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Earth and Planetary Science Letters 211 (2003) 371–380

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Correlation between Indian Ocean summer monsoon and North Atlantic climate during the Holocene

Y.T. Hong [a,*], B. Hong [a], Q.H. Lin [a], Y.X. Zhu [a], Yasuyuki Shibata [b], Masashi Hirota [b], Masao Uchida [b], X.T. Leng [c], H.B. Jiang [a], H. Xu [a], H. Wang [a], L. Yi [a]

[a] *State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, 73 Guanshui Road, Guiyang, Guizhou 550002, PR China*

[b] *Environmental Chemistry Division, National Institute for Environmental Studies, Onogawa 16-2, Tsukuba, Ibaraki 305-0053, Japan*

[c] *Institute of Peatmire, Northeast Normal University, Changchun, Jilin 130024, PR China*

Received 22 October 2002; received in revised form 12 March 2003; accepted 7 April 2003

Abstract

There has been a number of investigations for the correlation between the Asia monsoon and the North Atlantic climate for the last glacial; however, little research has been done for the present interglacial, the Holocene. Here we present for the first time a high-resolution composite proxy record for the Indian Ocean summer monsoon spanning around 12 000 years based on the $\delta^{13}C$ time series of both a single plant species (*Carex mulieensis*) remains cellulose and the total plant assemblage cellulose in the Hongyuan peat bog from the Tibet Plateau. The records show that the strength of the Indian Ocean summer monsoon had abrupt variations during the last 12 000 years. The weakest monsoon occurred in the Younger Dryas period. Following rapid strengthening from around 11 200 to 10 800 a BP the monsoon kept a generally strong level for around 5300 years. From around 5500 a BP onwards the monsoon strength tended to gradual decrease. In addition, there are a series of abrupt variation events of the monsoon strength on centennial to millennial time scales, which superimpose the general tendency of the monsoon variation. In every case when the ice-rafted debris events in the North Atlantic occurred, the summer monsoon strength decreased correspondingly. These evidences show that teleconnection between the Indian Ocean summer monsoon and the North Atlantic climate is present not only in the last glacial but also in the Holocene, which may be linked to abrupt reorganizations of the ocean thermohaline circulation, leading to redistribution of energy, changing temperature and moisture gradient over the southern subtropical Indian Ocean, and eventually controlling the variability of the Indian Ocean summer monsoon.

Keywords: monsoon; thermohaline circulation; ice-rafted debris events; peat; abrupt climate change; Holocene; China

1. Introduction

The monsoon climate distributing in the widespread area from West Africa through Central Asia to East Asia has been considered as an in-

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* Corresponding author. Tel.: +86-851-5891248; Fax: +86-851-5891609.
E-mail address: ythong@public.gz.cn (Y.T. Hong).

0012-821X/03/$ – see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0012-821X(03)00207-3

terhemispheric phenomenon. In this area the four splendid ancient human civilizations were born, and today more than half of the world population lives in the area that depends on monsoon rainfall for food and livelihood. It has been confirmed that during the last glacial the strong Indian Ocean monsoon was related with the interstadial climate events (Dansgaad–Oeschger events) in the North Atlantic; in contrast, the weak monsoon was associated with the cooling events (Heinrich events) [1,2]. As it has been revealed that during the Holocene there was also a series of cooling characterized by the ice-rafted debris (IRD) events in the North Atlantic [3,4], a question therefore is raised that whether the Indian Ocean monsoon also correlates with the climate changes in the North Atlantic during the Holocene.

