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Holocene variability of the East Asian summer monsoon from Chinese cave records: a re-assessment

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Abstract: Oxygen isotope records from stalagmites in caves in southern China, interpreted as proxy rainfall records reflecting the intensity of the East Asian summer monsoon, indicate gradual monsoon weakening for the last ~9000 years, as also documented for the Indian monsoon. Coupled with high-precision dating, the speleothem proxy records have been used to test monsoon links with orbital forcing, solar changes, iceberg discharges in the North Atlantic, ocean currents and atmospheric methane. However, these 'benchmark' cave records do not match other published, dated E Asian proxy rainfall records (specifically here, independently calibrated rainfall records from loess/palaeosol magnetic properties, and cave oxygen isotope intercomparisons), which show variable E Asian monsoon intensity through the entire Holocene. The strong correlation of the cave records with the extraregional Indian monsoon record yet their mismatch with these other dated Chinese rainfall records might be reconciled if the speleothem isotope variations reflect not changes in Holocene rainfall amount but in rainfall source. Declining Holocene influence of isotopically lighter, Indian monsoon-sourced moisture over China would have resulted in increasing proportions of isotopically heavier rainfall, sourced from the more oceanic E Asian monsoon. Individual speleothems may thus regionally record Holocene changes in Indian monsoon intensity and isotopic influence. Conversely, the other Chinese proxy records described here reflect changes in rainfall amount, and thus in E Asian summer monsoon intensity. For the Holocene, the E Asian and the Indian monsoon responses to orbital forcing are likely to have differed, specifically due to E Asian internal feedbacks and the seasonal contrasts between the two monsoon systems.

Key words: Asian monsoon, Holocene, magnetic susceptibility, Indian monsoon, oxygen isotope records, caves, China.

Introduction

The Asian monsoons, key mechanisms for transfer of heat and moisture to higher latitudes, demonstrate variability over Milankovitch, sub-Milankovitch and intra-annual timescales. Given they may affect climate on a near-global scale, through oceanic and atmospheric teleconnections (eg, Liu *et al.*, 2004; Wang, P. *et al.*, 2005) and that nearly half the world's population both depend on and are at risk from monsoonal rainfall, identification of their forcing mechanisms is essential.

High-resolution oxygen isotope records from speleothems from caves in southern China, including Dongge Cave, have become influential in Quaternary palaeoclimate studies. Combined with high-precision ^{230}thorium age control, they have been interpreted as a proxy for changes in rainfall amount, as the E Asian summer monsoon waxed and waned in intensity through the Holocene and past climate stages (Yuan *et al.*, 2004; Dykoski *et al.*, 2005; Wang, Y. *et al.*, 2005). For the Holocene, the Dongge Cave $\delta^{18}O$ values (Figure 1A) are isotopically lighter, more ^{18}O-depleted (–9.2 to –8.4‰) from ~ 9 to 7 ka BP, and then become progressively heavier (~ –8.4 to –7.0‰), with some return to lighter values from ~ 0.5 ka BP. Because a negative relationship is reported at the present day between rainfall $\delta^{18}O$ and rainfall amount (Dykoski *et al.*, 2005), Wang, Y. *et al.* (2005) interpret these variations as indicating high E Asian summer monsoon intensity in the early Holocene, followed by gradual monsoon weakening. Such a pattern is well established for the Indian monsoon (eg, Figure 1B), and has been causally related to declining Holocene Northern Hemisphere summer insolation (Figure 1A; Gupta *et al.*, 2005). Wang, Y. *et al.* (2005) suggest from these extraregional correlations that shifts in the position of the intertropical convergence zone (ITCZ) may control precipitation changes coherently across the entire Northern Hemisphere low latitude region, and that there is direct, in-phase orbital (precessional) forcing of all the major tropical monsoon systems.

