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Controls on the East Asian monsoon during the last glacial cycle, based on comparison between Hulu Cave and polar ice-core records

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A B S T R A C T

Previous studies have suggested a sound chronological correlation between the Hulu Cave record (East Asian monsoon) and Greenland ice-core records, which implies a dominant control of northern hemisphere climate processes on monsoon intensity. We present an objective, straightforward statistical evaluation that challenges this generally accepted paradigm for sub-orbital variability. We propose a more flexible, global interpretation, which takes into account a broad range of variability in the signal structures in the Hulu Cave and polar ice-core records, rather than a limited number of major transitions. Our analysis employs the layer-counted Greenland Ice-Core Chronology 2005 (GICC05), which was developed for Greenland records and has since been applied – via methane synchronisation – to the high-resolution $\delta^{18}O_{ice}$ series from EPICA Dronning Maud Land (EDML). The GICC05 chronology allows these ice-core records to be compared to the U–Th dated Hulu Cave record within relatively narrow (~3%) bounds of age uncertainty. Following previous suggestions, our proposed interpretation suggests that the East Asian monsoon is influenced by a combination of northern hemisphere 'pull' (which is more intense during boreal warm periods), and southern hemisphere 'push' (which is more intense monsoon during austral cold periods). Our analysis strongly suggests a dominant control on millennial-scale monsoon variability by southern hemisphere climate changes during glacial times when the monsoon is weak overall, and control by northern hemisphere climate changes during deglacial and interglacial times when the monsoon is strong. The deduced temporally variable relationship with southern hemisphere climate records offers a statistically more plausible reason for the apparent coincidence of major East Asian monsoon transitions with northern hemisphere (Dansgaard–Oeschger, DO) climate events during glacial times, than the traditional *a priori* interpretation of strict northern hemisphere control.

1. Introduction

Since publication of the intensively U–Th dated speleothem $\delta^{18}O$ record of the last glacial cycle from Hulu and Dongge Caves in Southern China (Fig. 1) (Wang et al., 2001; Yuan et al., 2004), there has been considerable interest in the general similarity of the millennial-scale signal structure of Chinese speleothem records with that of Greenland ice-core $\delta^{18}O_{ice}$ records (e.g., Wang et al., 2001, 2004; Shackleton et al., 2004; Denton et al., 2005; Clement and Peterson, 2008; Siddall et al., 2008; Skinner, 2008; Zhou et al., 2008). A new layer-counted timescale (GICC05) has become available for the Greenland DYE-3, GRIP and NGRIP ice-cores for the interval between the present and 60 thousand years ago (ka BP) (Andersen et al., 2006; Rasmussen et al., 2006; Vinther et al., 2006; Svensson et al., 2008), which allows temporal comparison with much reduced uncertainty between the Hulu Cave and Greenland climate proxy records. This comparison can now include Antarctic climate proxy records, because the new high-resolution $\delta^{18}O_{ice}$ series from EPICA Dronning Maud Land (EDML) is synchronised in detail to the GICC05-based Greenland $\delta^{18}O_{ice}$ records via methane concentration in air bubbles trapped within the ice (EPICA Community Members, 2006). The locations of the key records discussed in this paper are indicated in Fig. 1.

The composite Hulu Cave speleothem $\delta^{18}O$ record comprises data from several individual speleothems (Fig. 2) (Wang et al., 2001; Yuan et al., 2004). It is considered to reflect variations in the

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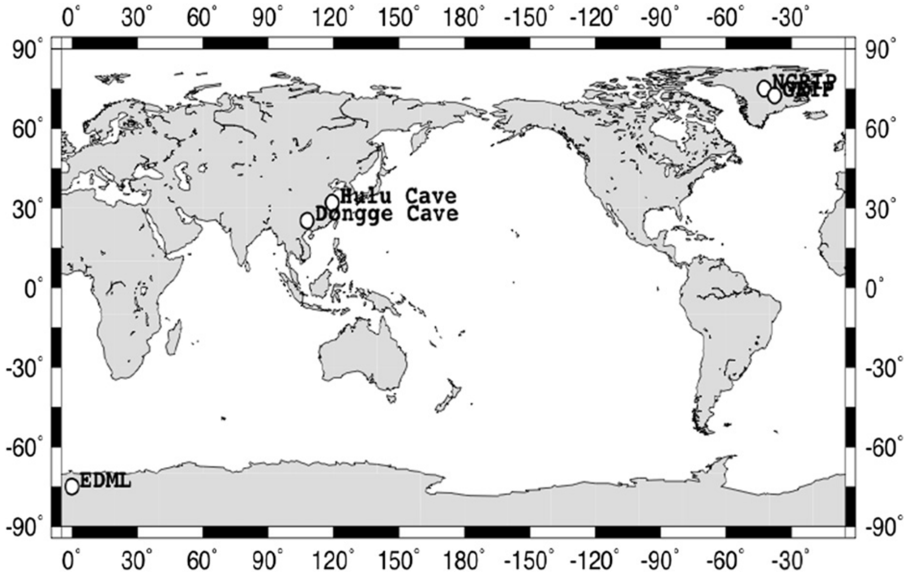

Fig. 1. Map of the sites discussed in the present paper, constructed with the GMT online map creation tool (Martin Weinelt, Kiel: http://www.aquarius.ifm-geomar.de/make_map.html). Site locations plotted are (Longitude, Latitude, Name): 119.2°E, 32. 5°N, Hulu Cave; 108.08°E, 25.28°N, Dongge Cave; 42.30°W, 75.001°N, NGRIP; 37.5°W, 72.5°N, GRIP; 0.0684°E, 75.0025°W, EDML.

East Asian summer monsoon intensity. This view is supported by other East Asian speleothem records (Cosford et al., 2008), which reveal good overall signal similarity with some superimposed differences. The monsoon influences the regional $\delta^{18}O$ of precipitation (and so speleothem carbonate) through the so-called 'amount effect', which causes lighter (more negative) $\delta^{18}O$ with enhanced precipitation/monsoon intensity (see Wang et al., 2001; Yuan et al., 2004). The high temporal resolution and detailed U–Th dating of the Hulu Cave record provides an excellent template for developing understanding of millennial-scale controls on the Asian monsoon. Based on results from the GISS climate model, which includes $\delta^{18}O$ simulation in the hydrological cycle, Schmidt (2007) suggested that monsoon region $\delta^{18}O$ variations are not necessarily a function of regional monsoon climate (near the study site), but that there is a strong component associated with general low-latitude $\delta^{18}O$ changes in the 'global' monsoon.

Northern hemisphere climate variability is a much-explored control on the Asian monsoon (see, among many others: Schulz et al., 1998; Wang et al., 2001, 2004; Burns et al., 2003, 2004; Rohling et al., 2003; Yuan et al., 2004; Ivanochko et al., 2005; Weldeab et al., 2007; Cosford et al., 2008; and references therein). Greenland ice-core $\delta^{18}O_{ice}$ records document a sequence of sharp Dansgaard–Oeschger (DO) warming events followed by cooling that is gradual at first and that then progresses abruptly, yielding a DO cycle with a distinct square-wave (or 'top-hat') character (Dansgaard et al., 1993; Grootes et al., 1993) (red in Fig. 3a). The warm DO interstadials loosely cluster into groups of progressively smaller amplitude and shorter duration (Bond et al., 1993). Marine sediment

