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Synchronous or asynchronous Holocene Indian and East Asian summer monsoon evolution: A synthesis on Holocene Asian summer monsoon simulations, records and modern monsoon indices

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A B S T R A C T

Holocene climate records obtained from the Asian summer monsoon domain suggest a regionally-delineated response to changing summer monsoon. The interaction between the East Asian summer monsoon (EASM) and the Indian summer monsoon (ISM), two subsystems of the Asian summer monsoon, has been considered as a factor that explains those inconsistent Holocene climate records. However, this assumption is not valid when the relationship between the two subsystems is not clear. This paper presents a literature review regarding climate simulation of the Asian summer monsoon for testing the long-term relationship. The absolutely-dated Holocene speleothem records in the EASM domain and the ISM domain were compared to verify the simulation results. In addition, a unified monsoon index, which has a unified solid dynamic basis and is appropriate for different monsoon regions, was used in order to identify the modern relationship between the two subsystems. The speleothem records show more synchronous than asynchronous on the Holocene millennial-scale monsoon evolution, furthermore the two subsystems respond to the Younger Dryas (YD) and 8.2 ka events in a similar way. However, these monsoon simulations roughly suggest that the two subsystems respond to Holocene climate change in different ways. While the simulations were mostly performed in a certain period of the Holocene, the speleothem records provided a relatively continuous Asian summer monsoon history. Therefore, time scales could affect the comparison between simulations and speleothem records. Then, we further discussed the interaction between the Asian monsoon subsystems according to simulations and modern monsoon indices. Overall, the relationship between the two subsystems is more complicated than synchronous or asynchronous, which is a dynamic relationship and related to the atmosphere–land–ocean–vegetation interaction. In addition, the relationship can vary over different time scales, and the links between time scales should be paid more attention to. Besides, the interaction between the westerly winds and the Asian summer monsoon in the mid-latitudes of East Asia will profoundly affect those areas in response to Holocene climate change. It is recommended that further research should be emphasized in dynamic mechanisms between the Asian summer monsoon subsystems and between the Asian monsoon and the westerly winds.

1. Introduction

The Asian monsoon climate system plays a significant role in the global energy and water cycle (Webster et al., 1998; Wang et al., 2005). Long-term trend and abrupt events of the Asian monsoon provide a context for recent Asian summer monsoon variability. Holocene Asian monsoon research is able to resolve the full spectrum of monsoon variability and to place the limited instrumental records in a long-term perspective. Holocene Asian monsoon history is complicated by inconsistent monsoon records from different parts of the Asian monsoon domain (An et al., 2000; He et al., 2004; Hong et al., 2005; An et al., 2006; Herzschuh, 2006; Chen et al., 2008; Y. Wang et al., 2010). The Indian summer monsoon (ISM) and the East Asian summer monsoon (EASM) are two main subsystems of the Asian monsoon, while there is a relatively broad range of boundary between them that is roughly divided at 100°–110°E (Tao and Chen, 1987; Wang and Lin, 2002; Ding and Chan, 2005, Fig. 1). Responding to the strength of the continental high- and low-pressure cells, the two subsystems interact with each other; however, they also have significant differences dictated by the contrasting sea–land distributions. The annual cycle of rainfall exhibits a remarkable difference between the two monsoon subsystems that are also closely interlinked (Wang and Lin, 2002). Scientists have seen the interaction between the two monsoon subsystems as a factor causing asynchronous Holocene climate change over East Asia. For example, Hong et al. (2005) showed the inverse phase oscillations between the East Asian and Indian Ocean summer monsoons during the Holocene by comparing plant cellulose $\delta^{13}C$ time series of peat bogs from the

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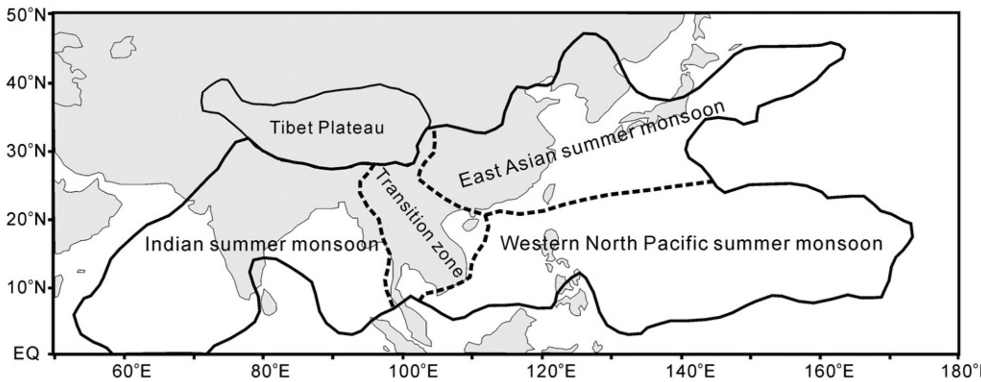

Fig. 1. Map showing that the Indian summer monsoon and the East Asian summer monsoon are two subsystems of the Asian summer monsoon (after Wang and Lin, 2002).

two subsystems. Y. Wang et al. (2010) synthesized 92 proxy records of moisture change in East and Central Asia, which reveal a strong spatial heterogeneity in Holocene moisture evolution between the EASM domain and the ISM domain, and proposed that the variability of Holocene Hadley Circulation could result in asynchronous millennial-scale climate change between the two Asian monsoon subsystems. Although this approach is interesting, it suffers from poor understanding of the interaction between the two subsystems, especially on the Holocene millennial-scale.

Numerical simulation of paleoclimate provides insights into why past climate changes have occurred, also helps in evaluating reliability of future climate predictions. Over the last two decades, there has been much progress in Holocene climate simulation (Joussaume and Braconnot, 1997; Kutzbach and Liu, 1997; Wang, 1999; Otto–Bliesner et al., 2006; T. Wang et al., 2010). Holocene Asian monsoon simulation provides information about the long-term driving mechanisms of the monsoon circulation (Kutzbach and Liu, 1997; Joussaume et al., 1999; Liu et al., 2003, 2004; T. Wang et al., 2010). In this review, we presented a synthesis on Holocene Asian monsoon simulations that largely focuses on the interaction between the EASM and the ISM. The absolutely-dated Holocene speleothem records in the domains of the two monsoon subsystems were used to verify those model results. In addition, a unified monsoon index (UMI), which has a solid dynamic basis and is appropriate for different monsoon regions, was used in calculating modern monsoon indices of the two subsystems that help explore the modern relationship between them. This combination of Holocene Asian monsoon simulations, monsoonal records and modern monsoon indices is helpful in evaluating the interaction between the two subsystems on different time scales.

2. Data and methods

2.1. Selection of Holocene Asian monsoon simulations

A large number of palaeoclimatic simulations from East and Central Asia has been published during the last two decades. While providing insights into the mechanisms of climate change, these simulations, however, have different focus, such as precipitation, temperature and evaporation. To ensure the simulations can be used to imply monsoon mechanisms, all of those included in our analyses were required to meet the following criteria:

1) Simulations should provide information for the Holocene epoch, at least some intervals in the Holocene.
2) Simulations should be indicative of monsoon intensity, monsoon water vapor transport, or monsoon rainfall.
3) Both the EASM domain and the ISM domain should be included in the simulations, so that we can detect the interaction between the two subsystems.

Totally, 13 simulations were selected for this study (see detailed information in Table 1). Eight simulations focus on the mid-Holocene (~6.0 ka) and the present-day or the pre-industry that can represent the late Holocene period. The other four simulations (CCSM 3.0, CLIMBER-2, FOAM-NCAR-CSM and FOAM-FSSTAM) compare the early Holocene simulations with the mid-to-late Holocene results. In these simulations, the monsoon status is usually shown by precipitation that is also complemented by pressure and wind fields. In order to further examine the relationship between the two monsoon subsystems, we

Table 1
Summary of Holocene climate simulations in the Asian monsoon domain.