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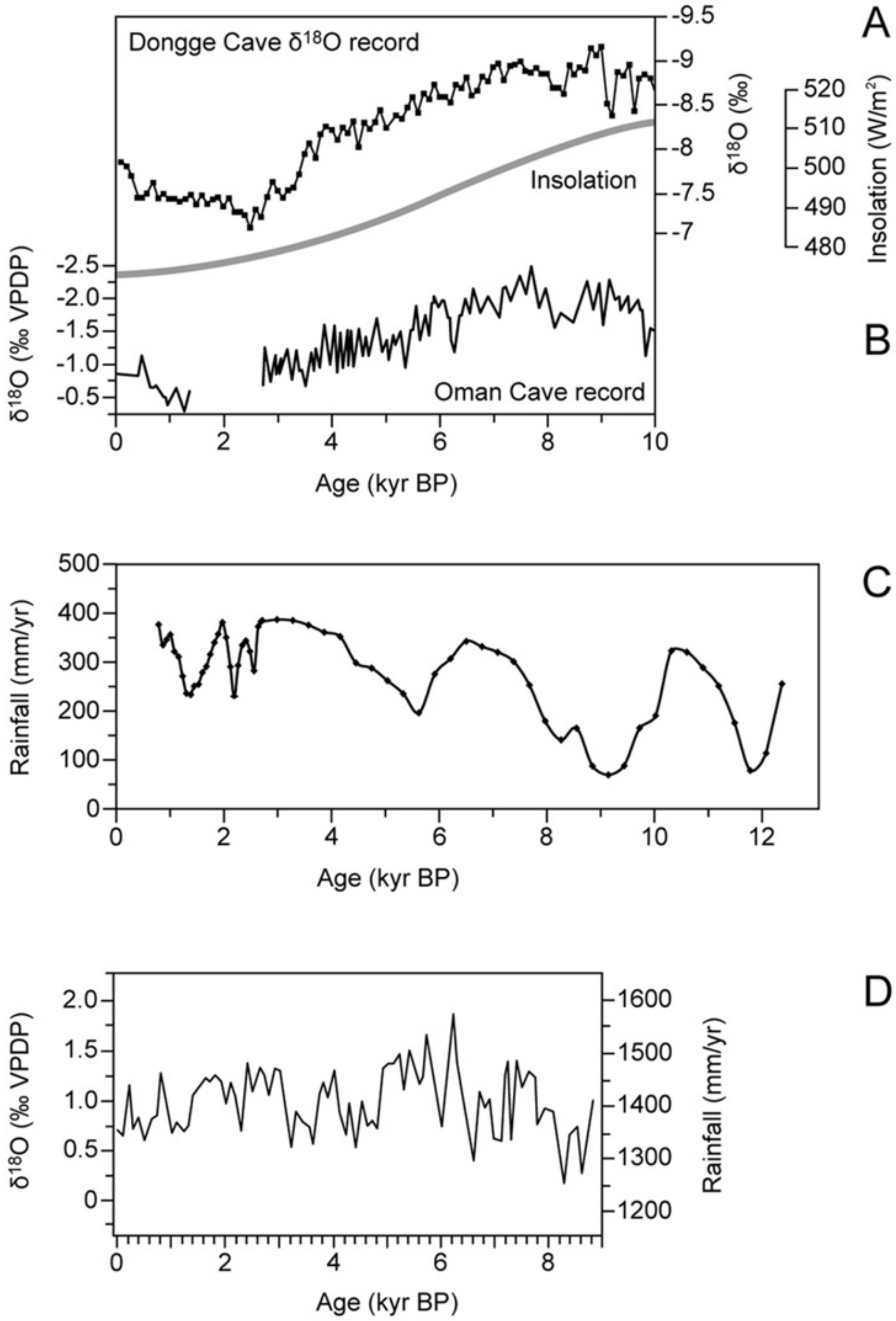

Figure 1 (A) Dongge Cave oxygen isotope variations through the Holocene and the precessional change in Northern Hemisphere summer insolation (June, July, August), calculated for 20°N (from Wang, Y. *et al*., 2005); (B) Indian monsoon intensity, from oxygen isotope analysis of a speleothem from the Qunf Cave, Oman (Fleitmann *et al*., 2003); (C) rainfall record from Duowa, from soil magnetism/rainfall transfer function (Maher and Hu, 2006); at this marginal site, rainfall varies by as much as +50% and −75% from the estimated present-day total (~ 265 mm/yr); (D) rainfall record from the difference in coeval oxygen isotope values from Dongge Cave and Heshang Cave (Hu *et al*., 2008); at this more humid, southerly site, rainfall varies by only ~ ± 8%