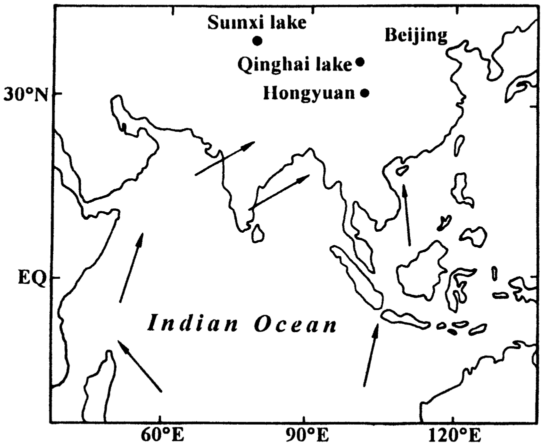


Fig. 1. Location of the Hongyuan peatland and the Indian Ocean summer monsoon. The arrows indicate generalized wind directions of the summer monsoon.

2. The study region and methods

The researched Hongyuan peat bog at an altitude of 3466 m above sea level is located in the eastern Tibetan Plateau (32°46′N, 102°30′E) (Fig. 1). The annual mean temperature and precipitation are around 1°C and 700 mm respectively. The Tibetan Plateau is the region where the climate is under the strong influence of the Indian Ocean summer monsoon [5,6]. In the summer season the water vapor from the Indian Ocean is transported into the Tibetan Plateau region through the Arabian Sea and the Bay of Bengal, respectively, by the Indian Ocean summer monsoon. Owing to the influence of the monsoon around 80% of the anneal precipitation in the Hongyuan region occurs in the months from June to August, and thick herbal peat deposition has been formed [5]. In addition, in the Tibetan Plateau region the growth season for herbal plants on the earth surface is shorter (around 5 months), but solar irradiation is stronger. After fast completion of the plant growth process during the growth season the herbal plants die fast along with the coming of the long cold and dry season. It can be seen that the humification degree of the herbal plants died is lower and the plant remains are preserved in peat deposition more intact. Therefore the Hongyuan region is an ideal place for investigating the activity of the Indian Ocean summer monsoon by means of the peat isotope records.

We sampled specimens of the 12 species of modern dominant plants growing on the Hongyuan peat bog and determined their $\delta^{13}C$ values of cellulose. The results show that the $\delta^{13}C$ values of the modern dominant plant cellulose range from −23.67‰ to −27.92‰ (Table 1), which all fall in the scope of the $\delta^{13}C$ values for C3 plants (−20‰ to −30‰) [7,8]. In addition, the $\delta^{13}C$ values of the Hongyuan peat entire profile range from −24.35‰ to −29.30‰. Therefore it can be considered that the Hongyuan peat consists of the C3 series plants. The $\delta^{13}C$ value of C3 plants is dependent on both the relative humidity and temperature of air [9] though the former may be considered as a major factor [7]. Either the decrease of relative humidity or the temperature drop would lead to an increase of the $\delta^{13}C$ value of C3 plants; on the contrary, either the increase of relative humidity or the temperature raise would lead to a decrease of the $\delta^{13}C$ value of C3 plants [9]. As mentioned before, since the precipitation in the Hongyuan region is a little in the cold season, the moisture of earth surface in the region depends mainly on rainfall caused by the Indian Ocean summer monsoon. Therefore, the stronger the activity of the moist and warm India

Ocean summer monsoon, or the moister and warmer the air in the Hongyuan region, the smaller the $\delta^{13}C$ value of C3 plants in the Hongyuan region, and vice versa. Therefore the variation of the $\delta^{13}C$ value of Hongyuan peat plant remains is closely related to the change of the Indian Ocean summer monsoon, and can be considered as a proxy indicator for the monsoon. The smaller the $\delta^{13}C$ of peat plant remains cellulose, the stronger the monsoon activity, and vice versa.