Models	Periods	Duration of the model experiment (years)	Whether the difference between the two subsystems can be detected	References
AGCM + SSiB	Present-day and 6 ka	11	Yes	Chen et al. (2002), Liu et al. (2002)
ECHAM5/JSBACH-MPIOM	Present-day and 6 ka	600	Yes	Dallmeyer et al.(2009), Dallmeyer and Claussen (2011)
CCSM 3.0	Pre-Industrial, 6 ka, and 8.5 ka	100 and 50	Yes	Li and Morrill (2010), Jin et al. (2012)
CLIMBER-2	9.0 ka to present-day	9000	Yes	Jin et al. (2005, 2008)
FOAM-NCAR-CSM	Present-day, 3 ka, 6 ka, 8 ka and 11 ka	120	Yes	Liu et al. (2003, 2004)
FOAM-FSSTAM	Present-day, 6 ka, and 11 ka	260	Yes	Li and Harrison (2010)
PMIP 1*	6 ka	10	Yes	Joussaume et al. (1999)
PMIP 2**	6 ka	500	Yes	T. Wang et al. (2010)
IAP-AGCM	6 ka	5	Yes	Wang (1999)
AGCM-BIOME	6 ka	5	Yes	Wang (2002)
RegCM2	Present-day and 6 ka	5	Yes	Zheng et al. (2004)
FGOALS-g1.0	Present-day and 6 ka	/	Yes	Zheng and Yu (2009)
LMD AGCM	6 ka	15	Yes	Texier et al. (2000)

* PMIP 1 includes 18 models: BMRC, CCC2, CCM3, CCSR1, CNRM2, CSIRO, ECHAM3, GEN2, GFDL, GISS, LMD4, LMD5, MRI2, MSU, UGAMP, UIUCll, UKMO and YONU.
** PMIP 2 includes 12 models: CCSM, CSIRO-Mk3L-1.0, CSIRO-Mk3L-1.1, ECHAM5-MPIOM1, FGOALS-1.0 g, FOAM, GISSmodelE, IPSL-CM4-V1-MR, MIROC3.2, MRI-CGCM2.3.4fa, MRI-CGCM2.3.4nfa and UBRIS-HadCM3M2.

Table 2
Summary of the high-resolution and absolutely-dated Holocene speleothem records in the Asian monsoon domain.

	Speleothem records	Long. (°E)	Lat. (°N)	Altitude (m)	Affiliation	Duration	References
(a)	Moomi Cave	54°0′	12°30′	400	IM	The Last Deglaciation	Shakun et al. (2007)
(b)	Qunf Cave	54°18′	17°10′	650	IM	The past 10.5 ka	Fleitmann et al. (2003)
(c)	Hoti Cave	57°21′	23°05′	800	IM	9.6–6.1 ka BP	Neff et al. (2001)
(d)	Jhumar Cave	81°52′	18°52′	600	IM	AD 1400–2008	Sinha et al. (2011)
(e)	Dandak Cave	82°0′	19°0′	400	IM	AD 600–1550	Berkelhammer et al. (2010)
(f)	Timta Cave	82°02′	29°50′	1900	IM	The Last Deglaciation	Sinha et al. (2005)
(g)	Tianmen Cave	90°04′	30°55′	4800	IM	8.7–4.3 ka BP	Cai et al. (2012)
(h)	Mawmluh Cave	91°52′	25°15′	1290	IM	12.4–3.6 ka BP	Berkelhammer et al. (2012)
(i)	Wah Shikar Cave	91°52′	25°15′	1290	IM	AD 1400–2008	Sinha et al. (2011)
(j)	Wanxiang Cave	105°0′	33°19′	1200	IM/EAM	The past 1810 years	Zhang et al. (2008)
(k)	Huangye Cave	105°07′	33°35′	1650	IM/EAM	The past 1860 years	Tan et al. (2011)
(l)	Dayu Cave	106°18′	33°08′	870	IM/EAM	AD 1249–1983	Tan et al. (2009)
(m)	Yamen Cave	107°54′	25°29′	570	IM/EAM	16.2–7.3 ka BP	Yang et al. (2010)
(n)	Dongge Cave	108°05′	25°17′	680	IM/EAM	The past 15.8 ka	Dykoski et al. (2005)
(o)	Jiuxian Cave	109°06′	33°34′	1495	IM/EAM	The past 19.0 ka	Cai et al. (2010)
(p)	Lianhua Cave	109°32′	29°29′	455	IM/EAM	The past 6.6 ka	Cosford et al. (2008)
(q)	Heshang Cave	110°25′	30°27′	294	IM/EAM	The past 9.5 ka	Hu et al. (2008)
(r)	Sanbao Cave	110°26′	31°40′	1900	IM/EAM	13.0–0.2 ka BP	Dong et al. (2010)
(s)	Shihua Cave	115º56′	39º47′	251	EAM	The past 2650 years	Tan et al. (2003)
(t)	Hulu Cave	119°9′	32°30′	100	EAM	The Last Deglaciation	Wang et al. (2001)
(u)	Nuanhe Cave	124°55′	41°20′	500	EAM	10.5–0.3 ka BP	Wu et al. (2011, 2012)

EASM = East Asia monsoon domain, ISM = Indian summer monsoon domain, IM/EAM = the transitional region of the two subsystems.

assigned these simulation results to the ISM domain and the EASM domain according to the present monsoon boundary, which is a broad range of boundary at 100 º ~ 110°E (Wang and Lin, 2002, Fig. 1).

2.2. Selection of the absolutely-dated Holocene speleothem records

In the past decade, scientists have reviewed Holocene Asian monsoon records by different methods (An et al., 2000; He et al., 2004; Hong et al., 2005; An et al., 2006; Herzschuh, 2006; Chen et al., 2008; Y. Wang et al., 2010). A variety of paleoclimate proxies (e.g., speleothems $\delta^{18}O$ and $\delta^{13}C$; lake sediments pollen assemblages, diatom abundance, % biosilica, grain-size, $\delta^{18}O$ and $\delta^{13}C$; corals $\delta^{18}O$; aeolian sediments grain-size and % total organic matter) have been used to reconstruct the Holocene Asian monsoon evolution. Different types of proxies respond to monsoon change in different ways; therefore, reviews that include all kinds of proxies can be influenced by this factor. In order to eliminate this effect, the present paper aims to summarize no more than one proxy that can be found both in the EASM domain and in the ISM domain. High-resolution and absolutely-dated speleothem records, which have been used to reconstruct the Asian summer monsoon change from Oman (Fleitmann et al., 2003) to China (Dykoski et al., 2005; Hu et al., 2008; Cai et al., 2010), are good indicators showing monsoon evolution and can be found in the two monsoon subsystems. Furthermore, the impact of monsoon variability on stalagmites can also be confirmed by a numerical simulation (Pausata et al., 2011). Twenty-one Holocene speleothem records were collected both from the EASM domain and from the ISM domain (Fig. 2, Table 2). While the present boundary of the two subsystems is roughly at 100° ~ 110°E

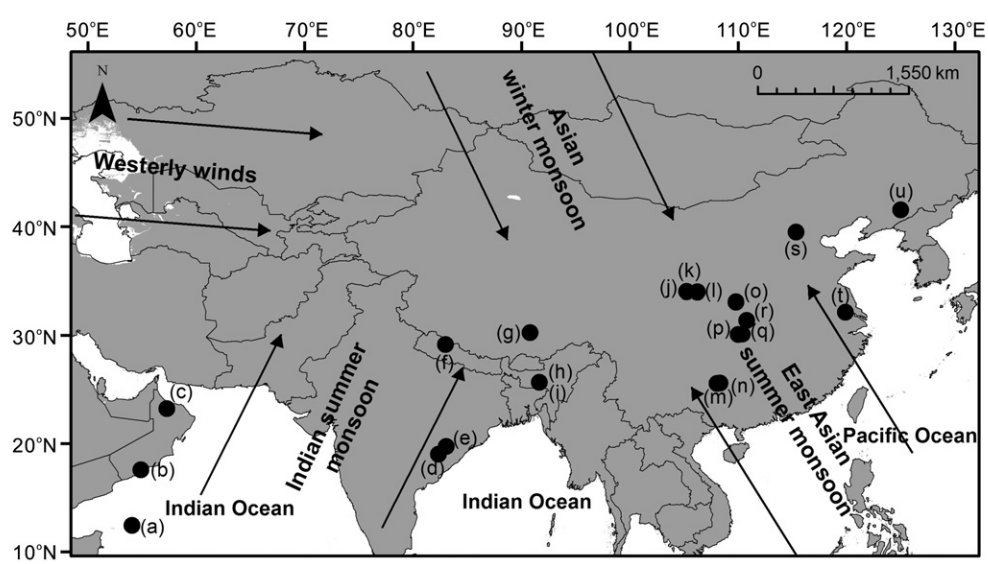

Fig. 2. Map showing East and South Asia. The arrows indicate the climate systems affecting East and South Asia, including the East Asian summer monsoon, the Indian summer monsoon, the westerly winds and the Asian winter monsoon. The black circles show the locations of caves that are cited in this research, including (a) Moomi Cave, (b) Qunf Cave, (c) Hoti Cave, (d) Jhumar Cave, (e) Dandak Cave, (f) Timta Cave, (g) Tianmen Cave, (h) Mawmluh Cave, (i) Wah Shikar Cave, (j) Wanxiang Cave, (k) Huangye Cave, (l) Dayu Cave, (m) Yamen Cave, (n) Dongge Cave, (o) Jiuxian Cave, (p) Lianhua Cave, (q) Heshang Cave, (r) Sanbao Cave, (s) Shihua Cave, (t) Hulu Cave and (u) Nuanhe Cave (see Table 2).