East Asian Holocene rainfall records

Notwithstanding the apparently strong *extraregional* correlations between the S China cave records and a host of Holocene climate indicators around the globe, there is clear mismatch between the cave-derived Holocene rainfall record and independent, quantitative rainfall proxies both from S China and from the widely distributed loess/palaeosol sequences of the north-central (NC) China region. The latter area, approaching the northern monsoon limits, is likely to be significantly more sensitive than S China to monsoon intensity changes and the resultant inland extent of monsoonal incursion. Undisturbed, reasonably high-resolution Holocene sequences of windblown loess and interbedded palaeosols occur very widely over the NC China region, spanning an area ~ 1500 km from west to east (~ 100–115°E) and ~ 10° of latitude (~ 35–45°N). In qualitative terms, palaeosols record intervals of increased summer monsoon intensity, producing significant inland incursion of summer monsoonal rainfall to this near-marginal zone. Porter and Zhou (2006) report 91 radiocarbon dates on prominent palaeosols within 19 loess/palaeosol sequences. Regional synthesis of these dated sites

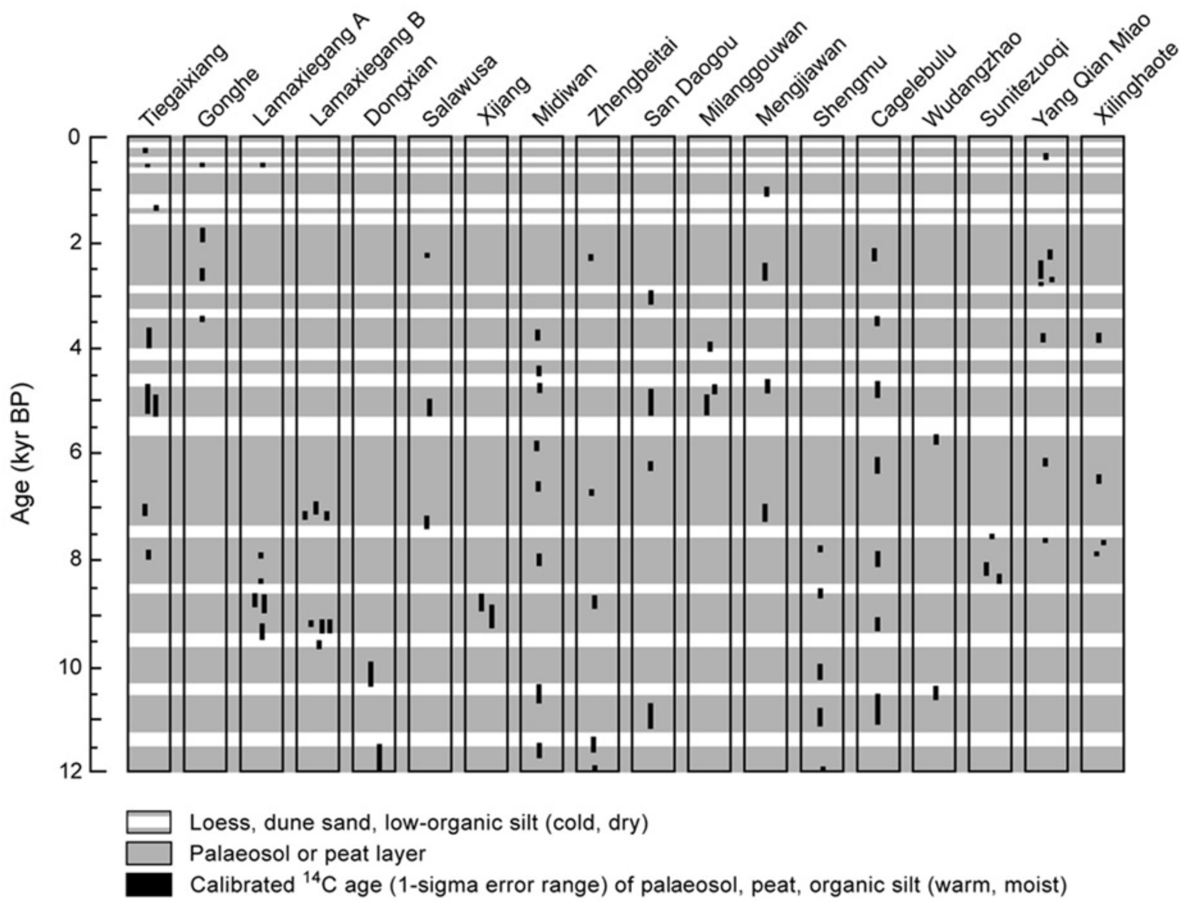

Figure 2 Synthesis of ^{14}C-dated Holocene loess and palaeosol sediments, NC China, showing the presence of palaeosols throughout the Holocene (Porter and Zhou, 2006)