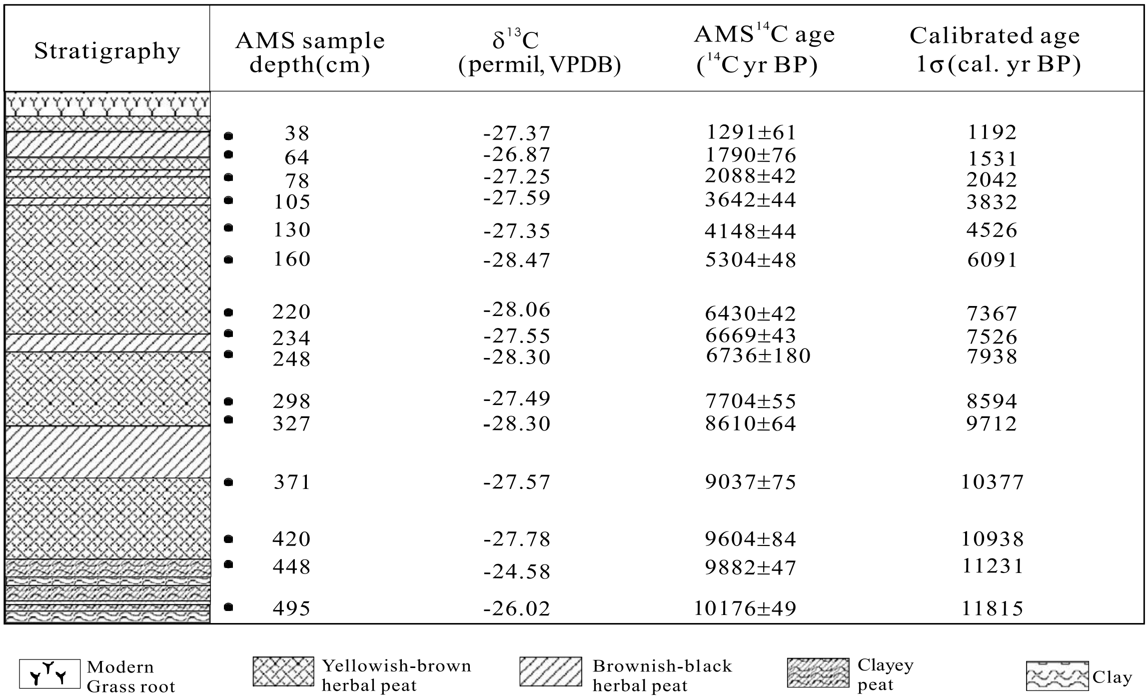
On a continuous peat deposition profile with 4.95 m depth in the Hongyuan peat bog we sampled peat specimens at intervals of 1 cm corresponding to a resolution of around 30 years. Each peat sub-specimen consists of a rectangle peat flat of around 35 cm long, 25 cm wide and 1 cm thick, that is provided for use of determination of the $\delta^{13}C$ of the peat plant remains cellulose or the peat total plant remains assemblage cellulose. In consideration of that in peat deposition there are normally the different species of plant remains which have the different $\delta^{13}C$ values (Table 1), and of that the possible changes of the relative composition of the different plant remains on the peat deposition profile may disturb the climate signals or may reduce the sensitivity of the peat plant cellulose as the proxy monsoon indicator, therefore, we at the same time picked out by hand under microscopy one of the most abundant plant remains, *Carex mulieensis*, from the sub-specimen at intervals of 1 sub-specimen, and extracted the cellulose of the *C. mulieensis* remains for the analysis of $\delta^{13}C$. Plant cellulose samples both from the peat mixed plants and from the mono-species plant (*C. mulieensis*) and their $\delta^{13}C$ values were prepared and analyzed respectively by the methods described in [10,11]. The value of $\delta^{13}C$ was expressed relative to the VPDB standard [12] and the overall precision was found to be better than ±0.1‰ (1σ). On the Hongyuan peat profile the 15 ^{14}C dates of the peat plant cellulose were measured by the accelerator mass spectrometry (AMS) at the Institute for Environmental Studies in Tsukuba, Japan (Fig. 2) [13]. The ^{14}C dates were calibrated using the calibration program CALIB-4.3 [14] and with linear interpolation we obtained a time scale in calendar years. All dates described in this text are based on the calibrated radiocarbon age.

