Chinese Science Bulletin 2006 Vol. 51 No. 18 2169—2177

DOI: 10.1007/s11434-006-2112-2

Interconnections between the Asian monsoon, ENSO, and high northern latitude climate during the Holocene

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Received April 11, 2006; accepted May 24, 2006

Abstract The article emphatically reviews the research progress in interconnections between the East Asian and Indian Ocean summer monsoons, between the Asian monsoon and the El Niño-Southern Oscillation (ENSO) activity, and between the monsoon, ENSO and the changing of the North Atlantic climate during the Holocene. According to the studies of recent years, it is found that the intensity variations of the East Asian and Indian Ocean summer monsoons show an opposite relationship, which may be closely related to the phenomena of ENSO in the equatorial Pacific Ocean and the variation of the deep-water formation of the North Atlantic Ocean on the interannual to orbital time scales. The 4k and 8k events occurring at around 4200 and 8200 a BP, respectively, might be the two in a series of severe paleo-El Niño events during the Holocene, strongly reflecting the interactions and influences of the monsoons, ENSO and the North Atlantic climate. In order to better understand the relationships between these paleoclimatic phenomena, scientists need to strengthen the research work on the Asian monsoon division and the comparison between monsoon proxy records, and the study on the proxy record of sea surface temperature with high time-resolution in the equatorial Pacific Ocean and the simulation research of paleoclimate condition.

Keywords: Asian monsoon, monsoon division, paleo-El Niño, 4k event, 8k event, thermohaline circulation, peat.

The International Geosphere Biosphere Program (IGBP), which promotes better understanding of the living environment, was initiated in the early 1990s. IGBP and other programs have uncovered much evidence that the Earth system is complex and nonlinear, exhibiting chaotic behavior, feedback mechanisms, bifurcation points, etc., and so its future evolution is not always deterministic[1]. To gain more accurate understanding of environmental evolution, we must consider the Earth as a whole system. For the second study plan of IGBP started in 2003, the integration of multi-disciplines was therefore emphasized. One of the effective ways for integrating understanding is to strengthen regional research and link important scientific phenomena firstly, and then to seek out their causal interconnections, thereby gradually coming to understand global change[1].

The Earth system includes several key regional action processes, which operate as threshold values, bottlenecks, or switch functions. The Asian monsoon and the phenomenon of the El Niño-Southern Oscillation (ENSO) in the Equatorial Pacific Ocean as well as the variation of the deep-water formation of the North Atlantic Ocean are examples of these key regional processes: if perturbed, they may trigger a global environmental change[2]. Investigation of their interconnections is therefore very important for understanding the operation of the Earth system. This paper attempts to explore the research progress achieved in understanding interconnections between these key processes during the Holocene, and possibly also at present, in order to promote further study of this important field.

1 Inverse phase relationship between East Asian and Indian Ocean summer monsoons

The Asian summer monsoon system consists of the East Asian summer monsoon (EAM) and the Indian Ocean summer monsoon (ISM), which together influences the life and production activities of 60% residents of the globe. It is therefore very important to improve the ability to predict monsoon changes. Because of complicated monsoon phenomenon and limited observations, a method of “separate study” has been used for monsoon investigation, that is, the researches of Indian and western scholars have been mainly focused on the Indian monsoon region, while scholars in the other Asian countries have mostly concentrated on the East Asian monsoon. Rarely have the relations between the Indian and the East Asian monsoons, or the connections between the Asian, Australian, and African monsoons been investigated. It is now apparent that such method is unsuitable for the demands of current Earth system science research. A new perspective on monsoon studies is thus developing, which advocates a global understanding achieved through research on the dynamic linkages between the monsoons in a wide variety of regions and over different time scales[3].

Summer rainfall on the Chinese Mainland is influenced by both of the EAM and the ISM. This reality renders the study of the Chinese monsoon more complex, while encouraging a focus on regional details. About twenty years ago, Tao *et al.*[4] asserted that the East Asian and the Indian monsoon systems are independent of each other. However, more recent studies have identified that is actually an inverse phase relationship between these two Asian summer monsoons.

