsistent with Zhou et al. (2004), our records show relatively colder and drier conditions during the YD period coinciding with the other manifestations (Dykoski et al., 2005; Wang et al., 2001; Zhou et al., 1999).

4.2 Holocene climate change

The multi-proxies record of K02 core suggests a transition from the last deglaciation to the Holocene at ca.

11,500 cal yr B.P. Stepwise variations of all the proxies reflect that the climate changes towards relatively wetter (and warmer) conditions since ca. 11,500 cal yr B.P. Our results indicate that the Holocene climate in Dahu Swamp in South China was actually unstable, and often interrupted by some abrupt cold events, such as three relatively colder events centered at ca. 9800–9400 cal yr B.P., 8800–8000 cal yr B.P. and 7000–6400 cal yr B.P. respectively. These cold events can be correlated well with those in the ice and stalagmite records (Grootes et al., 1993; Thompson, et al., 1998; Wang et al., 2001; Dykoski et al., 2005) (Fig. 5).

From ca. 10,000 to 6000 cal yr B.P., lower TOC, $\delta^{13}C$ values and higher DD values indicate relatively warmer and wetter conditions coinciding with the changes reflected by the pollen assemblages (Zhou et al., 2004). Coincident with the above proxies, the MAR-BS values were distinctively higher during the period of ca. 10,000–7200 cal yr B.P., indicating enlargement of water body of this swamp. Based on the pollen analysis, Zhou et al. (2004) estimated that during this period the average precipitation was around 1800mm, and average temperature was about 1–2℃ higher than the present one. Hence, we interpret this epoch (especially from 10,000 cal yr B.P. to 6000 cal yr B.P.) as the Holocene Optimum period in this region. However, the Holocene Optimum revealed by the multi-proxy records of K02 core seems to be different from that concluded by Shi et al. (1992), which originated about 1500 years earlier than that reported previously. Furthermore, this period occurred in conjunction with maximum Northern Hemisphere insolation (Dykoski et al., 2005), and our results from K02 core would provide a new record that reinforces the solar insolation forcing concept.

Two sudden decreases in DD, MAR-BS and increases in $\delta^{13}C$ values suggest that there were two cooling events initiated at ca. 8800 cal yr B.P. and 8000 cal yr B.P. inserting the early Holocene. Especially the latter cold event was likely related to the "8.2kyr cold event" (8400 to 8000 cal yr B.P.) identified in Greenland ice cores (Alley et al., 1997) and this event has been observed in multi-proxy climatic records elsewhere across the world (Wang et al., 2001; Magny and Begeot, 2004; Dykoski et al., 2005). Perhaps this event was correlative with the catastrophic drainage of Lake Agassiz through Hudson's Bay at 8400 cal yr B.P. (Barber et al., 1999; Teller et al., 2002) that resulted in cold, dry and windy conditions adjacent to the North Atlantic (Alley et al., 1997). The former abrupt cooling event occurred at ca. 8800 cal yr B.P. has been demonstrated by Hanne et al. (2007) as well, observed from a multi-proxies sediment core record on the continental margin off western Svalbard, European Arctic. Similar conditions (relatively colder and drier) were also observed at the period of ca. 9800–9400 cal yr B.P. and 7000–6400 cal yr B.P. respectively, which consisted well with the records of the stalagmites and ice cores.

The dry mid-Holocene period (6000–3000 cal yr B.P.), represented by our multi-proxy records, was inconsistent with the so-called warm and wet Holocene Optimum occurred in the mid-Holocene in China (Shi et al., 1992; An et al., 2000). And a similar viewpoint was also observed by Zhou et al. (2004), who considered that the length of the mid-Holocene dry period in South China, together with the extension of boreal forests elsewhere, and Sun and Li (1999) suggested a temperature-moderating mechanism caused by the forested areas and deforestation. The effects of the solar radiation and influence of La Niña activity might have contributed to the aridity in this region as well. The finding of the dry mid-Holocene observed from Dahu Swamp agrees well with the decreasing insolation values of solar radiation during the middle to late Holocene (Fig. 5). Additionally Bush (1999) demonstrated a prevalence of La Niña versus El Niño conditions during the middle Holocene, and Riedinger et al. (2002) considered that the cold sea surface temperature (SST) and La Niña conditions during the mid-Holocene might play a role in the aridity of East Asian monsoon areas.

5 Conclusions

The high-resolution study of the Dahu Swamp peat record adds some new information on the paleoclimatic changes from Late Glacial period to the Holocene for South China. In the late deglacial period, several evidently cold and dry events together with distinct wet and warm phases, which may coincide with the Oldest, the Older, the Younger Dryas cooling events and the Bølling and Allerød warming events, were revealed by our multi-proxies. The "8.2kyr" and the "8.8kyr" cool events were demonstrated during the Holocene as well.

A stepwise variation of climatic conditions towards relatively warmer and wetter occurred after the YD

event (ca. 11,500 cal yr B.P.). From ca. 10,000 to 6000 cal yr B.P., all our proxies indicate a pronounced warmer and wetter period that is confirmed as the Holocene Optimum. This period showed good agreement with the maximum Northern Hemisphere insolation and reinforced the solar insolation forcing concept. In addition, the Holocene Optimum period in this study region may have been inserted by several abrupt cold events. Another interesting finding is the dry mid-Holocene period (from ca. 6000 to 3000 cal. yr B.P.) suggested by our multi-proxies, which does not follow the traditional concept of the warm and wet mid-Holocene conditions observed in other regions in China. Variations of the Holocene climate over Dahu Swamp are consistent with the general trend of solar insolation, suggesting that the solar forcing may have played an important role in the Holocene climate in South China.

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