indicates widespread, submillennial intervals of palaeosol formation (ie, intense summer monsoon) throughout the entire Holocene, right across the NC China region (Figure 2). Building upon this sedimentary evidence of variable E Asian monsoon intensity through the Holocene, a high-resolution, well-dated rainfall record has been obtained by optically stimulated luminescence dating of a ~ 5 m loess/soil sequence (Duowa, eastern Tibetan Plateau, 35°25′N, 101°57′E, altitude ~ 2000 m), combined with a soil magnetism/rainfall transfer function (Maher and Hu, 2006). The transfer function (Maher *et al*., 2002a, b) was obtained by regression analysis of modern rainfall (30-yr averages, AD 1951–1980) and the *in situ*, pedogenic magnetic susceptibility of modern soils across the Chinese Loess Plateau and the loessic Russian steppe ($r = 0.94$). Rainfall maxima at Duowa (Figure 1C) appear concentrated at three intervals: ~ 11–10 ka BP, ~ 8–6.5 ka BP and, the wettest phase, from ~5 to 2.4 ka BP; again, with no evidence of gradual monsoon weakening. Similarly complex Holocene climatic variations – ie, successive humid phases through the Holocene and increased precipitation in the late Holocene – have also been reported from multiproxy analysis of lake sediments, as recently reviewed by Chen *et al*. (2008) for the northwest region of China. Evaluation of synchroneity between the NW and NC Chinese records is difficult owing to variable dating methods/quality but most show evidence for cold, dry conditions from ~ 9.5 to 8 ka BP, warmer and wetter conditions from ~ 8 to 6 ka BP and humid conditions from ~ 5 to 2.5 ka BP (Chen *et al*., 2008). Conversely, An *et al*.'s earlier (2000) review of lake sediment records across China suggests a more regionally delineated response to changing summer monsoon intensity, although the majority of zones show either high or intermediate lake levels in the late Holocene. It is notable that the S Chinese caves fall within An *et al*.'s 'Zone D', an area characterized by high lake levels both in the early and late Holocene.

A new, independent Holocene rainfall record has recently been obtained by calculating the differences in coeval δ^{18}O values for speleothems from Dongge Cave and Heshang Cave, 600 km directly downwind from Dongge, and regressing the modern difference values against modern rainfall to obtain a transfer function (Hu *et al*., 2008). The rationale for this approach is twofold: that the between-site differences will reflect the amount of rainfall and isotopic fractionation between the two sites; and that any isotopic influence of factors other than rainfall amount will be removed. Before calculation of the δ^{18}O differences, the two cave records appear similar (except that the downwind record always shows more depleted, rained-out values), ie, showing the gradual trend to less depleted values through the Holocene. In contrast, the rainfall record derived from the coeval isotopic differences shows significant variability throughout the entire period (Figure 1D), and with notably low rainfall values estimated for the early Holocene (~8–9 ka BP). Compared with the more marginal NC loess/palaeosol sequences, the S China records can be expected to show less variability in monsoonal rainfall as they are closer to the rainfall source.

Oxygen isotope records of East Asian rainfall: amount versus rainfall source

The apparent paradox of strong correlation of the individual, oxygen isotope cave records with the extraregional, Indian monsoon (as exemplified by the Oman cave record of Fleitmann *et al*., 2003; Figure 1B) yet their mismatch with these other dated Chinese