Using analyses of 500 hPa geopotential heights and the corresponding Northern Hemisphere sea surface temperature (SST) from 1951 to 1994, as well as outgoing longwave radiation (OLR) data for 1974 to 1993 from the National Center for Environmental Prediction-National Center for Atmospheric Research (NCAR), Sun *et al.*[5] studied the relationship between the intensity anomalies of the Western Pacific subtropical high (STH) and tropical circulation, especially that between the Asian monsoons in 1999. They found that a strong STH in the Western Pacific is accompanied by a strong Intertropical Convergence Zone (ITCZ) and associated strong convection in the tropical Western Pacific. This indicates that the EAM is strong in years of strong STH. During these periods, there also was a positive difference of OLR from the Indian Ocean to the Indian subcontinent, indicating weak convection in this area, and corresponding weak intensity of the ISM. On the contrary, the intensity of the two monsoons is reversed in a weak STH year, i.e. the EAM is weak while the ISM is strong. Sun *et al.*[5] obtained the same results from analysis of the low-level wind fields, i.e. the EAM is strong (weak) when the STH is strong (weak), while the ISM is weak (strong).

Zhang[6] obtained a similar result using NCEP-NCAR reanalysis data of monthly rainfall, monthly rainfall data of 160 stations compiled by the China Meteorological Administration from 1951 to 1998, and monthly OLR during 1974—1998 from the National Ocean and Atmospheric Administration (NOAA), USA. He found that the two monsoons are opposite in phase, as revealed by the relationship between the water vapor transport from the ISM and EAM in Northern Hemisphere summer, that is, more (less) ISM water vapor transport is accompanied by less (more) EAM transport and less (more) rainfall on the middle and lower parts of the Yangtze River. This study also showed that the water-vapor transport of the monsoon is closely related to the intensity of the STH: more (less) ISM water vapor transport corresponded to a weaker (stronger) STH, leading to less (more) northern water vapor transport in the East Asian monsoon to the west of the STH[6].

Recent research on the ancient Asian monsoons also indicates such an asynchronous relationship. Both the proxy climate record and the simulation research imply that the ISM was stronger and the ISM region was under continuous control of the strong summer monsoon moisture during the Holocene Megathermal Period[7,8]. According to some proxy climate records for the same time period, the EAM seemed to be also stronger. For instance, based on the paleomagnetic study of the Baxie loess section, An et al. noted that the climate of the Baxie region was humid at 9.7—5.3 ka BP[9], and the northern boundary of the EAM region expanded into the Chinese Mainland interior[10]. However, it is worth to reconsider whether the magnetic susceptibility change of the Baxie loess mostly reflected the ISM influence, since Baxie is located west of 105°E longitude, in the western half of the Chinese Mainland (Fig. 1).

In recent years, researches on the loess sections and lake sediments west of Baxie have yielded some new results. Zhou *et al*. found that the climate was dry and the EAM was weak from 7.5 to 3.5 ka BP, as indicated by the Midiwan loess profile[11]. Guo *et al.*[12] also reported a relatively arid climate in the Tengger Desert from 7 to 5.6 ka BP. The water level of Dali Nor Lake of Inner Mongolia also began to drop from as early as about 7 ka BP, and wind and sand then increased and lasted to about 4.5 ka BP[13,14]. Based on investigation of some indices of Yanhaizi in Inner Mongolia (e.g. sediment granularity, mineral composition, element content, total organic carbon content), Chen *et al.*[15] noted that the climate of this area during the Holocene Megathermal Period (between 8.0 and 4.3 ka BP) tended to be generally dry, but was punctuated abruptly by three shorter humid periods.

The above-mentioned ancient monsoon research sites are all located in the arid and semi-arid regions of the Loess Plateau or Inner Mongolia. The inverse relationship between the intensity of the two monsoons in the eastern parts of these regions, which are far-removed from ISM influence, is also reported. Based on the records and studies of peat cellulose δ^{13}C at Jinchuan in Jilin Province, Hong *et al.*[16−18] found that the intensity of the ISM variation was oppo-