(Wang and Lin, 2002, Fig. 1), the records within this range are considered to be affected by the combined effect of the two subsystems.

2.3. A unified monsoon index (UMI)

Monsoon possesses very strong seasonal variation, it is therefore a reasonable idea that strong and weak monsoons may be measured by use of the seasonal variation magnitude of wind field (Webster and Yang, 1992; Webster et al., 1998). Li and Zeng (2002) developed a unified monsoon index (UMI) that has a unified solid dynamic basis and is appropriate for different monsoon regions. The monsoon index exhibits a better correlation with monsoon intensity in the Asian monsoon domain than WYI and MHI do (Li and Zeng, 2002). UMI is given by:

$$\delta = \frac{\left\| \overrightarrow{V_1} - \overrightarrow{V_{m,n}} \right\|}{\left\| \overrightarrow{\overline{V}} \right\|} - 2$$

where $\overrightarrow{V_1}$ and $\overrightarrow{V_{m,n}}$ are the January climatological and monthly 850 hPa wind vectors at a point (n, year; m, month). $\overrightarrow{\overline{V}}$ is the mean of January and July climatological 850 hPa wind vectors at the same point. Monsoon indices for the EASM and the ISM are calculated according to the definition of monsoon domain proposed by Li and Zeng (2002): the EASM domain (10°–40°N, 110°–140°E) and the ISM domain (5°–22.5°N, 35°–97.5°E). The monthly mean wind vector data are obtained from the NCEP/NCAR reanalysis project (Kalnay et al., 1996).

3. Results

3.1. Holocene Asian monsoon simulations

3.1.1. PMIP 1 and PMIP 2

The Paleoclimate Modeling Intercomparison Project (PMIP) was initiated in order to coordinate and encourage the systematic study of AGCMs and to assess their ability to simulate large changes of climate such as those that occurred in the distant past (Joussaume and Taylor, 1995). The PMIP Phase I (PMIP 1) was carried out to address the Asian summer monsoon climate using atmospheric general circulation models (AGCMs) and AGCMs coupled with a slab ocean model (Joussaume and Braconnot, 1997; Kutzbach and Liu, 1997). The general finding of PMIP 1 is that amplification of the northern hemisphere seasonal cycle of insolation during the mid-Holocene can substantially strengthen the African and Asian monsoons (Joussaume et al., 1999). However, mid-Holocene monsoon precipitation has variable response to insolation change in different regions of the Asian monsoon domain. For example, in the ISM domain, the mid-Holocene precipitation increases dramatically between 10° and 20° N, and decreases in some regions between 0 and 10° N. While, in the north of 20° N, where the EASM prevails, the mid-Holocene monsoon precipitation has little change compared with the present condition (Joussaume et al., 1999; Chen et al., 2002). The second phase of the PMIP (PMIP 2) was also used to analyze the mid-Holocene Asian monsoon climate. Generally, these models reproduce warmer and wetter summer climate conditions in the Asian monsoon domain during the mid-Holocene, and the amount of summer precipitation is enhanced in most regions (Jiang et al., 2005; T. Wang et al., 2010). On the contrary, mid-Holocene summer precipitation decreases over the western North Pacific, which belongs to the EASM domain. The decreased precipitation is related to the obvious southerly wind anomalies and an anomalous anticyclone over the Northwest Pacific, which could be related to the strengthening and northward migration of the western North Pacific subtropical high.

3.1.2. CCSM 3.0, CLIMBER-2, FOAM-NCAR-CSM, FOAM-FSSTAM and FGOALS-g1.0

Ocean feedback and the large-scale features of atmospheric general circulation is a focus addressed by numerous Holocene Asian monsoon simulations. In the CCSM 3.0, there is an interesting increase in precipitation from 6.0 ka to Pre-industry in some coastal areas of Indian and South Asia, which are controlled by the ISM, whereas a rise in lake-level also appears in these areas (Li and Morrill, 2010). The result can be attributed to a negative oceanic feedback on precipitation, in which strong heating of the ocean by summer insolation, as at 6.0 ka, causes enhanced moisture convergence over the ocean, reducing convergence and precipitation over coastal areas (Liu et al., 2004). However, precipitation decreases from 6.0 ka to Pre-industry in most areas of the EASM domain according to the model. The difference shows that the two subsystems respond to the oceanic feedback in difference ways from mid-to-late Holocene. In the FOAM-NCAR-CSM and FOAM-FSSTAM models, it is found that the responses of the monsoons to insolation forcing and oceanic feedback differ substantially among regions, because of regional features of atmospheric or oceanic circulation and ocean–atmosphere interaction (Liu et al., 2003, 2004; Li and Harrison, 2010). Precipitation is increased substantially from northern India to central and western China from 11 to 6 ka according to the FOAM-NCAR-CSM simulation, representing a significant enhancement of the Asian monsoon; however, rainfall is reduced modestly in regions near the coast of India (Liu et al., 2003, 2004). The FOAM-FSSTAM simulation, forced with prescribed modern sea-surface temperatures (SSTs), indicates that the Holocene orbital forcing can enhance the amplitude of precipitation variability over southeastern China and northwestern China, however, reduce it over central India and North China (Li and Harrison, 2010). Therefore, the ocean could change the spatial distribution and local intensity of the orbitally-induced latitudinal atmospheric oscillation over the Asian monsoon domain. In the FGOALS-g1.0 model, the land-sea temperature gradient is enhanced during the mid-Holocene that tends to strengthen the large-scale Asian monsoon circulation (Zheng and Yu, 2009). As a result, the high-level easterly wind is enhanced between 20° and 30°N in the ISM region, while the low-level equatorial easterly wind and the cross equator southwest flow are also strengthened. On the contrary, the vertical and horizontal temperature gradient changes result in the weakening and the south shifting of the subtropical westerly jet over the EASM domain, which suppresses the monsoonal rainfall in North China. In addition to the ocean feedback and the large-scale features of atmospheric general circulation, ice sheets in the Qinghai–Tibet Plateau could also influence the monsoon circulation. The CLIMBER-2, which is an earth system model of intermediate complexity, has been used to investigate the sensitivity of simulated global climate to gradually increased snow and glacier cover over the Tibetan Plateau for the last 9 ka (Jin et al., 2005, 2008). The simulations show that the imposed mid-Holocene ice sheets over the Tibetan Plateau induces summer precipitation decreases strongly in South Asia, and increases in Southeast Asia.