3. A general variation trend of the Indian Ocean summer monsoon over the last 12 000 years

The evidence of variation of the Indian Ocean summer monsoon in the Hongyuan region over the last 12 000 years comes from two proxy records, in which the $\delta^{13}C$ time series of the peat mixed plant cellulose more clearly shows a general variation trend of the monsoon during the last 12 000 years (Fig. 3d) and the $\delta^{13}C$ time series of the *C. mulieensis* remains cellulose more sensitively shows the abrupt monsoon variation events that superimpose the general variation tendency (Fig. 3c). We can find that the intensity of the Indian Ocean summer monsoon inferred from

Table 1
Isotopic composition of modern plants in Hongyuan peatland

No.	Plant name	$\delta^{13}C$ (‰)	Std
HY1	*Carex mulieensis*	−27.093	0.005
HY2	*Carex meyeriana*	−25.668	0.008
HY3	*Kobresia tibetica*	−27.919	0.006
HY4	*Caltha scaposa*	−23.666	0.02
HY5	*Deschampsia caespitosa*	−25.401	0.013
HY6	*Chamaesium paradoxum*	−24.727	0.007
HY7	*Juncus concinnus*	−26.047	0.035
HY8	*Ranun culus reptans*	−25.339	0.025
HY9	*Potentilla enserina*	−26.104	0.004
HY10	*Thalictrum alpinum*	−25.601	0.008
HY11	*Cremanthodium lineare*	−25.482	0.012
HY12	*Blysmua sinocompressus*	−26.64	0.008



AMS sample depth(cm)	$\delta^{13}C$ (permil, VPDB)	AMS ^{14}C age (^{14}C yr BP)	Calibrated age 1σ(cal. yr BP)
38	-27.37	1291±61	1192
64	-26.87	1790±76	1531
78	-27.25	2088±42	2042
105	-27.59	3642±44	3832
130	-27.35	4148±44	4526
160	-28.47	5304±48	6091
220	-28.06	6430±42	7367
234	-27.55	6669±43	7526
248	-28.30	6736±180	7938
298	-27.49	7704±55	8594
327	-28.30	8610±64	9712
371	-27.57	9037±75	10377
420	-27.78	9604±84	10938
448	-24.58	9882±47	11231
495	-26.02	10176±49	11815

Fig. 2. Hongyuan peat stratigraphy and age.

our two peat isotope proxy records has undergone a series of abrupt variations during the last 12 000 years (Fig. 3c and d). During the period from around 11 200 to 11 800 a BP corresponding to the Younger Dryas the $\delta^{13}C$ values of both peat mixed and mono-species plant cellulose are highest, indicating lowest relative humidity and temperature in the Hongyuan site, which can be attributed to the weakest summer monsoon activity, because it led to a little precipitation and low temperature or much dry and cold climate condition in the region. The weakest summer monsoon during the Younger Dryas can be considered as the widespread phenomenon, because it also has been observed both from the sediment records of the Sumxi lake located in the northwestern Tibetan Plateau [15] and from the water level records of the Qinghai lake located in the northeastern Tibetan Plateau [16] (Fig. 1). From around 11 200 to 10 800 a BP abrupt variations occur in the two proxy records. The $\delta^{13}C$ values of both peat mixed and *C. mulieensis* cellulose suddenly decrease, which reflects abrupt transition from weak to strong activity of the Indian Ocean summer monsoon, coinciding with the results from the Sumxi and Qinghai lakes [15,16]. During the following Holocene section the two stages of the monsoon variation can be observed clearly. In the early–middle Holocene (around 10 800–5500 a BP) the two peat $\delta^{13}C$ time series show generally a low level (the mean values of the $\delta^{13}C$ are around −27‰ and −28‰ respectively) though they have fluctuating variations, which indicates large relative humidity and high temperature or reflects much wet and warm climate condition linked to the strong summer monsoon activity in the Hongyuan site. It was this period that precipitation in the northwestern [15], southern [5] and northeastern [16] regions of the Tibetan Plateau distinctly increased, and that the much widespread regions covering northern Indian, Pakistan, Arabia and even East Africa were under the influence of the strong summer monsoon moisture [17]. From around 5500 a BP onward, however, the two $\delta^{13}C$ time series show increases gradually, which indicates that the strength of the summer mon-