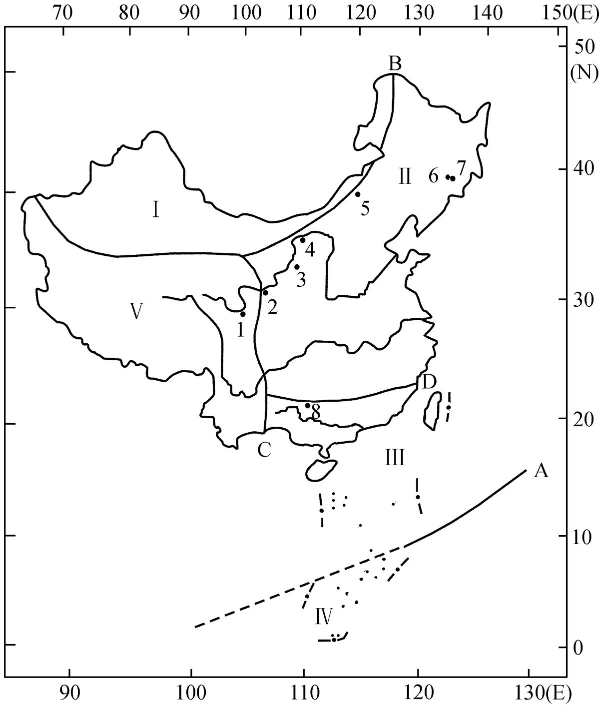

Fig. 1. Sketch map showing the monsoonal climate divisions of China[23] and the location of comparison research site in the text. A, The southern borderline of influence region of winter monsoon; B, the northern borderline of influence region of East Asian summer monsoon; C, the western borderline of influence region of winter monsoon; D, the northern borderline of influence region of Indian Ocean summer monsoon. Ⅰ, the westerlies region; Ⅱ, the subtropical monsoon region;Ⅲ, the tropical monsoon region; Ⅳ, the equatorial monsoon region; Ⅴ, the Qinghai-Xizang Plateau monsoon region. 1, Hongyuan, Sichuan; 2, Baxie, Gansu; 3, Midiwan, Shanxi; 4, Yanhaizi, Inner Mongolia; 5, Dali Nor, Inner Mongolia; 6, Jinchuan, Jilin; 7, Hani, Jilin; 8, Dongger Cave, Guizhou.

site in phase to that of the EAM during the past 6000 years. The similar relationship can also be seen in the δ^{13}C record of Hani peat cellulose (Fig. 2)[19]. For example, referring to Fig. 2(d) and (e), in the first half segment of the Holocene (from about 11000—6000 cal a BP), the Hongyuan peat record indicates that the ISM became gradually stronger on orbital time scales (Fig. 2(d)) while the Hani peat record indicates that the EAM became gradually weaker (Fig. 2(e)). On the contrary, in the second half of the Holocene, the EAM became stronger, and the ISM weaker. In addition, according to Fig. 2(d) and (e), there were a series of abrupt but opposite changes in monsoon intensity on centennial to millennial time scales, when the EAM rapidly strengthened while the ISM rapidly weakened. This pattern is consistent with the abrupt strengthening of the EAM that occurred in the Younger Dryas period and during some time intervals in the Holocene, as indicated by other proxy climate records[11,15,20].

In the southern Chinese Mainland, some high-resolution proxy climate records during the Holocene also have been obtained in recent years. Yuan *et al.*[21] and Wang *et al.*[22] determined the value of δ^{18}O of Dongger Cave in Libo County, Guizhou Province, and reconstructed the monsoon history since the last interglacial. It is seen from fig. 2 that the phase of the time series of the stalagmite δ^{18}O of Dongger Cave (Fig. 2(c)) is similar to that of the time series of the cellulose δ^{13}C of Hongyuan peat, reflecting ISM activity during the Holocene (Fig. 2(d)). What is shown in Fig. 2(c) also is similar to that of the proxy record of sediment from the Arabian Sea (Fig. 2(b)), but opposite to the phase of the time series of cellulose δ^{13}C of Hani peat (Fig. 2(e)), reflecting EAM activity during the Holocene. However, both Yuan *et al.* and Wang *et al.* avoid distinguishing the separate influence of the ISM or the EAM on the time series of the stalagmite δ^{18}O of Dongger Cave, instead, refer to this time series as a proxy for the temporal variations of the “Asian monsoon” generally.