3.1.3. AGCM-BIOME, AGCM + SSiB, ECHAM5/JSBACH-MPIOM, IAP-AGCM, LMD AGCM and RegCM2

There is significant difference between vegetation cover in different periods of the Holocene over the Asian monsoon domain. Generally, the impact of vegetation–atmosphere interaction during the mid-Holocene strengthens the summer monsoon circulation, the convection and the large-scale rainfall in the Asian monsoon regions, which complements the orbital forcing to explain the massive northward penetration of monsoon rains. The AGCM + SSiB and RegCM2 models show that the effect of the mid-Holocene vegetation reduces surface albedo and causes an increase in the winter temperature, which leads to weakening of the winter continental cold anticyclone over China (Chen et al., 2002; Liu et al., 2002; Zheng et al., 2004). These two models roughly indicate that the 6 ka BP precipitation over most of monsoon regions is more plentiful than that of the present. However, the vegetation cover has different effect to monsoon precipitation in the two subsystems: precipitation over southern Tibetan Plateau and Indian Peninsula, which are located in the ISM domain, is considerably increased; precipitation in southern and southwestern China, which is controlled by the EASM, is decreased or unchanged. The ECHAM5/JSBACH-MPIOM model focused on the impact of vegetation–atmosphere and ocean–atmosphere interactions on the mid-to-late Holocene climate change in Central and Eastern Asia (Dallmeyer et al., 2009; Dallmeyer and Claussen, 2011). The enhancement of monsoon precipitation prevails in most regions of the Asian monsoon domain during the mid-Holocene; however, on regional average, the ocean–vegetation–atmosphere effect tends to weaken precipitation of the EASM and strongly increases the ISM rainfall. In the IAP-AGCM model, associated with the strengthening of the mid-Holocene monsoon circulation and the convection, the large-scale rainfall in Asian monsoon regions is reinforced significantly. However, the decreased rainfall can be found over tropical Indian and western Pacific Oceans, while in regions with enhanced rainfall, the simulated ground wetness, moisture flux in the surface, and root zone water content are increased accordingly (Wang, 1999). The simulated mid-Holocene precipitation from the AGCM-BIOME simulation indicates that rainfall increase is smaller in magnitude over northern China and the region north to the Bay of Bengle, when comparing with rainfall simulated by the AGCM without the vegetation effect (Wang, 2002). In the LMD AGCM model, the mid-Holocene vegetation is more efficient in recycling water than a bare soil, and the release of latent heat in the atmosphere increases convection, which in turn helps maintain the onshore oceanic advection (Texier et al., 2000). Therefore, monsoon rains are significantly enhanced over Indian, especially in the southern margin of the Tibetan plateau. However, monsoon precipitation change is not apparent in the EASM domain.

3.2. Long-term trends and abrupt events of the Holocene Asian monsoon recorded by absolutely-dated speleothem records

3.2.1. Changing trends of the Holocene monsoon over the Indian and East Asian monsoon domains

In the west of the ISM domain, high-resolution oxygen isotope ($\delta^{18}O$) profiles of Holocene stalagmites from Qunf Cave and Hoti Cave in Oman provide detailed information on fluctuations in precipitation. The records reflect the amount of precipitation, which is primarily

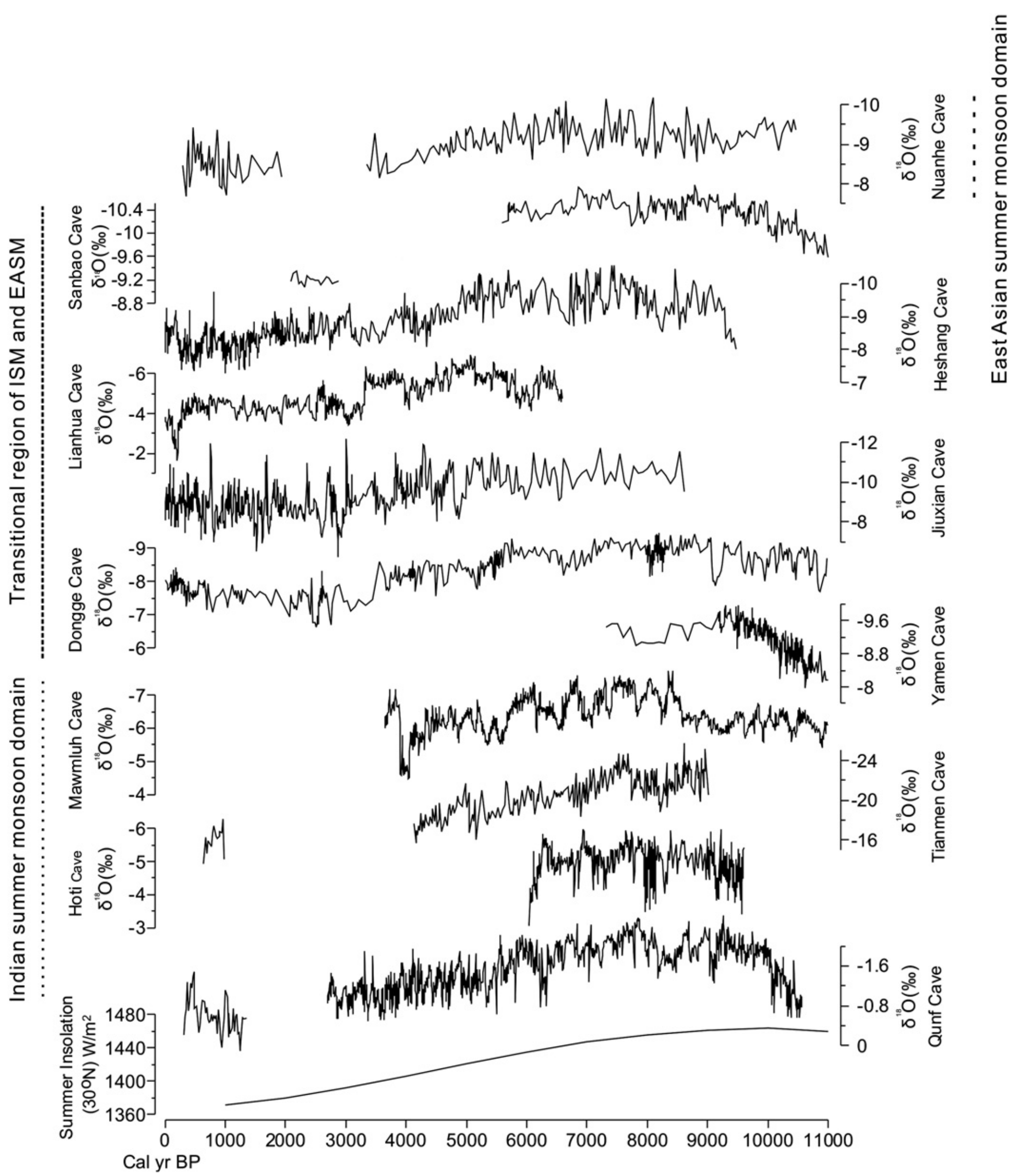

Fig. 3. Compilation of Holocene speleothem records in the East Asia and Indian summer monsoon domains, as well as the transitional region of the two subsystems showing the Holocene Asian summer monsoon evolution, including summer insolation at 30°N (after Berger and Loutre, 1991), $\delta^{18}O$(‰) from Qunf Cave (after Fleitmann et al., 2003), $\delta^{18}O$(‰) from Hoti Cave (after Neff et al., 2001), $\delta^{18}O$(‰) from Tianmen Cave (after Cai et al., 2012), $\delta^{18}O$(‰) from Mawmluh Cave (after Berkelhammer et al., 2012), $\delta^{18}O$(‰) from Yamen Cave (after Yang et al., 2010), $\delta^{18}O$(‰) from Dongge Cave (after Dykoski et al., 2005), $\delta^{18}O$(‰) from Jiuxian Cave (after Cai et al., 2010), $\delta^{18}O$(‰) from Lianhua Cave (after Cosford et al., 2008), $\delta^{18}O$(‰) from Heshang Cave (after Hu et al., 2008), $\delta^{18}O$(‰) from Sanbao Cave (after Dong et al., 2010) and $\delta^{18}O$(‰) from Nuanhe Cave (after Wu et al., 2011, 2012).

controlled by the dynamics of the ISM and the mean latitudinal position of the Inter-tropical Convergence Zone (ITCZ) (Neff et al., 2001; Fleitmann et al., 2003). The excellent correlation between the two records suggests that one of the primary controls on centennial- to decadal-scale changes in tropical rainfall and monsoon intensity during this time are variations in solar radiation. The rapidly decreasing $\delta^{18}O$ values during the early Holocene and the gradually increasing $\delta^{18}O$ values in response to solar insolation indicate shifts of the summer ITCZ and the ISM rainfall belt (Fig. 3).

Tianmen Cave and Mawmluh Cave are located in the northern part of the ISM domain. The Tianmen and Mawmluh records are in good agreement with speleothem records from Qunf Cave, Hoti Cave and peat bog records from southeast Tibetan Plateau, indicating that the ISM gradually weakened as Northern Hemisphere summer insolation declined since the mid-Holocene (Hong et al., 2005; Berkelhammer et al., 2012; Cai et al., 2012, Fig. 3). Moreover, due to joint effects of changes in monsoon precipitation, moisture source and temperature, the Tianmen $\delta^{18}O$ record shows much larger amplitude changes than speleothem $\delta^{18}O$ records from low-elevation Asian monsoon regions.