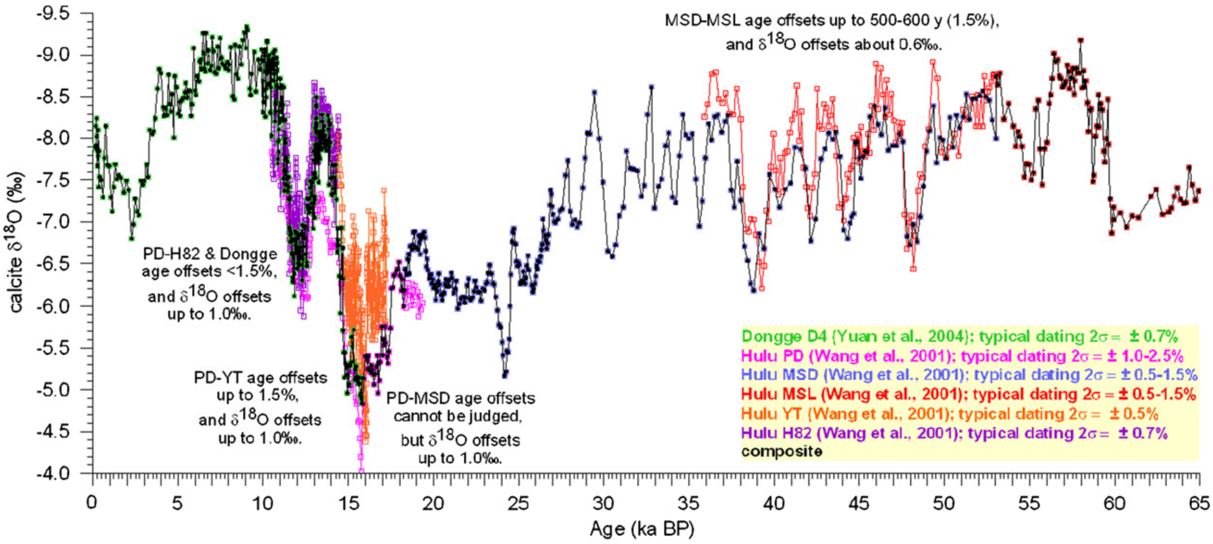

Fig. 2. The original Hulu and Dongge Cave data as available on the NCDC speleothem data server (http://www.ncdc.noaa.gov/paleo/speleothem.html) (Wang et al., 2001; Yuan et al., 2004). The different colours indicate individual speleothem datasets (see legend). The legend also indicates the typical (2σ) dating uncertainties reported for the source records. Age and $\delta^{18}O$ offsets between the different speleothem datasets are evident in this presentation. The black record is the composite record used for further analyses in the present paper.

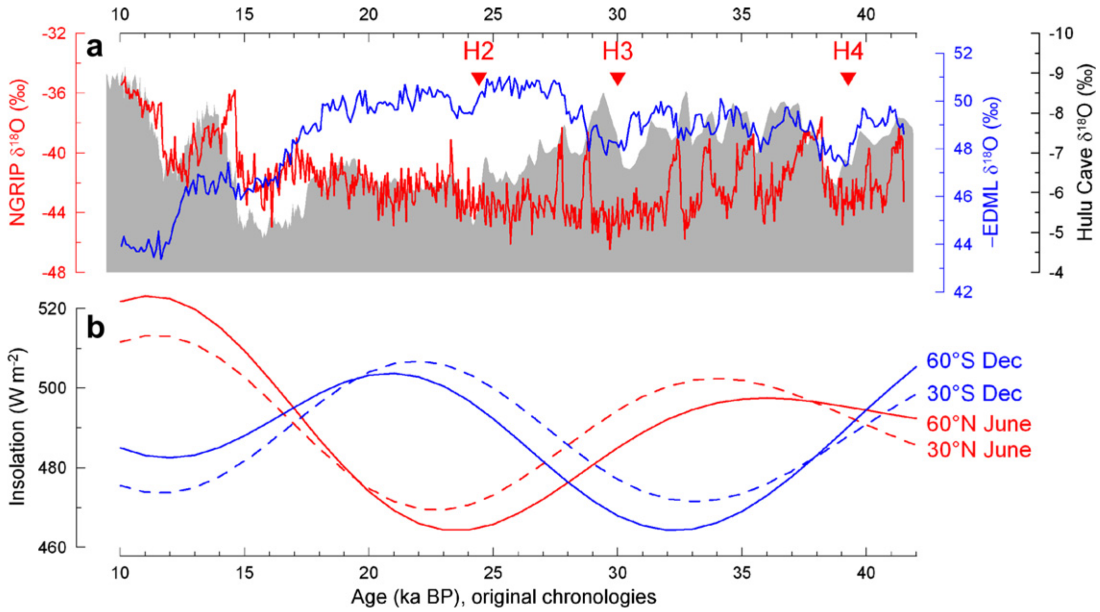

Fig. 3. Key data sets discussed in the present paper. (a) Composite Hulu Cave $\delta^{18}O$ time series on its original U–Th based chronology (grey); NGRIP $\delta^{18}O_{ice}$ series on the GICC05 timescale (red); and –EDML $\delta^{18}O_{ice}$ series on the GICC05 chronology (blue). The timings of Heinrich Events are indicated relative to NGRIP $\delta^{18}O_{ice}$ based on the position of significant dust anomalies in GISP2 relative to the GISP2 $\delta^{18}O_{ice}$ record (Rohling et al., 2003). (b) Summer insolation changes at 60°N, 30°N, 30°S, and 60°S (Berger and Loutre, 1991; Berger, 1992).

cores reveal that, at the cold culmination of each cluster, there is a pronounced DO stadial (sometimes called a 'Heinrich stadial'), which contains a so-called Heinrich event of massive ice-rafted debris (IRD) deposition in the North Atlantic (see review in Hemming et al., 2004). The Heinrich events took place during particularly intense cold episodes, with impacts throughout the northern hemisphere and possibly even on a wider scale (for overviews, see Voelker, 2002; Rohling et al., 2003; Hemming, 2004).

Proxy records attributed to monsoon variability are commonly correlated to the Greenland DO cycles (e.g., Schulz et al., 1998; Wang et al., 2001, 2004; Burns et al., 2003, 2004; Rohling et al., 2003; Yuan et al., 2004; Ivanochko et al., 2005; Weldeab et al., 2007; Cosford et al., 2008), where warmer Greenland conditions relate to intensified summer monsoons, and colder Greenland conditions relate to weaker summer monsoons. This inference is reasonable (especially on super-annual timescales) because the duration and intensity of winter snow cover over Asia exerts important control on the intensity of the summer monsoon (Meehl, 1994, 1997; Overpeck et al., 1996; Barnett et al., 1988). The above-cited monsoon records all have good initial radiometric chronological control, and comparison with the GICC05 chronology for Greenland $\delta^{18}O_{ice}$ records seems to support correlation between the monsoon records and the DO cycles observed in Greenland and in the layer-counted Cariaco Basin grey-scale record (Lea et al., 2003). However, combined uncertainties in the radiometric dating of monsoon records and in the layer-counted age models of the Greenland and Cariaco records preclude firm conclusions regarding the accuracy of temporal correlations on centennial time scales.

Chronological uncertainties highlight the importance of challenging the common paradigm whereby monsoon records, such as the Hulu Cave record, are correlated to Greenland ice-core records with respect to millennial-scale climate fluctuations. Alternative explanations should be tested and any such alternative solution should, given the radiometric age constraints, be similar in absolute timing to the common paradigm, but could nevertheless have important consequences for understanding processes that control monsoon intensity variations. It should also be noted that the U–Th dating of Hulu Cave is being used to 'anchor' other chronologies (e.g., Shackleton et al., 2004; Skinner, 2008), and even to constrain radiocarbon calibration (Weninger and Jöris, 2008). Any change in the correlation paradigm, even if only by a few centuries, may therefore affect our understanding of radiocarbon calibration through time.