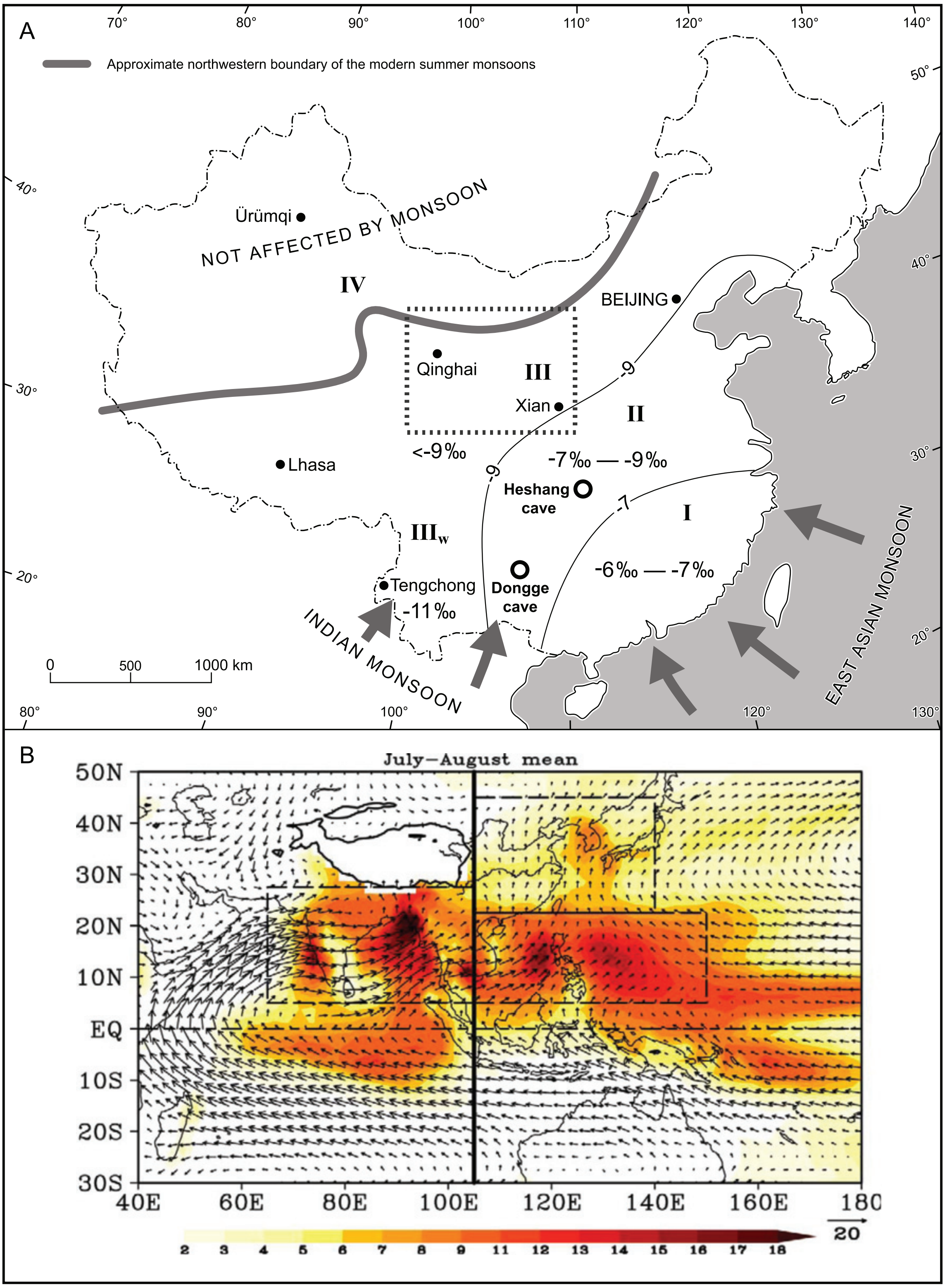

Figure 3 (A) Average annual oxygen isotope composition of modern rainfall (Wei and Lin, 1993) showing zones with differing relative influences of the Indian monsoon (isotopically more depleted owing to its longer transport path, greater continentality, rain-out and Rayleigh fractionation) and the E Asian monsoon (isotopically heavier, reflecting shorter transport, more oceanic source and lower amount of fractionation); Zone 1, dominated by the E Asian monsoon; Zone II, affected by both the Indian and E Asian monsoons; the western area of Zone III, dominated by the Indian monsoon; Zone IV, beyond the landward limits of the monsoons. The box marks the approximate area of the loess/palaeosol sequences; site locations for the cave records also marked. (B) Mean precipitation rates (mm/day) and 925 hPa wind vectors (arrows) for July/August, from CMAP (Wang *et al*., 2003). Summer precipitation dominates at all the loess and cave sites both in amount (> 80% of annual total) and isotopic composition (significantly lighter in summer); the peak in E Asian summer monsoon rain is in August; for the Indian monsoon, early June to mid July