In the transitional region of the Indian and East Asia monsoons, relatively continuous Holocene stalagmite calcite $\delta^{18}O$ records from Dongge Cave, Heshang Cave, Jiuxian Cave, Lianhua Cave and Sanbao Cave provide information on shifts in monsoon precipitation (Dykoski et al., 2005; Cosford et al., 2008; Hu et al., 2008; Cai et al., 2010; Dong et al., 2010). Throughout the Holocene, the intensity of monsoonal circulation declined in response to changes in insolation and a southward shift in the ITCZ (Fig. 3). The periodicities expressed in the stalagmite $\delta^{18}O$ records occur at both solar and non-solar frequencies and support interpretations that variability in monsoonal circulation responds to both solar forcing and internal climatic mechanisms. Comparison of these cave records with Holocene speleothem records from the ISM domain reveals that the changing trend of monsoonal circulation is similar in these two regions (Fig. 3). This supports the idea that shifts in the monsoon largely follow orbital-scale insolation change that is also tied to shifts in the mean position of the ITCZ.

Nuanhe Cave is located in East China, a typical site influenced by the EASM. Four stalagmites (NHS, NH12, NH13 and NH20) were collected in the deep site of the cave, and a composite $\delta^{18}O$ profile pieces all data measured from the four stalagmites, which provides a continuous history of the EASM intensity from 10.5 ka to 3.36 ka and 1.9 ka to 0.3 ka (Wu et al., 2011, 2012). The stalagmite $\delta^{18}O$ record reveals strong summer monsoon intensity between 10.5 and 5.5 ka and a long-term gradual decrease in monsoon intensity starting at 5.5 ka. After comparing this record with other speleothem records from the ISM domain and the transitional region of the two monsoons, it shows that the timing of the onset and termination of the Holocene strong monsoon period and the declining trend since the mid-Holocene are similar (Fig. 3). It means the Holocene ISM and EASM change in phase. This supports that shifts in the mean position of the ITCZ could be one of the reasons for the monsoon intensity throughout the entire Asia on orbital time scales.

These Holocene speleothem records show spatially coherent variability throughout the Holocene, while the Holocene lake records in the Qinghai-Tibet Plateau reveal a similar trend for the Asian summer monsoon evolution compared with the cave records. Fig. 4 shows the Holocene $\delta^{18}O$, $\delta^{13}C$ and pollen concentration variability in lake sediments from Ahung Co (Morrill et al., 2006), Seling Co (Morinaga et al., 1993), Koucha Lake (Mischke et al., 2008) and Qinghai Lake (Shen et al., 2005; Liu et al., 2007), which is consistent with the Holocene speleothem $\delta^{18}O$ records in this review.

3.2.2. The Younger Dryas (YD) Event

In Yemen, variations in stalagmite oxygen isotope ratios ($\delta^{18}O$) from Moomi Cave provide a robust and high-resolution paleoclimate record during the Last Deglaciation that is interpreted to be primarily driven by an amount effect related to the ISM and the mean position of the ITCZ. The ISM rainfall increased dramatically during the Bølling-Allerød (BA) period and decreased through the YD event, and then the Holocene began abruptly with increased precipitation at 11.4 ka, indicating that a North Atlantic–Indian Ocean teleconnection persisted through the end of the last glacial period (Shakun et al., 2007, Fig. 5). The Timta and Mawmluh Caves, in the north of India, document the ISM precipitation variations during the BA interstadial and the YD (Sinha et al., 2005; Berkelhammer et al., 2012). Compared with the YD record in Yemen, the monsoon precipitation is also enhanced during the BA and

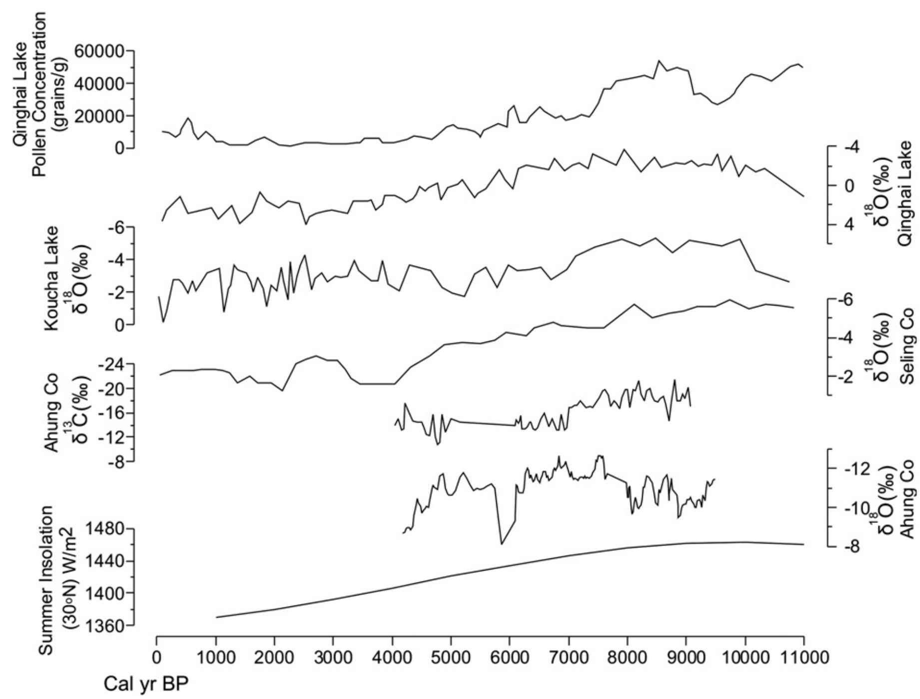

Fig. 4. Compilation of Holocene lake records in the Qinghai–Tibet Plateau showing the Holocene Asian summer monsoon evolution, including summer insolation at 30°N (after Berger and Loutre, 1991), $\delta^{18}O$(‰) from Ahung Co (after Morrill et al., 2006), $\delta^{13}C$(‰) from Ahung Co (after Morrill et al., 2006), $\delta^{18}O$(‰) from Seling Co (after Morinaga et al., 1993), $\delta^{18}O$(‰) of from Koucha Lake (Mischke et al., 2008), pollen concentration (grains/g) from Qinghai Lake (after Shen et al., 2005), $\delta^{18}O$(‰) of ostracode shells from Qinghai Lake (after Liu et al., 2007).

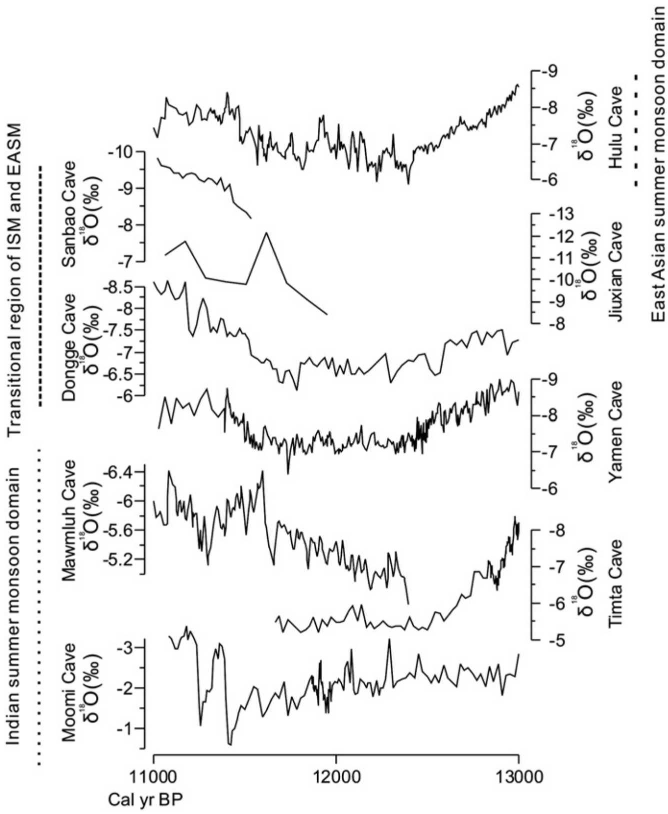

Fig. 5. Compilation of speleothem records during the Younger Dryas (YD) event in the East Asia and Indian summer monsoon domains, as well as the transitional region of the two subsystems showing the abrupt Asian summer monsoon change, including $\delta^{18}O$(‰) from Moomi Cave (after Shakun et al., 2007), $\delta^{18}O$(‰) from Timta Cave (after Sinha et al., 2005), $\delta^{18}O$(‰) from Mawmluh Cave (after Berkelhammer et al., 2012), $\delta^{18}O$(‰) from Yamen Cave (after Yang et al., 2010), $\delta^{18}O$(‰) from Dongge Cave (after Dykoski et al., 2005), $\delta^{18}O$(‰) from Jiuxian Cave (after Cai et al., 2010), $\delta^{18}O$(‰) from Sanbao Cave (after Dong et al., 2010), $\delta^{18}O$(‰) from Hulu Cave (after Wang et al., 2001).

decreased during the YD, which is apparently coupled to climate variations in the west of the ISM domain and the North Atlantic (Fig. 5).