In 1962, according to the seasonal data of fields of monsoon streamfunction, air pressure, humidity, and precipitation, Gao *at al.*[23] divided the Chinese Mainland and its marine border areas into five different monsoon climate regions (Fig. 1). Although Gao *et al.*[23] cautioned that this monsoon division is based on only 4 years’ observational data to “primarily determine the location of the frontal surface”, it actually has become a basic scheme for study of the eastern Asian ancient monsoon and has been simplified during actual application. Above all, the simplified scheme ignores the existence of the so-called tropical monsoon region where there is mutual influence of the ISM and EAM on the southern Chinese Mainland and its marine boundaries. This may explain why the aforementioned analyses of the Dongger Cave record are cautious in distinguishing ISM from EAM variations. In addition, it views 105°E longitude as a rigid boundary line, thereby ignoring the existence of a transitional area. As a result, the Chinese Mainland is divided into three blocks: the northwestern area being perennially under the influence of the Westerly winds, the ISM region to the westward of 105°E longitude, and the EAM region to the eastward of 105°E. Although this monsoon division scheme is compact and lucid, it cannot correctly reflect the scope of influence of the different monsoons, and it adversely impacts research on the Asian ancient monsoon. In the future, Chinese researcher should

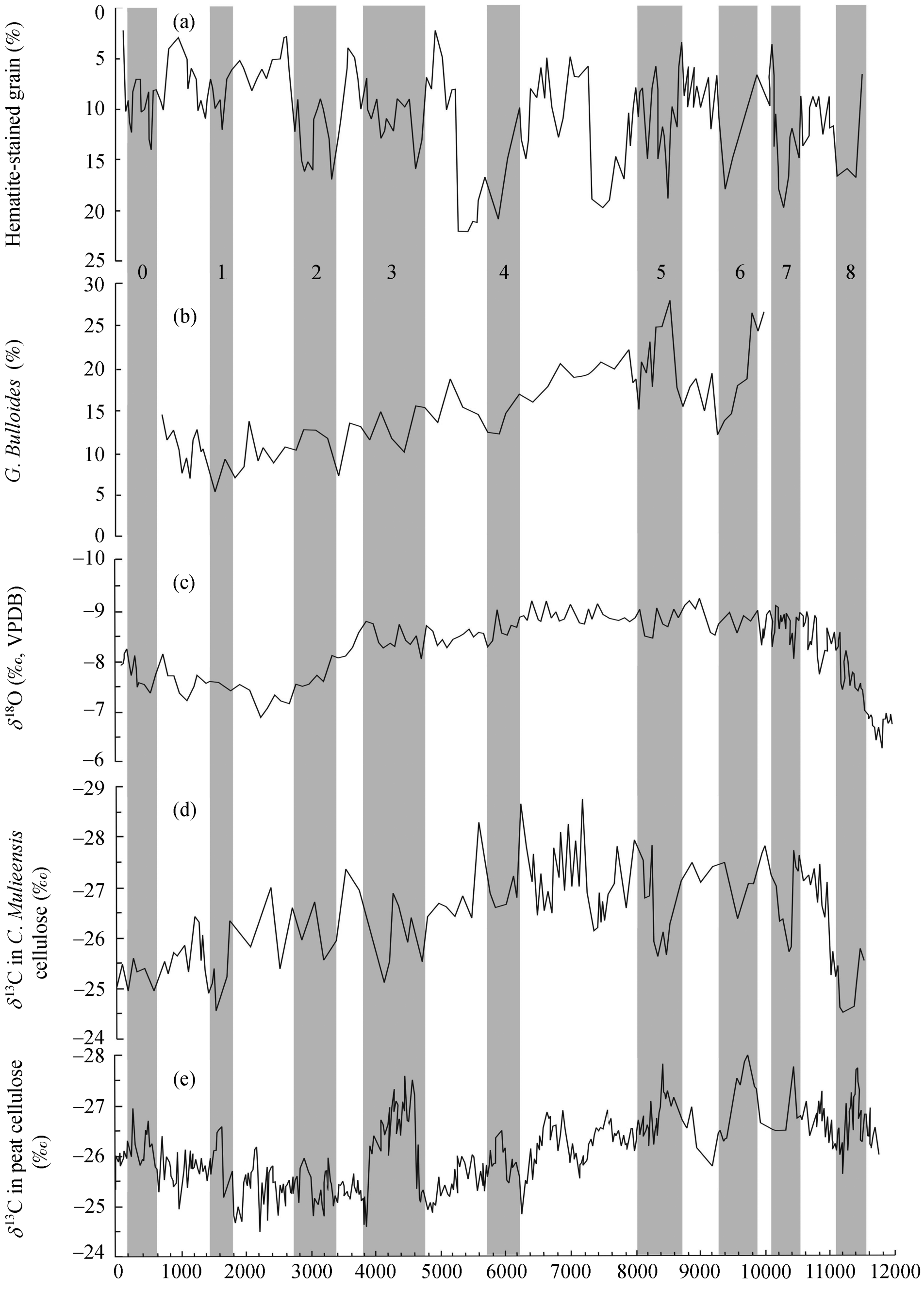

Fig. 2. Comparison of the inverse phase variations between the two Asian monsoons with the climate changes of the North Atlantic Ocean. (a) Holocene record of drift ice for the MC52-VM29-191 core in the North Atlantic; (b) proxy record for the Indian Ocean summer monsoon from the content of *G. bulloides* in Hole 723A and bax core RC2730 from the Arabian Sea; (c) proxy record for the Asian monsoon from δ^{18}O time series of stalagmite of Dongger Cave[21]; (d) proxy record for the Indian Ocean summer monsoon from δ^{13}C time series of the *C. mulieensis* remains cellulose in the Hongyuan peat bog in the eastern Tibetan Plateau[17]; (e) proxy record for the East Asian summer monsoon from δ^{13}C time series of the plant remains cellulose in the Hani peat bog in the northeastern China[19]. 1—8, ice-rafted debris events of the North Atlantic. 0 indicates ‘Little Ice Age’ event.