The present study was motivated by Cai et al. (2006), who suggested that the monsoon-related $\delta^{18}O$ changes in Xiaobailong Cave (SW China) may contain information regarding teleconnections with southern hemisphere climate variations. Those authors relate their suggestion to previous work that focused on the importance of cross-equatorial airflow for monsoon intensity (Clemens et al., 1996; An, 2000; Cai et al., 2006). Unfortunately, Cai et al. (2006) studied only a limited time interval (53–36 ka BP), and made a brief qualitative case based only on visual comparison using old ice-core chronologies. Nevertheless, their study marks an important re-direction of focus to a potential alternative 'driver' of millennial-scale monsoon variability that has received disproportionately little attention.

The concept of southern hemisphere influences on cross-equatorial airflow, which then modulates monsoon intensity, is not new. Early work on a monsoon intensity index suggested that, even on orbital (multi-millennial) timescales, there might exist not only a northern temperature control ('pull' on the monsoon), but also a control from the temperature contrast between the southern and northern tropics ('push' on the monsoon) (Rossignol-Strick, 1985). The 'push' would relate to an enhanced pole to equator temperature gradient in the southern hemisphere, leading to intensified trade wind surges that enhance and intensify the boreal summer monsoon intensity and its northward penetration (see overviews in Pedelaborde, 1963; Rossignol-Strick, 1985). Teleconnections between the Indian monsoon system and middle and upper tropospheric flow patterns in the southern hemisphere have been frequently reported (Krishnamurti and Bhalme, 1976; Ramaswamy and Pareek, 1978; Rodwell, 1997). Xue et al. (2004) corroborated this observation, and extended the concept to include the East Asian monsoon.

On monthly timescales (30–60 day oscillation), southerly surges caused important intensification of the boreal summer monsoon in the Indian and Pacific regions during 1979–1983 (Shresta and Murakami, 1988). Similar (related) oscillations appear to affect the East Asian monsoon (Love, 1985; Xue et al., 2004). On multi-annual timescales, a positive correlation exists between cold/high phases of the Southern Oscillation Index and enhanced intensity of the Indian summer monsoon (Hastenrath, 1991). On multi-decadal timescales, early work suggested a correlation between 2 to 4° displacements of 40-year average latitudes of the main atmospheric circulation features in the southern Indian Ocean and Australasian sector, and variations in the strength of the east Asian monsoon (Lamb, 1972, p. 300). Rohling et al. (2003) proposed that southern hemisphere cooling may have intensified boreal summer monsoons on centennial–millennial timescales as well, and that monsoon-related interhemispheric latent heat transfer might (partially) explain the anomalously long durations of DO interstadials that coincided with marked Antarctic cooling events (especially interstadials 12, 8, and 1: Blunier et al., 1998; Marchal et al., 1999; Shackleton et al., 2000; EPICA Community Members, 2006). The Xiaobailong Cave record (Cai et al., 2006) supports this notion. Further support comes from a detailed study of the (end of the) Younger Dryas in Africa (Talbot et al., 2007).

The above discussion illustrates that some sort of 'push' mechanism could be important for the boreal summer monsoon. In addition, it is possible that oscillations on short (seasonal to interannual) timescales do not portray the complete potential dependence of the monsoon on southern hemisphere processes associated with sustained (millennial-scale) global climate change. In this paper, we adopt a 'diagnostic' approach, using a key record of millennial-scale monsoon variability to investigate whether it contains statistically significant signs of variability that correspond with well-established southern hemisphere climate fluctuations. Specifically, we evaluate whether there are any indications that a 'push' mechanism may have affected boreal summer monsoon intensity on millennial timescales by comparing (using straightforward and transparent statistics) the Hulu Cave $\delta^{18}O$ record with the most recent high-resolution EPICA Dronning Maud Land (EDML) $\delta^{18}O_{ice}$ record from Antarctica (EPICA Community Members, 2006) and the high-resolution NGRIP $\delta^{18}O_{ice}$ record from Greenland (NGRIP members, 2004) (Fig. 3). These ice-core records are 'methane synchronised' to within a few centuries (EPICA community Members, 2006), and are both presented on the same GICC05 timescale. However, in such a comparison, it is important to consider the correct sense for comparing boreal monsoon records with Antarctic ice-core records, so that colder Antarctic conditions (stronger 'push') correspond to intensified monsoons, and warmer Antarctic conditions (weaker 'push') correspond to weaker monsoons. Consequently, we consider an 'inverted' form of the EDML record for comparison with the Hulu Cave record (indicated as –EDML) (Fig. 3).

It has been convincingly suggested that the long-term changes at Hulu Cave closely record orbital insolation changes (Wang et al., 2008), and we will not focus on that aspect again. Instead, we aim to characterise the relative importance of 'pull' and 'push' on short-term (millennial-scale) variations in the boreal monsoon through time, by quantifying to what extent variance in the Hulu Cave speleothem $\delta^{18}O$ record during the Lateglacial and deglaciation (42–10 ka BP) can be ascribed to variance in Greenland and Antarctic $\delta^{18}O_{ice}$ records, respectively. Our chosen time period is delimited by the availability of uninterrupted high-resolution data on the GICC05 timescale for both ice cores. We limit our focus to the last 42 kyr to avoid problems associated with a 'gap' in the high-resolution Antarctic data series (EPICA Community Members, 2006), and because GICC05 age uncertainties exceed 4% prior to about 40 ka BP (i.e., they become roughly twice the uncertainty of U–Th ages; see discussion in the following sections). We also avoid the Holocene interglacial because we are primarily concerned with monsoon variations within the large-amplitude abrupt climate changes of the last glacial cycle.

Our study is intended as a 'proof of concept' analysis to explore the hypothesis that there may be important (temporally variable) contributions of southern 'push' to the millennial-scale fluctuations in monsoon intensity. The selected interval of time offers a suitable test-bed for this analysis because it covers three climatically different episodes, namely: (1) the last deglaciation, with massive abrupt climate variations superimposed on a rapid reduction of global ice volume and general warming into the Holocene interglacial; (2) the interval between about 28 and 16 ka BP, which brackets the Last Glacial Maximum (LGM), and which contains relatively minor millennial-scale variability; and (3) the period before about 28 ka BP, which was a time during the last glacial cycle that was marked by distinct millennial-scale climate variability.

2. Hulu Cave comparison with ice-core and 'Hybrid Ice-Core' (HIC) records

The chosen study interval spans many rapid climate changes that have distinctly different expressions in Greenland and Antarctic ice-core records. Variability in NGRIP $\delta^{18}O_{ice}$ is also sufficiently dissimilar from that in –EDML $\delta^{18}O_{ice}$ to allow distinction between both potential drivers of the monsoon variations (Fig. 3). Nevertheless, it is also important to emphasise that high-resolution comparison of Greenland and Antarctic ice-core records – which has become possible with the NGRIP $\delta^{18}O_{ice}$ and –EDML $\delta^{18}O_{ice}$ data – reveals close relationships between the signal structures even on short millennial time scales, which agree well with the so-called bipolar see-saw model (Stocker and Johnsen, 2003; EPICA Community Members, 2006). The Hulu Cave speleothem $\delta^{18}O$ record is shown in Figs. 2 and 3 (grey shading) on its own U–Th based timescale.

Given that the GICC05 timescale is layer-counted, and that the Hulu Cave record is extensively U–Th dated, there should be good agreement within uncertainty bands of several centuries. The uncertainty limits increase with age because errors in the GICC05 timescale are cumulative, amounting to about 0.9% at around 12 ka BP to about 3.5% at around 32 ka BP (Rasmussen et al., 2006; Andersen et al., 2006). The U–Th age uncertainties in the Hulu Cave record also increase with age, but typically remain around 1.5% (with a maximum of 2.5%; Fig. 2) (e.g., Wang et al., 2001, 2004; Yuan et al., 2004). Visual inspection of the records in Fig. 3 reveals distinct similarities between the Hulu Cave and NGRIP records, as has been explored before (Shackleton et al., 2004). This is especially the case through the last deglaciation, in the post-15.8 ka BP section of the composite record, even though a prominent feature like the peak Bølling warm event between about 14.7 and 14.0 ka BP is not well represented in Hulu Cave (Figs. 2 and 3).