In the transitional region of the two monsoon subsystems, Dongge and Yamen Caves provide monsoon records covering the Last Deglaciation and early Holocene. The BA and YD events are also characterized by strong and weak millennial-scale monsoon events, while the timing of changes in the monsoon shows no significant phase differences according to a comparison with the records from Moomi, Timta and Mawmluh Caves (Dykoski et al., 2005; Yang et al., 2010, Fig. 5). In addition, the speleothem records from Sanbao and Jiuxian Caves don't cover the entire period of the YD, but an increasing trend in monsoon precipitation is apparent during the ending period of the event, which is consistent with the records from Dongge and Yamen Caves (Cai et al., 2010; Dong et al., 2010, Fig. 5). Hulu Cave is located in East China, where the climate is controlled by the EASM with little influence from the ISM. The oxygen isotope record during the YD from Hulu Cave bears a remarkable resemblance to stalagmite oxygen isotope records from the ISM domain and the transitional region of the two subsystems, suggesting that the EASM intensity changes in concert with the ISM (Wang et al., 2001, Fig. 5).

3.2.3. The 8.2 ka Event

The prominent 8.2 ka event was well documented in the Greenland ice cores and the North Atlantic Ocean (e.g. O'Brien et al., 1995; Alley et al., 1997). In the low-to-mid-latitude regions, the 8.2 ka event expressed as an anomaly superimposed on a 400–600 years cold/aridity background (Rohling and Palike, 2005). The Holocene abrupt climate event is also recorded by high-resolution oxygen isotope ($\delta^{18}O$) from cave stalagmite records in the two subsystems of the Asian monsoon: Qunf Cave (Fleitmann et al., 2003), Hoti Cave (Neff et al., 2001), Tienmen Cave (Cai et al., 2012) and Mawmluh Cave (Berkelhammer et al., 2012) in the ISM domain; Yamen Cave (Yang et al., 2010), Dongge Cave (Dykoski et al., 2005), Jiuxian Cave (Cai et al., 2010) and Sanbao Cave (Dong et al., 2010) in the transitional region of the two subsystems; Nuanhe Cave (Wu et al., 2011, 2012) in the EASM domain (Fig. 6). These oxygen isotope records indicate a monsoon failure roughly between 8.6 and 8.1 ka BP largely associated with changes in the monsoon rainfall $\delta^{18}O$ during summer season. The signal from the 8.2 ka event is more significant in the ISM domain than other parts of the Asian monsoon system. An interpretation for the significant difference is likely that the EASM and the ISM belong to subtropical and tropical monsoon systems, respectively. The weak signal of $\delta^{18}O$ records from the mid-latitudes implies that the low-latitude process is more sensitive to the impact of the North Atlantic. Although the speleothem records from the two subsystems have different sensitivity to the

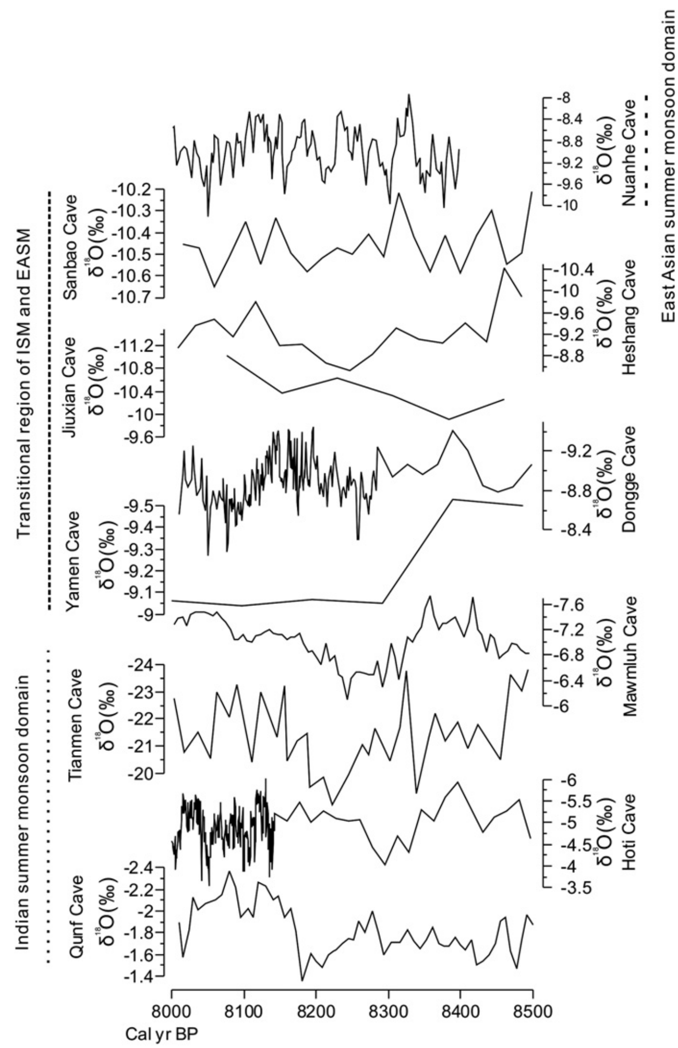

Fig. 6. Compilation of speleothem records during the 8.2 ka event in the East Asia and Indian summer monsoon domains, as well as the transitional region of the two subsystems showing the abrupt Asian summer monsoon change, including $\delta^{18}O$(‰) from Qunf Cave (after Fleitmann et al., 2003), $\delta^{18}O$(‰) from Hoti Cave (after Neff et al., 2001), $\delta^{18}O$(‰) from Tianmen Cave (after Cai et al., 2012), $\delta^{18}O$(‰) from Mawmluh Cave (after Berkelhammer et al., 2012), $\delta^{18}O$(‰) from Yamen Cave (after Yang et al., 2010), $\delta^{18}O$(‰) from Dongge Cave (after Dykoski et al., 2005), $\delta^{18}O$(‰) from Jiuxian Cave (after Cai et al., 2010), $\delta^{18}O$(‰) from Heshang Cave (after Hu et al., 2008), $\delta^{18}O$(‰) from Sanbao Cave (after Dong et al., 2010) and $\delta^{18}O$(‰) from Nuanhe Cave (after Wu et al., 2011, 2012).

8.2 ka event, they don't show the out-of-phase response to the Holocene abrupt climate change.

3.2.4. The past 2000 years

In Central India, the instrumentally calibrated stalagmite oxygen isotope records from Jhumar Cave and Dandak Cave (Berkelhammer et al., 2010; Sinha et al., 2011, Fig. 7) provide a millennial length history of monsoon rainfall variations over the core monsoon zone of India, while the multicentennial-length speleothem $\delta^{18}O$ record from Wah Shikar Cave reveals a history of monsoon rainfall variations over northeast India (Sinha et al., 2011, Fig. 7). On centennial timescales, precipitation variability from these two regions exhibits opposing behavior, while the opposing behavior also exists in the transitional region of the two subsystems during the past 2000 years. A speleothem $\delta^{18}O$ record from Wanxiang Cave characterizes an Asian monsoon history over the past 1810 years. The summer monsoon correlates with solar variability, Northern Hemisphere and Chinese temperature, Alpine glacial retreat, and Chinese cultural changes, while it was generally strong during the Medieval Warm Period (MWP) and weak during the Little Ice Age (LIA) (Zhang et al., 2008, Fig. 7). Not far from Wanxiang Cave, the speleothem $\delta^{18}O$ from Huangye Cave reveals monsoon precipitation change for the past 1860 years. The reconstructed monsoon precipitation variations correlate well with the Wanxiang Cave record, suggesting synchronous precipitation changes on decadal to centennial scales (Tan et al., 2011, Fig. 7). However, another 2–3-year resolution record of stalagmite oxygen isotope record from Dayu Cave in central China reveals that the monsoon precipitation variations over the past 750 years indicate a wetter climate during the LIA, suggesting a regional difference