carefully revise the eastern Asian Mainland monsoon division of modern and geological historical periods according to new observational data. A new monsoon division scheme should also assess whether the monsoon boundary at 105°E is appropriate, and should define the scope of the transitional region. Moreover, a future scheme also should determine whether the northern boundary (Fig. 1, D) of the overlapping region of the two monsoons activities should be moved northward, and whether precipitation in the area of the Westerly winds is influenced by the EAM or the ISM.

The inverse relationship of the ISM and EAM illustrates the complexity of the factors affecting precipitation on the Chinese Mainland. At the scale of the Mainland, consideration of only a single monsoon's effect is insufficient to predict future variations in rainfall. The different contributions of the EAM and ISM should be synthetically considered. At the regional scale, it is necessary to explain which monsoon plays the dominant role, and to examine the relative influence of each monsoon, which is determined by various driving factors on different time scales.

2 Linkages of the Asian monsoons with the ENSO and North Atlantic climate

The factors and processes that may produce changes in the Asian monsoons include fluctuations in the heating effect of the Tibetan Plateau, variations in snow cover on the European-Asian continent and the extent of the polar ice sheet, the thermal conditions of the Equatorial Pacific and Indian Oceans, changes in STH pressure and circulation and in the climatic state of the North Pacific Ocean, and variations in solar radiation or volcanic activity. At present, there are mainly two hypotheses that attempt to explain the driving mechanisms of abrupt paleoclimatic change[24]. One hypothesis emphasizes the influence of the ocean's thermohaline circulation (THC), and assumes that the THC may slow down or even stop due to a catastrophic release of freshwater to the North Atlantic Ocean, thereby changing the global energy distribution and impacting other elements of the global climate. Thus, for this hypothesis, the high latitudes of the North Atlantic Ocean are perceived as key regions for triggering global climate change. The other hypothesis mainly emphasizes the influence of changes in the tropical ocean-atmosphere system, thus assuming that tropical convection is the main driver of the climate system. For this hypothesis, the trigger of abrupt climate change resides in the region of the ENSO, namely the Equatorial Pacific Ocean. Because the Asian monsoons exist in the low to middle latitudes situated between these two key regions, interconnections of the monsoons with the ENSO or with North Atlantic climate may be substantial.