Despite the above similarities, considerable – and apparently non-systematic – timing offsets and structural differences between the NGRIP $\delta^{18}O_{ice}$ series (on GICC05) and the (U–Th dated) Hulu Cave speleothem $\delta^{18}O$ record are evident in Fig. 3. First, between 30 and 40 ka BP, correlation of the Hulu Cave record with NGRIP requires larger temporal adjustments than correlation with the –EDML series. Also, the signal structure of the Hulu Cave record is much more similar to –EDML than to NGRIP, showing broader and more symmetrical features. Second, there is a minimum in the Hulu Cave record at around 24 ka BP that has no equivalent in the NGRIP record (there is an interval of lighter values at this time in GISP2, e.g., Cosford et al., 2008), but which is prominently present in the –EDML series. This interval broadly coincides with the double-peak eolian dust maximum in Greenland ice cores that has been correlated to Heinrich Event 2 (Rohling et al., 2003). Third, there is a distinct gradual shift in the Hulu Cave record from about 20 to 17 ka BP, which is not evident at all in NGRIP, but which is also obvious in –EDML. In short, the Hulu Cave record is considerably similar to the –EDML series, which has not been previously recognised or explored.

A peculiarity of the Hulu Cave record (32°30′N, 119°10′E, 140 m above sea level, ASL) is an apparent shift in the mean at 28.6 ka BP (Fig. 3), which has no equivalent in NGRIP, and which is opposite to any equivalent changes in –EDML. The 41–28.6 ka BP values seem to peak at similar levels as the Bølling and Early Holocene, which is not a common structure in the climate proxy records, or in global sea level/ice volume records (e.g., Shackleton et al., 2000; Waelbroeck et al., 2002; Siddall et al., 2003). This shift is not seen in stalagmite X3 from Xianshui Cave (25°15′ N, 110°55′E, 380 m ASL), and it is weakly represented only in stalagmite YB1 from Yaoba Cave (28°48′ N, 109°50′E, 420 m ASL) (Cosford et al., 2008). The description of the Hulu Cave speleothem sampling does not offer any explanation because the shift does not coincide with a splice point between sample series (Fig. 2). The offset might be considered in view of the long-term response of the Hulu Cave record to insolation (Wang et al., 2008). However, we note that such an explanation would not agree with the aforementioned absence, or only weak presence, of the offset in other high-resolution speleothem records from the East Asian monsoon region. Regardless, we formulate our arguments on the basis of the original Hulu Cave record (Fig. 3a). We develop our statistical comparisons with ice-core records over the intervals 10.00–15.80, 15.85–28.55, and 28.60–41.00 ka BP (original Hulu Cave U–Th chronology). This subdivision ensures that any isotope shift at around 28.6 will only affect the intercept of the regressions, which can then be objectively evaluated for any systematic offset (or not).

Overall, the millennial-scale variability seems to be sharper and more pronounced in the Hulu Cave record than in the –EDML record, yet it is less sharp and pronounced than in NGRIP (Fig. 3). Although differences between the Hulu Cave and NGRIP records might be attributed to differences in resolution (Fig. 2), this does not account for signal comparison between Hulu Cave and –EDML. We propose that the signal differences should be evaluated using a more diagnostic approach. Our approach considers 'mixed' combinations of the NGRIP and –EDML records, using simple addition of the two synchronised ice-core records in different proportions (100:0, 90:10, 80:20, … 0:100). These synthetic 'Hybrid Ice-Core' records (HICs) are made using the actual $\delta^{18}O_{ice}$ values (inverted for EDML), so that the HICs properly account for the real amplitude differences between NGRIP and –EDML. The various HICs are distinguished using a subscript that indicates the relative proportion of the NGRIP contribution, so that HIC_{20} represents an addition of NGRIP and –EDML in 20:80 proportions. Our analysis focuses on variance comparisons, so we remove the complexities associated with scaling absolute values between records by normalising each HIC into unit standard deviation changes around a zero mean, using $(x-\mu)/\sigma$ where μ is the mean and σ the standard deviation, as determined over the entire series. A similar normalisation is performed on the Hulu Cave record, and the normalised records are then compared (Fig. 4). All records are interpolated at equally spaced 0.05-kyr intervals, to allow point-to-point comparison (in cross-plots used later in this paper).

To account for potential dating-related temporal offsets between the HICs and the Hulu Cave record, we perform a simple synchronisation between the HIC (on the GICC05 time scale) and Hulu Cave chronologies. We perform an initial tuning of the Hulu Cave chronology to that of HIC_{50} (the 50:50 case, which ensures that no preference was given to the Greenland or Antarctic signal structure), while ensuring the least possible distortion to the original Hulu Cave U–Th chronology (Fig. 5). In contrast to the correlation proposed by Shackleton et al. (2004), we refrain from assuming that either the U–Th chronology of Hulu Cave or GICC05 would need 'correction', and that the other would not. Instead, we tuned the Hulu Cave chronology using GICC05 as the 'reference', because errors in layer-counted age models (GICC05) should be cumulative rather than random, and we wanted to avoid such constraints when determining the smallest (random) adjustments that would result in a reasonable synchronisation. Adjustments are kept well within the combined age uncertainties of the Hulu Cave and GICC05 chronologies, as discussed below under *chronological implications* (Table 1, Fig. 6). The visually selected tie points used for synchronisation are indicated along with HIC_{50} in Fig. 5. The 'tuned' Hulu Cave record was re-interpolated at equally spaced 0.05 kyr intervals, to allow point-to-point comparison.

3. Results

The coefficient of determination (R^2) is shown in Fig. 7a for correlations between the original (normalised) Hulu Cave record and the various (normalised) HIC records, as portrayed in Fig. 4. This reveals clearly that during the last 15.8 kyr, the Hulu Cave record correlates best with HIC_{100} (i.e., the pure NGRIP record). However, in the intervals 28.55–15.85 ka BP and older than 28.6 ka BP, the Hulu Cave record correlates best with HIC_0 (i.e., the pure –EDML record). Especially in the latter interval, the coefficient of determination is low, but it can be seen in Figs. 3 and 4 that this low coefficient is likely due to minor disagreements between the age models of the Hulu Cave and ice-core records, rather than to a difference in signal structure. Chronological 'fine-tuning' (Fig. 5) allows us to investigate how chronology affects the coefficients of determination.

The coefficient of determination is shown in Fig. 7b for the correlations between the records in Fig. 5, after chronological tuning to HIC_{50}. Note that the tuning has slightly shifted the age of the plot interval boundary from 28.6 ka BP in the original Hulu Cave chronology to 28.2 ka BP. In Fig. 7b, as in Fig. 7a, the interval younger than 15.8 ka BP correlates best with HIC_{100} (i.e., the pure NGRIP record). The interval between 28.2 and 15.8 ka BP reveals a best correlation of the Hulu Cave record with HIC_{10}, and the interval older than 28.2 ka BP correlates best with HIC_{30}. Relative to the case without chronological tuning (Fig. 7a), where correlations prior to 15.8 ka BP were weak but entirely dominated by the –EDML signal, the case with chronological tuning (Fig. 7b) reveals correlations prior to 15.8 ka BP that suggest weak influence of the NGRIP signature in addition to a dominant influence of the –EDML signature.