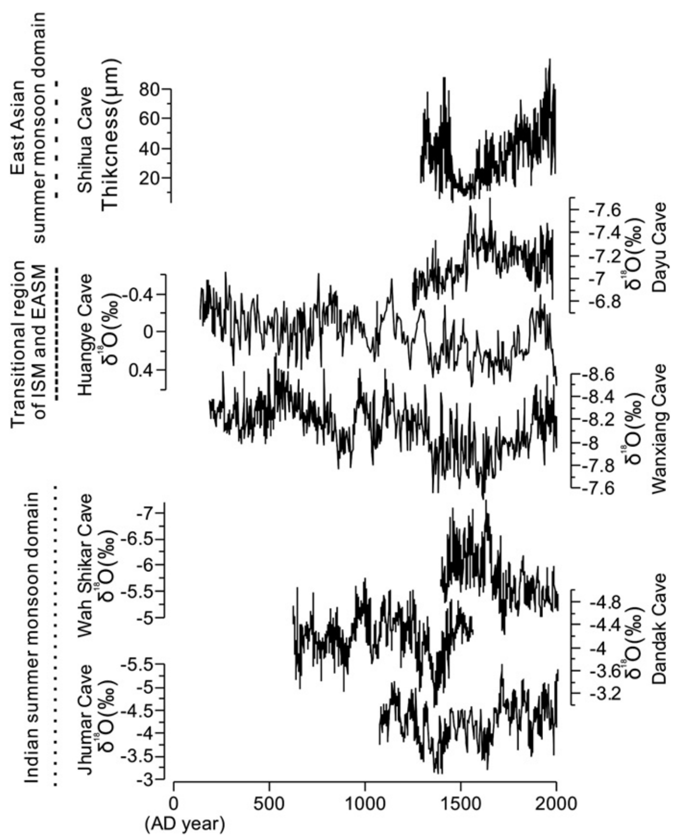

Fig. 7. Compilation of speleothem records for the past 2000 years in the East Asia and Indian summer monsoon domains, as well as the transitional region of the two subsystems showing the Asian summer monsoon evolution, including $\delta^{18}O$(‰) from Jhumar Cave (after Sinha et al., 2011), $\delta^{18}O$(‰) from Dandak Cave (after Berkelhammer et al., 2010), $\delta^{18}O$(‰) from Wah Shikar Cave (after Sinha et al., 2011), $\delta^{18}O$(‰) from Wanxiang Cave (after Zhang et al., 2008), $\delta^{18}O$(‰) from Huangye Cave (after Tan et al., 2011), $\delta^{18}O$(‰) from Dayu Cave (after Tan et al., 2009), thickness(μm) from Shihua Cave (after Tan et al., 2003).

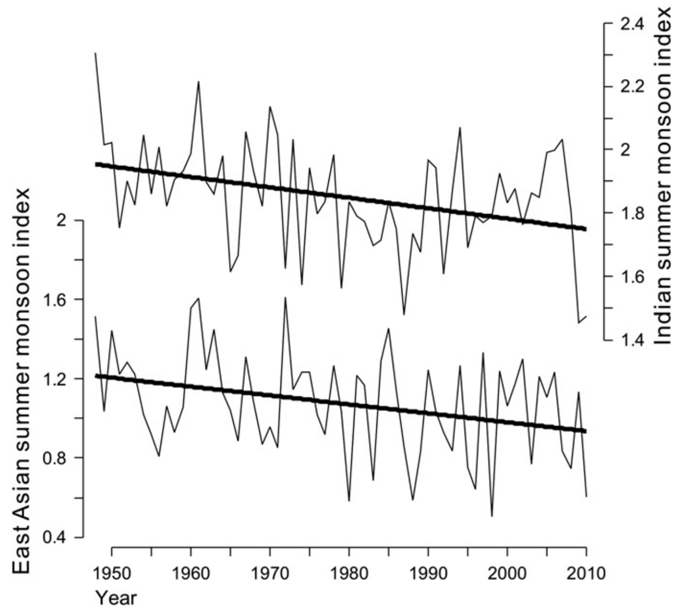

Fig. 8. Indian and East Asian summer monsoon indices (1948–2010), calculated by the method proposed by Li and Zeng (2002). The straight lines show the results of the linear regression.

in monsoon precipitation variability on the decadal- to centennial-scale (Tan et al., 2009, Fig. 7). In the EASM domain, a stalagmite thickness record, which is verified by instrumental meteorological records, reveals the temperature variation for the past 2650 years. This reconstruction reveals that the MWP and LIA are characterized by warm and cold climate, and the wet MWP and dry LIA can be implied by the monsoonal warm-wet and cold-dry climate patterns in the EASM domain (Tan et al., 2003, Fig. 7). Overall, the two monsoon subsystems have complicated responses to climate change of the past 2000 years, respectively, especially during the MWP and LIA.

3.3. Modern monsoon indices

Fig. 8 shows indices of the EASM and the ISM (1948–2010) calculated by the Unified Monsoonal Index. The correlation coefficient between indices of the two subsystems is 0.322, which is significant at 0.01 level. On the decadal-scale, the changing trend of the two indices is similar, while the decreasing trend is apparent in the two subsystems since the mid-1970s. The ISM index is positively correlated with summer precipitation over Indian. However, precipitation in different regions of East Asia has variable response to the EASM index (Li and Zeng, 2005).

4. Discussion

4.1. A comparison between different simulations

In our literature review of Holocene monsoon simulation, the PMIP 1 and PMIP 2 suggest that the two subsystems of the Asian monsoon have different response to Holocene climate change. Mid-Holocene monsoon precipitation was strengthened more intensively in the ISM domain than that in the EASM domain according to the two projects. The PMIP 2 result addressed the atmospheric general circulation with a higher resolution, which is in better agreement with proxy data than the PMIP1 simulations (T. Wang et al., 2010). The ocean feedback and large-scale circulation is a focus in the Holocene Asian monsoon simulation. Based on the simulations of CCSM 3.0, CLIMBER-2, FOAM-NCAR-CSM, FOAM-FSSTAM and FGOALS-g1.0, the complex pattern of precipitation change in Asia implies a stronger heterogeneity of monsoon dynamics between the two subsystems that is related to the ocean feedback and the large-scale features of atmospheric general circulation. This result is also consistent with the present understanding of the dynamics of the Asian monsoon (Lau et al., 2000). Besides, the Holocene long-term ocean-vegetation–atmosphere effect is another focus addressed by six Holocene monsoon simulations. Associated with changes of the seasonal cycle of insolation, the impact of vegetation cover change was applied to these six Holocene climate models (AGCM-BIOME, AGCM + SSiB, ECHAM5/JSBACH-MPIOM, IAP-AGCM, LMD AGCM and RegCM2) in the Asian monsoon domain to study the role of the changing vegetation. The Holocene long-term ocean–vegetation–atmosphere effect can enhance monsoon precipitation over most parts of the ISM domain, but tends to weaken or have little influence to monsoon rainfall in the EASM domain according to the six Holocene monsoon simulations.

However, the monsoon evolution implied by Holocene speleothem records from the two monsoon subsystems indicates a similar trend that can be linked to the Holocene low-latitude solar insolation change; furthermore, the two subsystems respond to the YD and 8.2 ka events in a similar way which is characterized by abruptly weakened monsoon precipitation. During the past 2000 years, the monsoon evolution seems more complicated than other periods of the Holocene. Regional differences in monsoon precipitation variability on the decadal- to centennial-scale can be detected in each sub-system. Generally, the Holocene speleothem records show that the Holocene monsoon evolution in the two subsystems is more synchronous than asynchronous. Holocene monsoon simulations collected in this research were mostly carried out in some periods of the Holocene, which are not continuous centennial-to-millennial-scale simulations. As a result, the difference between the EASM and the ISM detected in those simulations cannot be used to infer the Holocene continuous and long-term relationship between the two subsystems, but the simulations are helpful to understand the dynamic relationship between the two subsystems. It is suggested that future Holocene monsoon simulation should focus on the continuous decadal-to-centennial-to-millennial-scale climate simulation. Moreover, during the past 2000 years, monsoon precipitation is more complicated than other periods of the Holocene according to the speleothem records. Whether human impacts are related to the variable response is another interesting topic.