Research progress along these lines of inquiry has been made in studies of the Indian monsoon. Based on analysis of a statistical relationship between Indian monsoon rainfall and the ENSO over the past 100 years, Shukla *et al.*[25] found that ISM rainfall tends to weaken in an El Niño year, but to strengthen in a La Niña year. Further study shows that this relationship may be strong enough to allow incidences of ENSO to be forecast[26]. However, Kumar *et al.* [27] noted that this relationship had been seemingly broken down in the 1990s. In 1997, when a strong El Niño event occurred, the ISM rainfall was roughly its climatological mean value, whereas in the strong El Niño year of 1877, a severe drought in India caused widespread famine. Kumar *et al.*[27] speculated that the change of the relationship between the monsoon and ENSO might be associated with Eurasian warming. However, the above-mentioned "normal" relationship between the monsoon and ENSO seems to have recently returned, with the Indian monsoon being weakened during the moderate El Niño event of 2001/2002[28].

Many researches on the relationship between the EAM and ENSO have also been carried out. Using the data of atmospheric reanalysis, SST and rainfall from NCEP-NCAR, Wang *et al.*[29] analyzed the different responses of the Asian monsoon corresponding to phase changes of the ENSO from development to decay. They found that an elongated anticyclonic ridge extending from the western Maritime Continent of the Indian Ocean to the Indian subcontinent during the summer of El Niño development leads to a weakening ISM on the interannual time scale. To the north of the ridge, however, abnormal Westerlies lead to the generation of frequent tropical storms on the West Pacific Ocean adjacent to Asia. In this phase of the ENSO, the southwesterly monsoon on the Arabian Sea weakens, while the monsoon on the Southern China Sea strengthens. During the summer of El Niño decay, the southwesterly monsoons on both the Arabian and South China Seas weaken, while the rainfall associated with the East Asian subtropical front tends to increase[29]. Thus, when the intensity of the ISM is continuously suppressed during the period from development to decay of an El Niño event, precipitation in the East Asian sector may be enhanced through frequent tropical storm activity in the West Pacific, a strengthening monsoon in the South China Sea, and in particular, through increasing rainfall associated with the East Asian subtropical front.

This research result is supported by the evidence of asynchronous changes in the EAM and ISM. Zhang[6] distinguished when the ISM was weak, the water vapor transport of EAM was strong in the years of 1953, 1964, 1966, 1976, 1977, 1983, 1988, 1995, 1996 and 1998 respectively[6]; but Zhang did not explain why the monsoon change in these years was a reversal of the usual pattern. These years of strong EAM and weak ISM were almost all El Niño years (1953 and 1996 excepted), as determined from the record of the 12 El Niño events during the period of 1951 to 2000 noted by Wang *et al.*[29]. In addition, during almost all of these years (except for 1976), the El Niño was in its decay phase with a positive SST anomaly present in the Niño 3 region. The anomalous occurrences of 1998 were especially noteworthy. The 1997/1998 El Niño was the strongest in the past ten years. This event triggered catastrophic flooding on the west coasts of Peru and Ecuador, and drought in Indonesia, New Guinea and Australia. Huge forest fires on Kalimantan brought about a thick cloud of smoke over Southeast Asia and crippled air travel in Singapore, Malaysia[28]. Widespread catastrophic flooding also occurred on the Chinese Mainland[30].

Asynchronous variation of the two Asian monsoons on the interannual scale results from their different spatial structures caused by the different land-ocean configurations, as well as their different responses to the ENSO driver[25,26,29]. Therefore, it can be assumed that the Asian monsoon and the ENSO have some structurally close linkage, which implies that a relationship may also exist between the ancient monsoon and the ENSO similar to what now exists on the interannual scale[19]. During the early Holocene, while the intensity of the EAM tended to gradually weaken and that of the ISM to strengthen on orbital time scales[19], a long-term La Niña-like pattern developed in the Equatorial Pacific Ocean[31]. When the EAM of the late Holocene was gradually strengthening and the ISM weakening[19], the Equatorial Pacific Ocean instead showed a long-term El Niño-like pattern[32]. It is clear that the asynchronous change of the EAM and ISM monsoons on the orbital time scale and the ENSO-like pattern in the Equatorial Pacific Ocean is analogous to that between these monsoons and the ENSO on the interannual time scale. The 9 abrupt strengthenings of EAM and 9 abrupt weakenings of ISM in Fig. 2 therefore possibly indicate 9 El Niño-like patterns in the Tropical Pacific Ocean during the last 12000 years. They correspond also to the 9 ice-rafted debris events in the North Atlantic, which thus may show the close correlation of the ENSO-like pattern in the tropical Pacific Ocean, the asynchronous change of the Asian monsoons, and the abrupt climatic cooling of the North Atlantic during the Holocene[19]. This hypothesis requires corroboration by more proxy climate records, in particular the sensitive high-resolution SST records during the Holocene, as well as by climate model simulation. The close relationship between the Asian monsoons and ENSO on the interannual time scale thus leads to a possible investigation of paleo-ENSO and paleo-monsoon interconnections.