In Figs. 8–d, we show the regression plots that underlie the R^2 maxima identified in Fig. 7b (i.e., after chronological tuning). The slopes of the regressions in Figs. 8a–c are all similar, but the intercept changes across 28.2 ka BP (i.e., 28.6 ka BP in the original U–Th chronology). In Figs. 8e–h, we show the same plots, but after applying a correction for our suggested $-1.5‰$ isotope shift at 28.2 ka BP, which effectively 'flattens' the long-term trend in the Hulu Cave record similar to that in the Xiangshui Cave record (Cosford et al., 2008). This tentative 'correction' clearly changes the regression characteristics for the overall 41–10 ka BP comparison between the Hulu Cave and ice-core records from bimodal (Fig. 8d) to unimodal (Fig. 8h). At this stage, our suggestion of a shift is no more than a suspicion with support from other speleothem records (Cosford et al., 2008); further work is needed to determine whether it can be validated. The main point of our work is independent from the existence (or not) of this apparent offset.

The R^2 summary in Fig. 7b (after chronological fine-tuning) strongly corroborates the best correlations found between the

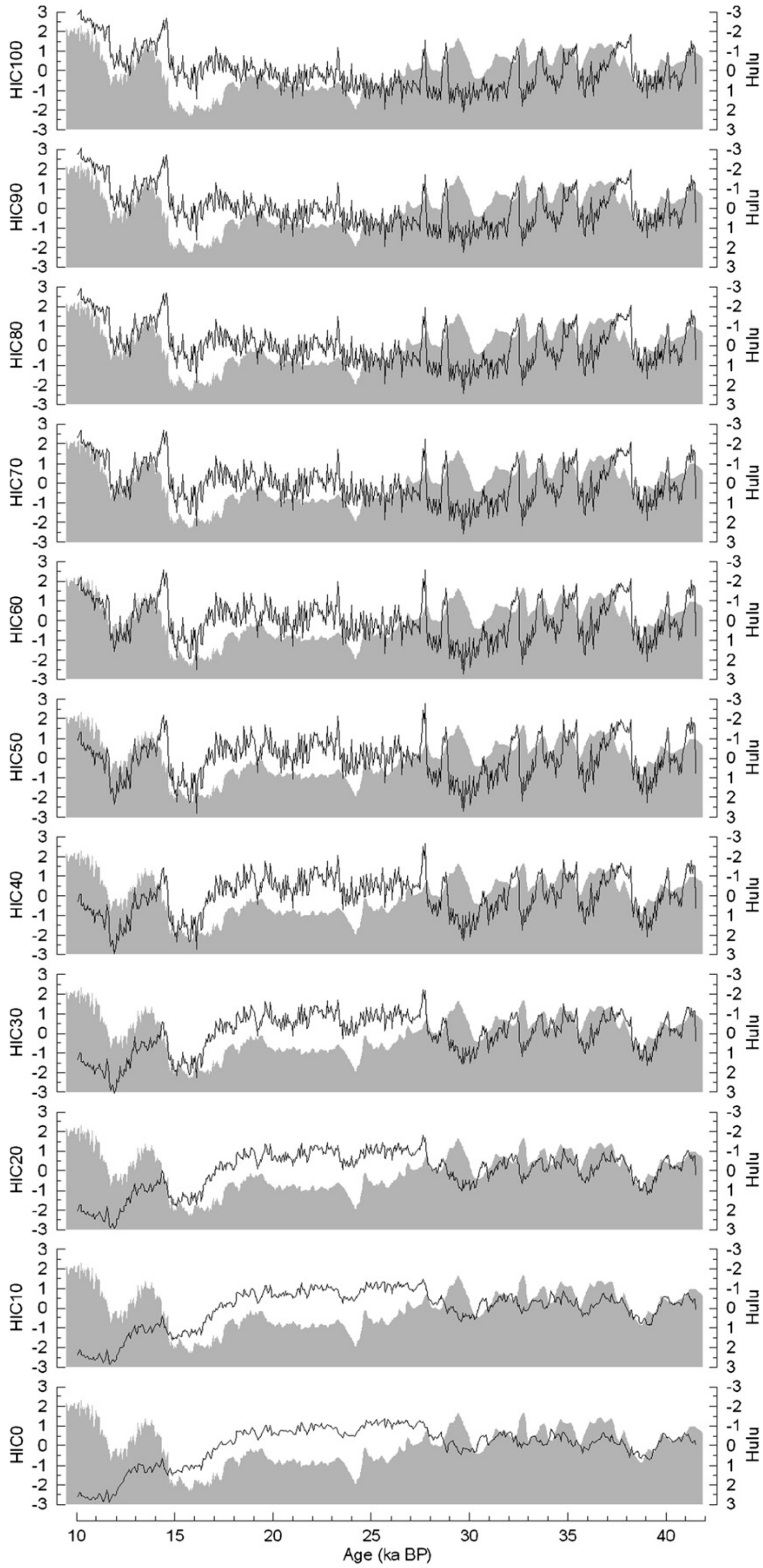

Fig. 4. Comparison between the normalised composite Hulu Cave $\delta^{18}O$ series on its original U–Th based chronology (grey) and the normalised Hybrid Ice-Core (HIC) series as described in the present paper (black lines). Coefficients of determination for regressions in each case are summarised in Fig. 7a.