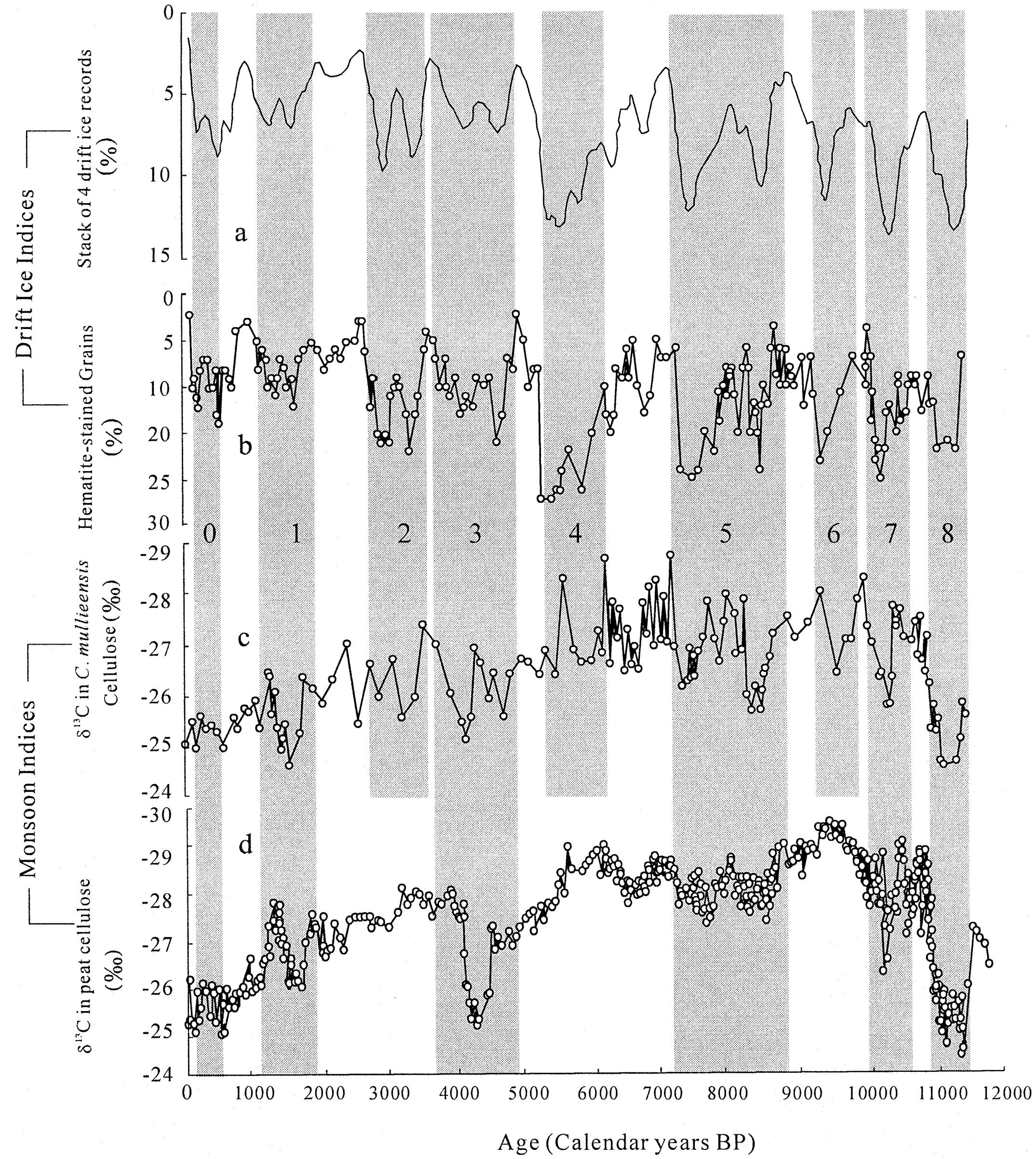


Fig. 3. The comparison between the peat proxy records of the Indian Ocean summer monsoon and the drift ice records in the North Atlantic Ocean. (a) Stack of four drift ice records from MC52-VM29-191 and MC21-GGC22 cores in the North Atlantic [4]. (b) Holocene record of drift ice for the MC52-VM29-191 core in the North Atlantic [4]. (c) and (d) Holocene proxy records for the Indian Ocean summer monsoon from δ^{13}C time series of the *C. mulieensis* remains and mixed plant cellulose of the Hongyuan peat. Numbers from 1 to 8 indicate each of eight IRD events of the North Atlantic [4]. Number 0 indicates 'Little Ice Age' event [4].

soon generally tends to gradual decrease in the Hongyuan site, coinciding with aridification condition in the other regions of the Tibetan Plateau [15]. Therefore our composite time series have reasonably reflected the variation history of the Indian Ocean summer monsoon on the several millennial time scales during the past 12 000 years in the Tibetan Plateau region.

4. Abrupt variations of the Indian Ocean summer monsoon and their linkage with the North Atlantic climate changes

The abrupt variations of the monsoon on the centennial to millennial time scales in the lower latitudes have been reported. However the mechanism for the variations is still not clear and several hypotheses have been presented [18–22]. In particular, it has been suggested that the variation of the Atlantic Ocean thermohaline circulation may take the responsibility for droughts in the lower latitudes, for example, in the North African [20], but no direct mechanism has been found relating