3 8k and 4k events——two key points for interconnection research on global climate

Paleoclimatic records show evidence for the occurrence of an abrupt climatic-change event in the Northern Hemisphere at around 8200 a BP. While different scientists refer to this event by a variety of names, Alley *et al.*[33] call it the 8k event, in accordance with its date of occurrence. At that time, the δ^{18}O record of the ice core from the middle part of Greenland indicated that the local temperature was reduced by about 7.4℃, while the snow accumulation rate decreased and the wind speed increased. Although no Southern Hemisphere effects of the event have been recorded, the Northern Hemisphere response included an intensely cold Europe and moderately cold North America, which was accompanied by mostly dry conditions in northern and southern Europe and in the U.S. Great Plains, as well as across the Sahara and in the western Asian monsoon region[33]. However, this global climate change apparently is not the only reason for the international scientific attention to the 8k event. The more important reason is the triggering and influence mechanism of this event.

Some geophysical research studies indicate that big ice lakes were situated around the North American Laurentide ice sheet during the last deglaciation period, of which the Lake Agassiz was the largest one. With the increasing temperature conditions of the early Holocene, the Laurentide ice sheet was gradually shrinking, and hydrokinetic action led finally to the collapse of the Lake Agassiz ice bank. A great deal of fresh water (around 10^{14} m^3) stored in the lake flowed suddenly into the Northern Atlantic Ocean about 8400 years ago, bringing about a climate abnormality in the subsequent 200 to 300 years[33−35]. From this perspective, the 8k event is a typical natural catastrophe caused by melting ice.

How does the large bulk of fresh water flowing into the North Atlantic relate to the subsequent climate abnormality? In the past decade, a large body of research has addressed the influence of freshwater additions on the North Atlantic[33]. The ocean conveyor theory of Broecker et al. asserts that when cross-equatorial ocean water flows towards the North Atlantic Ocean and reaches high latitudes, the increasing salinity of seawater results in its descending into the deep ocean and forming the deep-layer water that flows back south, thereby completing the important THC chain. Once a great deal of freshwater enters the North Atlantic Ocean, the seawater at high latitudes is thinned down abruptly. The results of many simulation models then show that the THC slows down or even stops, resulting in a large decrease of northward heat transfer, the cooling of the North Atlantic region, the weakening of rainfall from the African and west Asian monsoons, and the southward movement of the ITCZ near South America. The slow THC promotes the warming of the South Atlantic Ocean and the increased formation of southern Atlantic deep water[36−39]. These simulation results also are in agreement with some climate proxy records[33]. The 8k event is believed to be a large perturbation to the Earth system prior to the time when human activities could have any impact. This event thus provides a unique opportunity to study complex interconnection mechanisms in the Earth system, and especially to simulate the system's response to a strong natural perturbation.

It is noteworthy that Alley's distribution map of the global climate abnormality in relation to the 8k event shows no information on the East Asian monsoon[33]. Alley *et al.*[33] quoted the results of statistical research by Morrill *et al.*[40] that "no conclusive evidence for a change is found in the Asian monsoon at ≈8.2 cal ka, as suggested by several previous studies, and more high-resolution data may be needed to observe this short-lived event". In fact, new developments pertaining to the response of the Asian monsoon to the 8k event appeared two years after the publication of the paper by Morrill *et al.* Information from stalagmite[41], sea sediment[42], and peat[17] proxy records shows that the ISM weakened in response to the 8k event, and the EAM strengthened[19,43]. These proxy data again provide evidence for the asynchronous variations of the EAM and ISM intensity on paleoclimatic time scales, and imply the possible presence of a long-term El Niño-like pattern in the Equatorial Pacific Ocean[19] (Fig. 2). These data thus suggest a new and important perspective for further study of the 8k event.