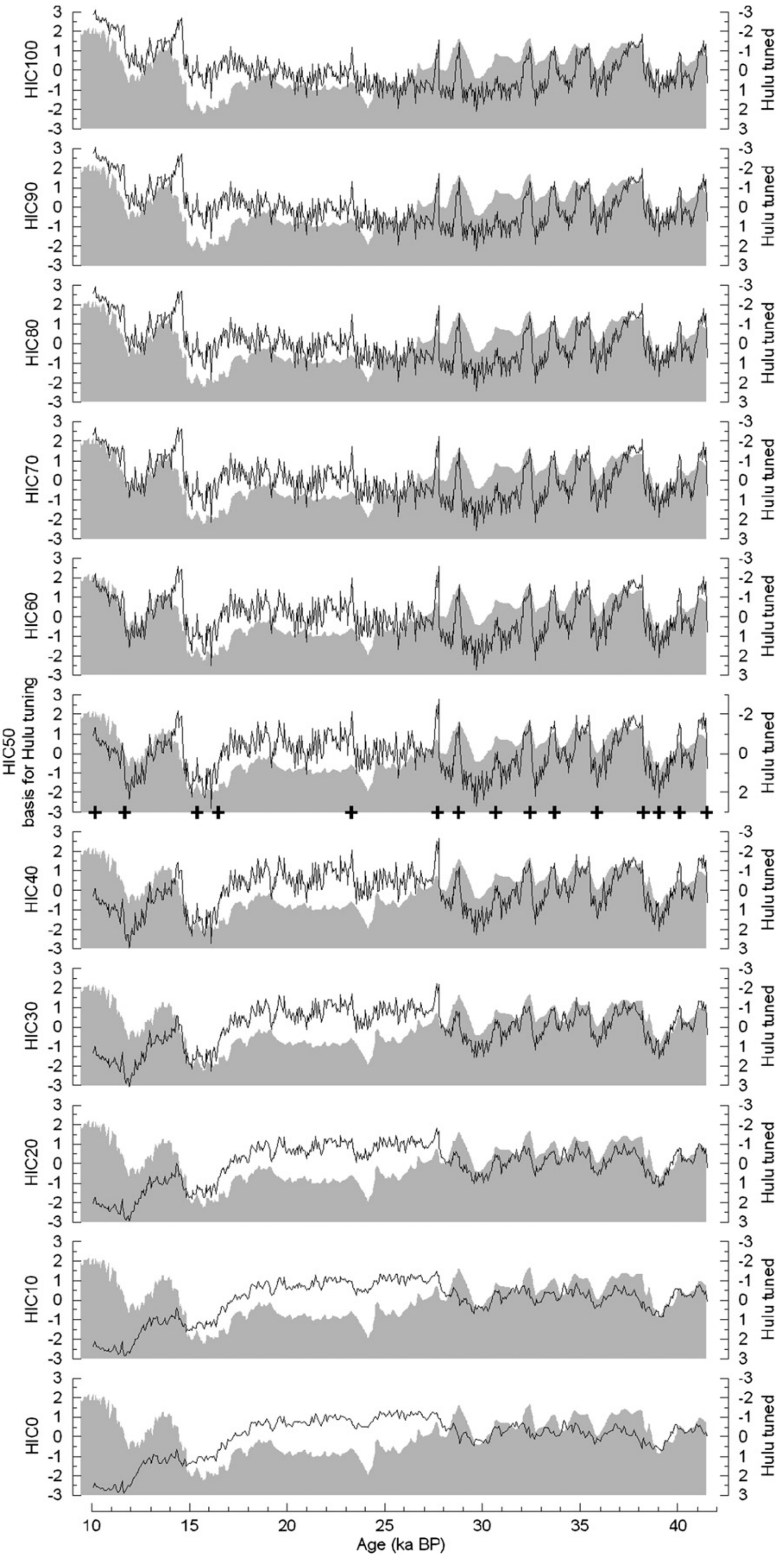

Fig. 5. Comparison between the normalised Hybrid Ice-Core series (HIC; black lines) and the normalised composite Hulu Cave $\delta^{18}O$ series (grey) after chronological fine-tuning of the Hulu Cave record to HIC_{50} as discussed in the present paper, and summarised in Fig. 6. Coefficients of determination for regressions in each case are summarised in Fig. 7b.

Table 1
Tie points for chronological tuning of Hulu Cave ages to GICC05 ages.

HULU age U–Th (ka BP)	HIC_{50} age GICC05 (ka BP)	Hulu-HIC_{50} Δage (kyr)
10.193	10.173	0.020
11.557	11.677	−0.120
15.240	15.380	−0.140
16.896	16.475	0.421
23.322	23.296	0.026
27.855	27.681	0.174
29.409	28.778	0.631
31.333	30.672	0.661
32.768	32.423	0.345
33.775	33.671	0.104
35.580	35.854	−0.274
37.323	38.214	−0.891
38.764	39.037	−0.273
39.755	40.089	−0.334
41.857	41.464	0.393

original (untuned) Hulu Cave record and the various HICs (Fig. 7a), as well as the visual observation that there are distinct similarities between the Hulu Cave record and −EDML (Figs. 3–5). The Hulu Cave record appears to represent a mix between northern and southern hemisphere signals, and the proportions of this mix are not stationary through time.

4. Discussion

4.1. Northern and Southern controls on monsoon variability

During the last deglaciation and the Holocene, variation in the monsoon intensity record appears to have been dominated by variation in northern hemisphere conditions (Figs. 7 and 8). Given that this was a time of dramatic climate change and widespread northern hemisphere deglaciation, it is not surprising that these

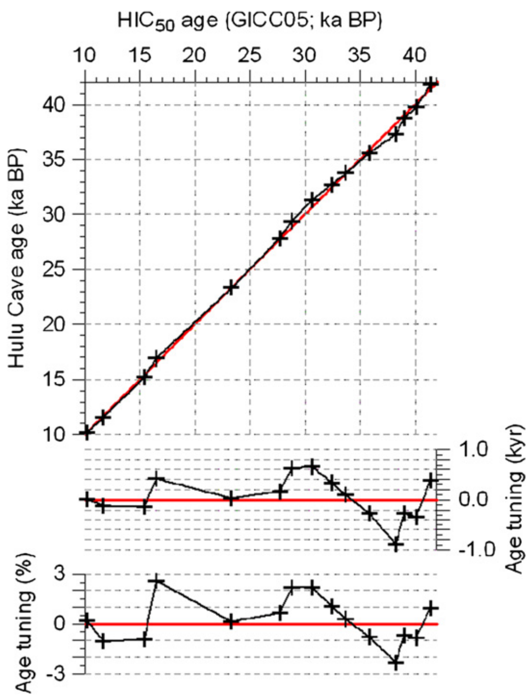

Fig. 6. Details of the chronological fine-tuning between the normalised composite Hulu Cave $\delta^{18}O$ series and HIC_{50}. Red lines indicate zero change. Crosses indicate the tie points as shown in Fig. 5 and detailed in Table 1. Lower panels are plots of the inferred Hulu-HIC_{50} offsets from the (red) zero-line, in terms of age (kyr), and in terms of percentage relative to the GICC05 age of the tie point, respectively.

major adjustments dominated monsoon variations. The widespread abrupt warming and deglaciation events that characterised the post-15.8 ka BP interval would have caused major fluctuations in the monsoon 'pull'. Through the same time interval, an underlying increase in orbitally induced insolation on the northern hemisphere (Fig. 3b) caused a strong long-term trend of increasing global monsoon intensity towards the early Holocene maximum (Kutzbach and Street-Perrott, 1985; Rossignol-Strick, 1985; Kutzbach and Guetter, 1986; Prell and Kutzbach, 1987; COHMAP Members, 1988; Kutzbach and Gallimore, 1988). It is therefore not surprising to find that northern hemisphere processes dominated monsoon variability after 15.8 ka BP; any potential southern hemisphere influences would have been swamped by major northern hemisphere changes from the end of the LGM through to the deglaciation and the early Holocene monsoon maximum.

Before 15.8 ka BP in general, and between 28.2 and 15.8 ka BP in particular, we infer (Figs. 7 and 8) that millennial-scale monsoon variability was dominated by southern hemisphere processes, so that enhanced monsoon intensity ('push') coincided with cold intervals in Antarctic climate records. From 28.2 to 15.8 ka BP, the absence of major DO fluctuations, the enormously increased global (mostly northern hemisphere) LGM ice volume with sea level 120 m or more below the present (e.g., Fairbanks, 1989; Bard et al., 1996; Rohling et al., 1998; Yokoyama et al., 2000; Siddall et al., 2003; Peltier and Fairbanks, 2006), and a long-term northern hemisphere insolation minimum (Fig. 3b), seem to have collectively negated any northern hemisphere 'pull' on the monsoon. This was a period of weak overall boreal summer monsoon activity, with a globally distinct southward displacement of the intertropical convergence zone (ITCZ) (e.g., Arz et al., 1998; Peterson et al., 2000; Baker et al., 2001; Koutavas et al., 2002; Wang et al., 2004, 2006; Peterson and Haug, 2006; Weldeab et al., 2007). Whatever residual variability there was in the boreal monsoon seems to have been dominated by southern hemisphere processes between 28.2 and 15.8 ka BP.

Prominent DO fluctuations in the pre-28.2 ka BP interval resulted in a non-negligible northern hemisphere influence on the monsoon, although southern processes appear to have been more important, given that the best correlation is found with HIC_{30} (Figs. 7 and 8). With global sea level between −60 and −90 m relative to present during this interval (Siddall et al., 2003, 2008 and references therein), the northern hemisphere would still have had an ice volume that was roughly equivalent to that of the modern Antarctic ice-sheets. Although less so than during the LGM, this period was therefore still in the grip of an ice age, with the ITCZ in a generally more southward position, especially during cold periods (e.g., Arz et al., 1998; Peterson et al., 2000; Baker et al., 2001; Koutavas et al., 2002; Burns et al., 2003, 2004; Wang et al., 2004, 2006; Peterson and Haug, 2006; Weldeab et al., 2007). Although higher than during the LGM, boreal summer insolation was low during the pre-28.2 ka BP interval (Fig. 3b), with consequently reduced long-term global monsoon activity relative to the strong insolation maximum of the early Holocene. Glaciation and/or persistent snow cover in the Himalayas/Tibetan Plateau would have severely weakened any monsoon 'pull' (e.g., Meehl, 1994, 1997; Overpeck et al., 1996; Barnett et al., 1988). Although the distinct DO cycles of the pre-28.2 ka BP interval appear to have imposed some detectable influences, the generally weak monsoon pull during this period seems to have allowed southern hemisphere processes to appear more prominent in modulating monsoon intensity.