the intensity of the ocean thermohaline circulation to the monsoon strength [21]. Recent investigations have revealed that during the last 12 000 years there are at least eight abrupt ocean surface coolings characterized by the IRD events in the North Atlantic, with peaks at about 1400, 2800, 4200, 5900, 8100, 9400,10 300, and 11 100 a BP respectively (Fig. 3a and b) [3,4]. In addition, the comparison between the proxies of drift ice measured in deep-sea sediment cores in the North Atlantic Ocean and the proxies of solar variability inferred from production rates of the cosmogenic nuclides carbon-14 and beryllium-10 has shown a close correlation [4]. These new progresses have led to the presentation of the hypothesis that through the entire Holocene the high northern latitude atmospheric cooling triggered by reduced solar irradiation perhaps leads to the coincident increases in North Atlantic drift ice, cooling of both the ocean surface and atmosphere above Greenland, reductions in North Atlantic thermohaline overturning, and potentially enhancing of the climate response in low-latitude climates [4].

In the case of the Indian Ocean summer monsoon, we consider that two aspects of study work should be carried out at least. First, we should further make careful comparison between the peat $\delta^{13}C$ proxy records of the monsoon and the proxy records of drift ice, so that we can see if teleconnection between the abrupt variation events occurring in both the Indian Ocean summer monsoon and the North Atlantic climate during the entire Holocene can be identified. Second, if so we would probe further into a direct mechanism for it.