rainfall and lake records might be resolved if the speleothem isotope variations at any one site dominantly reflect not changes in rainfall amount but in rainfall source and air mass trajectory. Despite the potentially complex processes that can vary speleothem oxygen isotope composition (including drip rate, degassing rate, evaporative effects, temperature, rainfall, seasonality), the observed trend to heavier $\delta^{18}O$ values through the Holocene appears regionally coherent through S China, indicating regional-scale forcing. At the present day, the oxygen isotope composition of rainfall over much of China varies with the relative influence of the more continental, significantly more depleted, Indian monsoon winds (Figure 3A and B). Conversely, correlations between rainfall isotopic composition and rainfall amount at the present day appear weak and spatially variable (Johnson and Ingram, 2004; International Atomic Energy Agency/World Meteorological Association (IAEA/WMO), 2006; Dayem *et al*., 2007). Based on published and spatially classified (Figure 3A) modern isotope data (Wei and Gasse, 1999), Zone 1 (SE China) is dominated by the more oceanic E Asian monsoon (rainfall $\delta^{18}O$ values least depleted, ~ −6 to −7‰). Zone II, stretching inland to Beijing and Xi'an, is affected by both the Indian and E Asian monsoons (rainfall $\delta^{18}O$ values −7 to −9‰). The western area of Zone III is dominated by the far-travelled, more continental Indian summer monsoon (rainfall $\delta^{18}O$ values most depleted, > −9‰). Zone IV, to the north, lies beyond the monsoons' landward fronts. The present-day Indian monsoon influence is exemplified at Tengchong and Xi'an (Figure 3A), approximately equidistant from the coast but with Xi'an ~ 10° further north (Wei and Lin, 1993; Feng *et al*., 1999). Summer (1980) rainfall $\delta^{18}O$ values in Tengchong (dominated by the Indian monsoon) are more depleted, ~ −11‰, compared with Xi'an (affected by both Indian and E Asian monsoons), ~ −9‰. As the Indian monsoon weakened through the Holocene, its degree of inland incursion across China would have diminished. The E Asian-dominated monsoon Zone I (Figure 3A) is thus likely to have expanded northwards through the Holocene as the Indian monsoon declined, gradually changing the oxygen isotopic composition of summer rainfall to more oceanic, less depleted values. This gradual Holocene change appears to have been regionally recorded at Dongge Cave and other similar caves presently located in mixed-monsoon, more isotopically depleted, Zone II (Figure 3A). Quantitative interpretation of the observed shifts in the speleothem $\delta^{18}O$ records requires reconstruction of the different monsoon pathways of air and moisture masses to their site of rain-out (Hoffmann and Heimann, 1997).

Contrasts between the Indian and East Asian monsoon

Although the Indian and E Asian summer monsoons are obviously linked in that they both respond to the strength of the continental summer high-pressure cells, their contrasting geographical contexts create significantly different land–sea distributions and thus a mechanism for significantly different responses and feedbacks to changing Holocene insolation (Wang *et al*., 2003; Maher and Hu, 2006). In contrast to its Indian counterpart, the response of the E Asian monsoon to peak insolation changes (and their seasonal timing in relation to monsoon onset) is likely to have been significantly modified by changing sea surface temperatures (SSTs), both locally and remotely, especially through its stronger interaction with the El Niño/Southern Oscillation (Wang *et al*., 2003; Gagan *et al*., 2004), and resulting internal feedbacks via changes in land–ocean temperature gradients (Li *et al*., 2007; Basil and Bush, 2001). Liu *et al.* (2004), running a fully coupled AGCM, also identify the key influence of ocean feedbacks in diminishing the intensity of the Asian monsoon at the mid-Holocene insolation peak. Another key difference between the Indian and E Asian monsoons is the significant contrast in the timing of their peak activity; the Indian summer monsoon peak is from early June to mid-July, whilst the E Asian monsoon peak is later, from August to September. The precession-driven shift in timing of the Northern Hemisphere peak in insolation is thus likely to have amplified contrasts between the two monsoon systems.

In the context of enhanced, anthropogenic global warming, increased convection in the oceanic sectors of the ITCZ has been predicted (Meehl and Arblaster, 2003; Lu *et al*., 2007), because of increasing SSTs in the western tropical Pacific, leading to enhanced monsoon intensities. More detailed understanding of past changes in E Asian monsoon intensity and rainfall, and incorporation of specifically E Asian internal SST forcings and feedbacks into climate models, appear critical for any robust prediction of future climate change both in this populous region and beyond.

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