Another abrupt climate-change event occurred about 4200 years ago (herein called the 4k event), which also has attracted the attention of paleoclimatic researchers. Like the 8k event, a large-scale climate abnormality occurred and the Asian monsoons also showed asynchronous variations (Fig. 2). At that time, the monsoon rainfall was decreasing, and the climate was dry in the regions influenced by the ISM, such as the Tibetan Plateau[7,17], the Indian region[42,44], western Asia[45], and eastern Africa[46,47]. However, rainfall in the EAM region was increasing[15,19], and there were floods in the Yangtze River and Yellow River basins[48,49]; severe drought occurred in the interior of North America[50]; there was cooling of the climate of the Northern Atlantic Ocean[50]. In contrast to the 8k event, the 4k event occurred in the early stages of recorded history, and its influence on ancient civilizations thus can be identified. Several researchers have pointed out that the severe and continuous drought conditions in the Indian monsoon area may be related to the collapse of the Akkadian empire of western Asia, the decline of the early ancient civilization of Greece and Egypt, and the Harappan civilization in the Indus valley[45,51,52]. By contrast, the flood of the eastern Asian monsoon region may have significantly affected the decline of the Longshan and Liangzhu Cultures during the same period[19,49,53,54].

The foremost differences between the 4k and the 8k events, however, may be their respective triggering mechanisms. On the one hand, inverse changes occur to the Asian monsoons in the 4k event[19]. From the SST record of the cold tongue of the eastern Equatorial Pacific Ocean, there is an elevated peak value[31] that may indicate the existence of a long-term El Niño-like pattern. In the meantime, the North Atlantic Ocean was cold, and an ice-rafted debris event similar to the 8k event occurred[55]. These results imply that there may be similar interconnections between the Asian monsoon, ENSO, and the North Atlantic Ocean climate during the 4k and 8k events (Fig. 2). On the other hand, the hypothesis of THC reorganization caused by interior dynamics of the ice sheet is obviously not applicable to the 4k event, due to the retreat of the Northern Hemisphere ice sheet. This clearly indicates that another kind of triggering mechanism possibly exists in the Earth system that also causes global climate changes similar to those associated with the 8k event. Hong *et al.*[19] speculate that either the catastrophic input of fresh water to the northern Atlantic or the increase of drift ice caused by reduced solar output would result in reductions in North Atlantic THC overturning or in its reorganization, which would further exert differential influences on the climate at both high and low latitudes. For instance, the weakening cross-equatorial ocean circulation may transport less heat drawn from the Southern Hemisphere to the North Atlantic, which not only leads to cooling of northern latitudes, but also contributes to the storage of heat in the south, leading to formation of enhanced SST there. These conditions would favor an increase of the temperature contrast between the surface Pacific warm pool and the deep ocean, which, in turn, would contribute to the occurrence of the El Niño-like pattern in the tropical Pacific and the inverse phase variations of the Asian monsoons[19].

4 Conclusion

The investigation of monsoon phenomena has entered a new stage, that of global research. According to observations and related studies in recent years, the EAM and ISM have an asynchronous relationship, i.e. one monsoon's intensity rises while the other declines. This relationship is strongly dependent on the thermal state of the Equatorial Pacific Ocean. On orbital and millennial time scales, a suddenly strong EAM, a weak ISM, and a long-term ENSO-like pattern in the Equatorial Pacific Ocean are coincident with the ice-rafted debris events of the North Atlantic Ocean during the Holocene, but the mechanism for these interconnections is unknown. Because these phenomena are centered on the 8k and the 4k events, it is possible to gain a new understanding of the operation of the Earth system through comparative investigation of these events.

Acknowledgements The authors sincerely thank three anonymous referees for their thoughtful reviews and suggestions. This work was supported by the National Natural Science Foundation of China (Grant Nos. 40231007, 40573004).

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