Based on the results outlined above (Figs. 7 and 8), we now formulate a new composite HIC ($HIC_{comp.}$), which consists of HIC_{30} in the pre-28.2 ka BP interval, HIC_{10} in the 28.2–15.8 ka BP interval, and HIC_{100} in the post-15.8 ka BP interval. $HIC_{comp.}$ is plotted alongside the (chronologically tuned; Fig. 6) Hulu Cave record (Fig. 9). We propose that HIC_{comp}, with its temporally variable mix

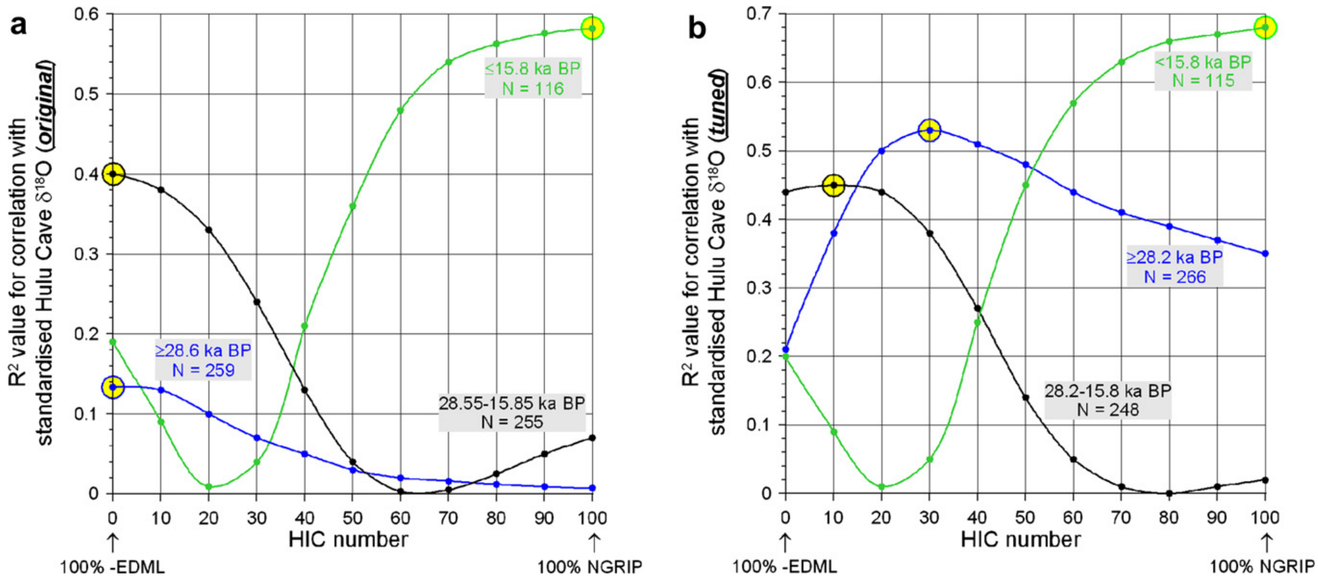

Fig. 7. (a) Summary of coefficients of determination (R^2) for three separate time intervals (see text) in each of the record comparisons displayed in Fig. 4 (i.e., using the original chronologies). Yellow markers identify the correlation cases with the highest R^2 score for each interval. (b) As (a) for each of the record comparisons displayed in Fig. 5 (i.e., after chronological fine-tuning).

of both northern and southern hemisphere influences, provides a statistically more robust explanation of the high-latitude controls on Asian monsoon intensity than the original correlation of the Hulu Cave record with Greenland ice-core data (Wang et al., 2001).

4.2. Chronological implications

It is worth considering some more detailed aspects of the compared chronologies. The differences are not systematically distributed; for example, they do not monotonically increase or decrease (Fig. 6). Layer-counted errors in GICC05 are cumulative with increasing age, amounting to 4% at around 40 ka BP, and because they are cumulative they cannot be the cause of rapid changes between positive and negative offsets. Hence, the diagnosed offsets (Fig. 6) cannot be fully ascribed to uncertainties in GICC05. Instead, the offsets most likely reflect addition of error from several sources in addition to GICC05 uncertainty, as outlined below.

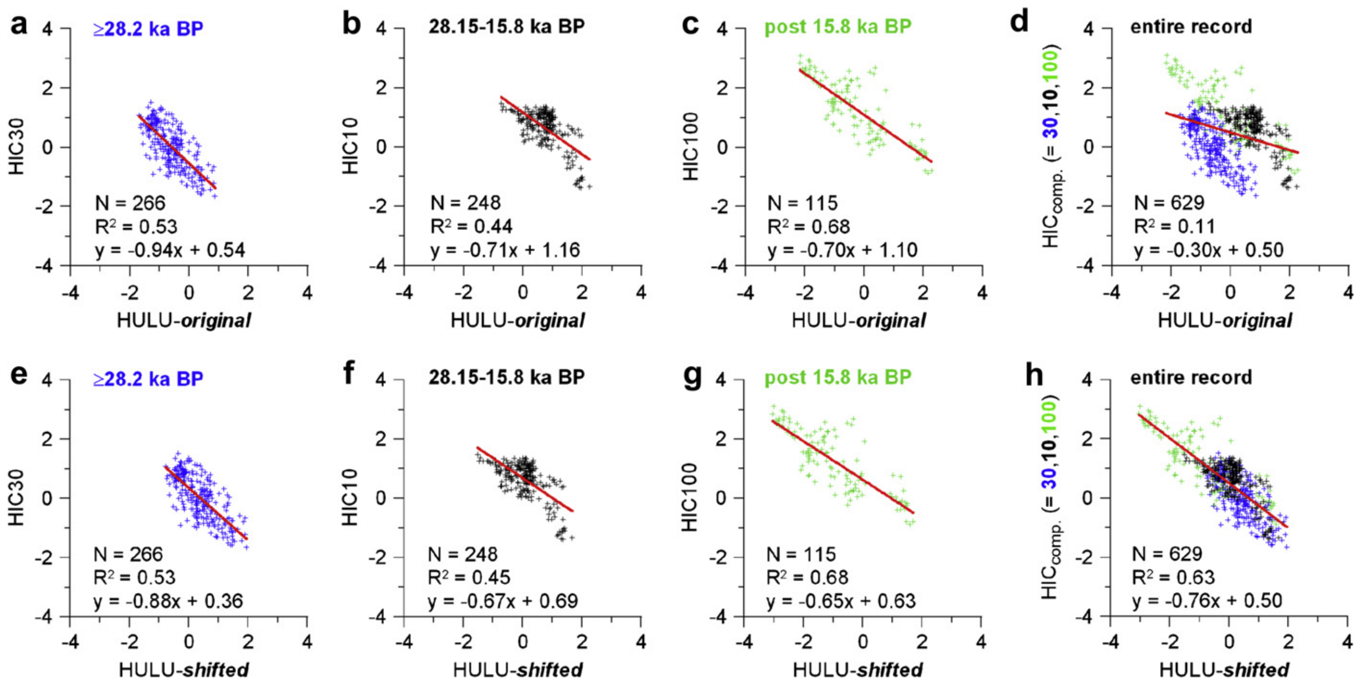

Fig. 8. (a–c) Details of the regressions underlying the maximum R^2 scenarios displayed in Fig. 7b (i.e., after chronological fine-tuning that optimised the R^2 scores). These plots were made without 'correction' for the potential −1.5‰ isotope offset in the Hulu Cave record inferred in the present paper (at around 28.6 ka BP in its original U–Th based chronology – see Fig. 3 – and at around 28.2 ka B after chronological fine-tuning). (d) Combined plot of (a–c), which clearly displays the bimodal nature caused by an apparent offset between Hulu Cave values before and after 28.2 ka BP. (e–h) As in (a–d), but now after our tentative 'correction' for the inferred −1.5‰ isotope offset in the Hulu Cave record (see text).