Our two peat $\delta^{13}C$ time series, in particular the $\delta^{13}C$ time series of the *C. mulieensis* remains cellulose, show that during the last 12 000 years there are also a series of abrupt variations of the monsoon strength on the centennial to millennial time scales, which superimpose the general tendency of the monsoon variation mentioned above(Fig. 3c and d). The comparisons between the peat proxy records of the Indian Ocean summer monsoon and the proxy records of drift ice (Fig. 3) show that corresponding to each of the eight IRD events there is a clear drop in the *C. mulieensis* cellulose $\delta^{13}C$ record. We can find nearly a one to one correspondences between the $\delta^{13}C$ record of *C. mulieensis* and the drift ice records. Even for the $\delta^{13}C$ record of the peat mixed plant cellulose with a little lower sensitivity as mentioned before, also there are five clear drops corresponding to cooling events of the North Atlantic (events 8, 7, 5, 3, 1) (Fig. 3d), which however have covered all of the well-documented cooling events. For instance, during the period from around 11 200 to 11 800 a BP corresponding to the Younger Dryas (event 8) the intensity of the monsoon inferred from our two peat $\delta^{13}C$ proxy records was weakest and it can be regarded as the reappearance of the conclusion on the relationship between the monsoon in lower latitudes and the North Atlantic climate during the glacial period [1,2]. In addition, it has been confirmed that both event 7 and event 5 are the well-documented cooling changes in the widespread area of the Earth that are expressed as the distinct decrease of $\delta^{18}O$ and the increase of sea salt Na concentration in Greenland ice core GISP2 [23], which have been attributed to an oscillating ocean surface circulation that can be slowed or stopped by fresh water supplied to the North Atlantic [3,24,25]. At those times our two peat proxy records show the clear weakening of the summer monsoon, which may imply that the Indian Ocean summer monsoon changes may be linked to the variations of the ocean circulation. The recent investigation for the flux of Iceland–Scotland overflow water (ISOW), one of the components of North Atlantic deep water (NADW), has shown that since around 8000 years ago, corresponding to the period from event 4 to event 1, there were decreases in the flux of ISOW [26]. The paleochemical data from the Bermuda Rise core also show the reduction of NADW production [27]. Correspondingly our two peat proxy records then show weakness of the Indian Ocean summer monsoon strength at those times.

The weakening of the monsoon that occurred at around 4200 a BP (corresponding to event 3) may be worth paying particular attention, because the severe drought condition possibly caused by the weakening monsoon activity at that period also has been observed in the widespread area besides the Hongyuan site, including the western Tibetan Plateau [15], the Mesopotamian plain in western Asia [28], the western Africa and Mexico region [20], which has been considered to hinder severely the development of ancient civilization in the areas [28]. These results show that on the centennial to millennial time scales the weakening of the Indian Ocean summer monsoon may synchronize with the abrupt ocean surface cooling in the North Atlantic within error limits of ^{14}C dating. There is a close correlation between the strength variation of the Indian Ocean summer monsoon and the climate change of the North Atlantic, which is present not only in the last glacial [1,2], but also in the entire Holocene. This pervasive correlation may imply the presence of the same driving mechanism for the climate variation of the two regions.

5. On a mechanism for the linkage of the Indian Ocean summer monsoon with the North Atlantic climate

The monsoon climate system is one of the most important or basic climate systems on the Earth, which represents dynamic interactions between atmosphere, ocean and continents. The Indian Ocean monsoon is forced by transport of latent heat from the southern subtropical Indian Ocean to the Tibetan Plateau [29,30]. During boreal summer (austral winter) there is differential sensible heating for land and ocean, which leads to the seasonal formation of low atmospheric pressure over the Tibetan Plateau. At the same time, high atmospheric pressure occurs over the southern subtropical Indian Ocean because sea surface temperature (SST) of the southern subtropical Indian Ocean is relatively colder during boreal summer. The large temperature and humidity gradients force cross-equatorial transport of latent heat and the strong summer monsoon winds through the Arabian Sea and the Bay of Bengal respectively to the Tibetan Plateau.