4.2. Modern monsoon indices and dynamics

Previous studies have proposed a number of monsoon indices, e.g. All Indian Rainfall Index (AIRI) (Shukla and Paolino, 1983), Webster and Yang Index (WYI) (Webster and Yang, 1992), Convection Index (CI) (Wang and Fan, 1999), Monsoon Hadley Circulation Index (MHI) (Goswami et al., 1999), Unified Monsoon Index (UMI) (Li and Zeng, 2002) and Australian Monsoon Index (AMI) (Hung and Yanai, 2004). To examine the relationship between the EASM and the ISM, T. Wang et al. (2010) and Y. Wang et al. (2010) used Monsoonal Hadley Index (MHI), defined by Goswami et al. (1999), and the NCEP/NCAR reanalysis data to examine the modern relationship between the EASM and the ISM, which supported the idea that the Holocene monsoon evolution between the two-systems is asynchronous. The MHI was derived originally from WYI, which is based on the dynamic premise that the monsoon flow is a first baroclinic response to the diabatic heating over the south Asian region (Webster and Yang, 1992). However, this index is based on the kinetic mechanism of the tropical monsoon system, which may not be applicable to the EASM system that can even reach the mid-latitudes. In this study, we chose a general applicable monsoon index (the Unified Monsoonal Index) to examine the relationship between the two monsoon subsystems. Modern monsoon indices from the two subsystems show a similar changing trend, which supports the Holocene long-term speleothem records, although not all the interannual-scale events can be correlated well with each other.

Modern MHI and Southerly Shear Index (SSI2) showed a negative correlation between the ISM and EASM (Wang and Fan, 1999; T. Wang et al., 2010; Y. Wang et al., 2010). The MHI was derived originally from WYI that was originated from South Asia (Webster and Yang, 1992). However, the EASM prevails in the mid-latitudes of East Asia, and the two subsystems are driven by different boundary thermal conditions associated with land-ocean configuration and topography. The SSI2 was defined in the areas of (5°–15°N, 120°–145°E) and (5°S–5°N, 90°–120°E), which belongs to western North Pacific summer monsoon domain (WNPSM), and is not included in the EASM domain (Wang and Fan, 1999, Fig. 1). Therefore, these two indices are inappropriate to describe the relationship between the two subsystems. In South Asian, two of the major precipitation maxima, associated with areas of intensive convective activity, are located near the Bay of Bengal and in the vicinity of the Philippines, and the variations of monthly mean outgoing longwave radiation in the two regions are poorly correlated. The enhanced convection over the Bay of Bengal and Indian is coupled with reinforced monsoon circulation west of 80°E over India, while the convection in the vicinity of the Philippines is more related to the Indochina peninsula, South China Sea, Philippine Sea (Wang and Fan, 1999). In fact, the negative correlation implied by MHI and SSI2 indicates the out-of-phase condition between these two regions in South Asia.

On the interannual-scale, the out-of-phase condition between the Bay of Bengal and the vicinity of the Philippines is primarily due to internal factors of the coupled atmosphere–ocean–land system, while the ENSO events can have remote impacts to the relationship. In the summer of a positive ENSO developing year, the ISM over the Arabian Sea and the Bay of Bengal weakens, while the monsoon in the vicinity of the Philippines is strengthened. In extreme positive ENSO events, the reduction of the Arabian Sea summer monsoon precipitation can reach about 11%; on the other hand, the monsoon precipitation over the vicinity of the Philippines is enhanced by 27% (Wang et al., 2003). Since the positive ENSO developing event could weaken the ISM while strengthening the summer monsoon in the surroundings of Philippines. Hong et al. (2005) proposed that the Holocene ENSO effect could trigger the inverse phase oscillations between the East Asian and Indian Ocean summer monsoons. However, the monsoon over the vicinity of the Philippines is not included in the EASM domain (Wang and Lin, 2002, Fig. 1).

Based on modern monsoon research, the onset of the Asian summer monsoon is a key indicator characterizing the abrupt transition from the dry season to the rainy season. Precipitation in different locations responds to the advance and retreat of the monsoon in the different ways. For example, Malik et al. (2010, 2011) analyzed monsoon precipitation over Indian, and their results indicated that during the active phase of a monsoon event an increase in monsoon rainfall only appears in certain areas of Indian. Furthermore, over decadal to millennial time scales, the intensity of the Asian monsoon circulation has been used to explain changes in surface processes, glaciers processes, terrestrial environments and marine sediment records (Bookhagen et al., 2005; Scherler et al., 2011). Whether these records and processes are linked to the monsoon circulation or just local precipitation still needs further investigation. Therefore, it is recommended that the monsoon–precipitation dynamics over different time scales, especially on the links between time scales, should be paid more attention to in the further research.

4.3. Lake records in monsoon marginal zones

This review of Holocene climate simulations, speleothem records and modern monsoon indices suggests that the hypothesis, asynchronous evolution of Holocene Indian and EASM, cannot fully explain those asynchronous Holocene climatic records in East and South Asia. In the marginal regions of the East Asia summer monsoon and arid Central Asia, the Holocene lake records indicate that lake-level and effective moisture condition reach their highest level during the mid-Holocene: e.g. Zhuye Lake (Li et al., 2009a,b), Daihai Lake (Xiao et al., 2004; Peng et al., 2005), Dali Lake (Xiao et al., 2008), Hulun Lake (Wen et al., 2010), Bosten Lake (Wünnemann et al., 2006) and Wulungu Lake (Liu et al., 2008). These Holocene lake records cannot support the Holocene Asian summer monsoon history implied by speleothem records, while these lake records have been used to illustrate the asynchronous evolution between the two subsystems of the Asian monsoon (Y. Wang et al., 2010). The water balance of a lake is governed by many water fluxes (e.g., on-lake precipitation, lake evaporation, surface runoff in the catchment) and these fluxes are controlled by many climatic and hydrologic processes (Morrill, 2004). Therefore, lake records in monsoon marginal zones can be used to imply the paleo-hydrological and paleo-ecological processes that are related to the monsoon precipitation, lake surface evaporation and basin-wide evapotranspiration. A series of models, the NCAR CCSM3, a lake energy-balance and a lake water-balance model, were introduced by Li and Morrill (2010) to simulate Holocene lake-level change in East and Central Asia, which provides a clue for those high mid-Holocene lake-level in the marginal region of the Asian monsoon and Central Asia. Instead of the monsoon impacts, the long-term evolution of lake surface evaporation is an important factor for the mid-Holocene high lake-level according to the model results. Furthermore, the Asian summer monsoon and the westerly winds interact in the mid-latitude regions of East Asia, so that climate change there is influenced by the combined effect of the two climate systems that can cause the out-of-phase relationship in precipitation between East and Central Asia (Li et al., 2012). The Holocene long-term out-of-phase precipitation change was also verified by a precipitation model (Jin et al., 2012). Previous studies focused less on the interaction between the westerly winds and the Asian monsoon that also can result in asynchronous Holocene climate change in East Asia. Therefore, in addition to internal interactions in the monsoon system, the interaction between the monsoon and the westerly winds over different time scales should be another research focus in exploring the long-term climate change mechanisms.

5. Conclusions

A literature review of Holocene monsoon simulations suggests that climate change has different impacts to the EASM and the ISM, but the results are not consistent in different models. Overall, the ISM shows a relatively strong and steady trend during the mid-Holocene while the EASM has different impacts on the various regions of East Asia. The speleothem records from the EASM and ISM domains show a relatively consistent changing trend during the Holocene, while the YD and 8.2 ka events also have a similar impact to the two subsystems, which cannot be supported by those monsoon simulations. In addition, modern monsoon indices from the two subsystems show a consistent trend that supports the relatively synchronous Holocene Asian summer monsoon evolution in the two subsystems. The inconsistency between monsoon simulations and monsoon records/indices can be affected by the comparison between different time scales; therefore, further continuous monsoon simulation is recommended. During the past 2000 years, regional response to monsoon variability is complicated than other periods of the Holocene. It is important to evaluate human impacts to the different regional response. The Asian summer monsoon and the westerly winds interact in mid-latitudes of East Asia, which is an influencing factor regarding asynchronous Holocene climate records in East Asia. Further climate simulations focusing on relationships between the Asian monsoon subsystems and between the monsoon and the westerly winds are needed for investigation of climate change mechanisms in East and Central Asia.

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