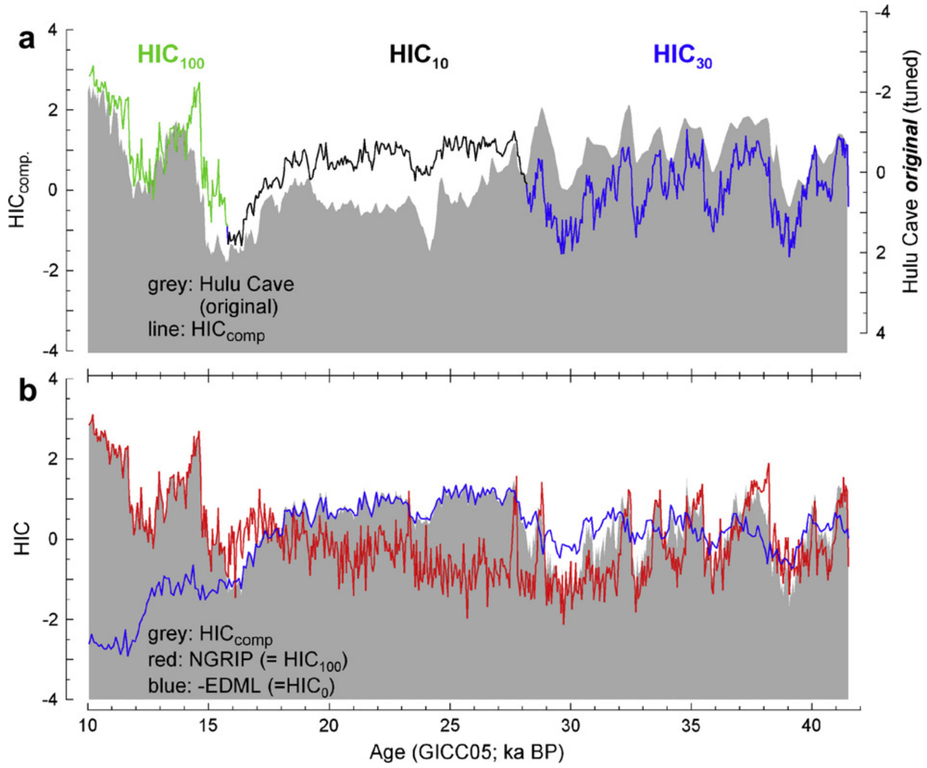

Fig. 9. (a) Comparison of the composite HIC record (HIC_{comp}) with the normalised Hulu Cave $\delta^{18}O$ series (grey). HIC_{comp} comprises HIC_{100} in the post-15.8 ka BP interval (green), HIC_{10} between 28.2 and 15.8 ka BP (black), and HIC_{30} in the pre-28.2 ka BP period (blue). The composite records are based on the optimum correlations found in Figs. 7b and 8. In (a), the original (normalised) composite Hulu Cave series is used (after chronological fine-tuning – see Figs. 5, 6, and 7b). (b) Comparison between HIC_{comp} (grey) and the pure NGRIP (red) and pure –EDML (blue) time series. Note that the use of HIC_{comp} does not imply changes in the ages of major transitions relative to the traditional use of pure NGRIP as a correlation target.

U–Th dated series (Hulu Cave) tend to have two sources of random age uncertainties. First, there is the external precision of the datings, which in the reported Hulu Cave data ranges mostly from 0.5 to 1.5%, although 2.5% uncertainties are apparent in the ages reported for the PD stalagmite (2σ level) (Fig. 2). Second, there is unavoidable bias associated with assumptions about the rate of stalagmite growth between dating points. Overall, typical age offsets of about 1.5% are apparent between the chronologies of different speleothem records used to compose the Hulu Cave record (Fig. 2). The tuning between the Hulu Cave and (GICC05) ice-core series that is applied here (Figs. 5 and 6; Table 1) also contains a level of subjectivity during tie point selection, and concerning the assumed (linear) interpolation between tie points. Finally, there is uncertainty in the methane synchronisation of the NGRIP and EDML ice-core records. This uncertainty may amount up to about 250–500 years (EPICA Community Members, 2006; Ahn and Brook, 2007; Loulergue et al., 2007), and introduces slight uncertainty about the fine structure of the various HIC records compiled in the present paper. Despite these sources of bias, we find an exceptional overall dating agreement between two entirely independent records, with a maximum range of disagreement of only ±2.5% (Table 1; Fig. 6). These inferred age offsets remain numerically within the combined age uncertainties and other sources of assumption and uncertainty, although there remains room for improvement in intervals where the signal agreement between the Hulu Cave and HIC records is weakest – notably between 29.4 and 27.9 ka BP on the Hulu Cave chronology (Table 1, Fig. 6). Overall, however, we consider our level of chronological ‘tuning’ to be warranted within the chronological constraints.

Our re-interpretation of the high-latitude controls on monsoon intensity does not significantly affect the ages of the major transitions (Fig. 9b), given the combined dating uncertainties, relative to the major transitions in the 100% NGRIP record (Fig. 6). Adoption of our re-interpretation would therefore not affect Hulu Cave U–Th age assignments to the major transitions in the ice-core records. Notably, however, our results improve our understanding of chronological relationships across the LGM, where correlation between Hulu Cave and HIC_{100} is hindered by a lack of signal structure agreement. Overall, therefore, our new correlation does not alter the accepted chronological coincidences between the Hulu Cave record and the NGRIP record, but it does two important things: (a) it offers a sound comparison between the GICC05 ice-core timescale and the U–Th Hulu Cave chronology in the interval 16–27 ka BP; and (b) it reveals new arguments about the reasons (mechanisms) why the Hulu Cave and NGRIP records seem to agree within the combined chronological uncertainties.

5. Conclusions

Although previous work has found (except across the LGM) a sound chronological correlation between the Hulu Cave record and Greenland ice-core records, the correlations may have been based upon fundamentally incorrect assumptions. Our analysis challenges the previous assumption that East Asian monsoon records reflect DO cycles due to some control by northern hemisphere processes alone, and suggests that it should be replaced by a more flexible, global interpretation, which takes into account all aspects of the various signal structures, rather than just a few major transitions. We propose a new interpretation that includes dominant control on monsoon variability by southern hemisphere climate changes during glacial times when the monsoon is weak overall, and control by northern hemisphere climate changes during deglacial and interglacial times when the monsoon is strong. Southern hemisphere control on the monsoon is recognised by taking the inverse of the southern hemisphere climate variability, so that increased monsoon intensity coincides with cold phases in the Antarctic climate records, as was suggested by Cai et al. (2006). Our statistical analysis suggests that this temporally variable relationship with the inverse of southern hemisphere climate records is a more likely reason for the apparent coincidence of major East Asian monsoon transitions with northern hemisphere (DO) climate events during glacial times, than the traditional interpretation of strict northern hemisphere control.

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