We consider that if balance of the earth surface energy was changed or redistributed, and SST varied, the strength variation of the summer monsoon would follow. A considerable amount of evidences has suggested that the direct effect of the ocean thermohaline circulation (THC) is redistribution of energy on the Earth [31–33]. While strong northward flux of warm near surface water transports heat drawn from the Southern Hemisphere to the North Atlantic, it tends to a warming in the north that is synchronous with a cooling in the south, as a result of which the southern subtropical Indian Ocean SST would decrease. We infer that due to the reason mentioned before this would contribute to strengthening of the atmospheric pressure and the temperature and humidity gradients over the southern subtropical Indian Ocean, leading to strengthening of the Indian Ocean summer monsoon. On the contrary, a decrease in the cross-equatorial ocean circulation would tend to cool the north and to warm the south, and the southern subtropical Indian Ocean SST would increase. This would weaken the atmospheric pressure and the temperature and humidity gradients over the southern subtropical Indian Ocean, leading to the formation of the weak summer monsoon at the same time of cooling of the North Atlantic. This correlation may differ from one between the ocean surface cooling in the North Atlantic and the Asia winter monsoon. For the latter, cold North Atlantic sea surface temperature effects on regions directly downwind in Europe and Asia continental through atmospheric forcing [34]. But for the former, both the ocean surface cooling in the North Atlantic and the strength weakling of the Indian Ocean summer monsoon all seem to be linked to the variations of the ocean thermohaline circulation. They could be considered as two teleconnective climate subsystems associated with the changes of the ocean thermohaline circulation.

If this ideal model for the linkage of the Indian Ocean summer monsoon with the North Atlantic climate is correct, the terrestrial record of the Indian Ocean summer monsoon could provide signals for understanding the variations of ocean circulation. For instance, during the period from the Medieval Warm Period (around 1100 a BP) to the Little Ice Age (LIA) (around 500 a BP) the planktonic foraminiferal $\delta^{18}O$ record from the Sargasso Sea shows the changes from a low to a high peck value [27]. At the same time ISOW flow intensity changes from faster to slower [26]. These observations seem to imply association between LIA and THC on a few degrees. In our composite records the summer monsoon corresponding to the Medieval Warm Period shows a stronger peck value. In contrast, corresponding to LIA (event 0), our composite records show a clear drop, indicating weakening of the monsoon (Fig. 3c and d). Our results coincide with the observations mentioned above and provide new data for understanding the correlation between LIA and ocean circulation variations. However, the linkage between the monsoon in the lower latitudes and the North Atlantic climate may also have a relation to other atmospheric processes, for example, cooling in the North Atlantic could cause a change in the Hadley circulation which in turn could perhaps impact the monsoon activity in the lower latitudes [4], therefore much works remain to be carried out, including synchronous observations for the climates of the Tibet Plateau, the North Atlantic and the southern subtropical Indian Ocean and the modeling of GCM.

6. Conclusion

1. The evolution history of the Indian Ocean summer monsoon over the last 12 000 years in the eastern Tibetan Plateau has been reconstructed based on the $\delta^{13}C$ time series of both a single plant species (C. mulieensis) remains cellulose and the total plant assemblage cellulose in the Hongyuan peat bog from the Tibet Plateau. The results show that the weakest monsoon occurred in the Younger Dryas. Following rapid strengthening from around 11 200 to 10 800 a BP the monsoon intensity kept a generally strong level for around 5300 years. From around 5500 a BP onwards the monsoon strength tended to a gradual decrease. In addition, there are a series of abrupt variation events of the monsoon strength on centennial to millennial time scales, which superimpose the general tendency of the monsoon variation.
2. On centennial to millennial time scales there is a close teleconnection between the Indian Ocean summer monsoon variations and the abrupt climate change events characterized by the IRD events in the North Atlantic over the last 12 000 years. Corresponding to each of the eight IRD events in the North Atlantic the monsoon strength decreased clearly, which shows that the close correlation between the Indian Ocean summer monsoon and the North Atlantic climate is present not only in the last glacial, but also in the Holocene.
3. An ideal model for the linkage between the Indian Ocean summer monsoon and the North Atlantic climate has been presented. The model suggests that the ocean thermohaline circulation may play a linking role for the teleconnective variations between the Indian Ocean summer monsoon and the North Atlantic climate. The linkage could be considered as a response to the global seesaw effect caused by the ocean thermohaline circulation.

Acknowledgements

We sincerely thank two anonymous reviewers for their thoughtful reviews and suggestions. This work was supported by the National Natural Science Foundation of China (grant No. 40231007 and No. 49733130) and by the Innovation Program of the Chinese Academy of Sciences.***[BOYLE]***

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