An updated astronomical timescale for the Plio-Pleistocene deposits from South China Sea and new insights into Asian monsoon evolution

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\textbf{A B S T R A C T}

Here we present an improved astronomical timescale since 5 Ma as recorded in the ODP Site 1143 in the southern South China Sea, using a recently published Asian summer monsoon record (hematite to goethite content ratio, Hm/Gt) and a parallel benthic \( \delta^{18}O \) record. Correlation of the benthic \( \delta^{18}O \) record to the stack of 57 globally distributed benthic \( \delta^{18}O \) records (LR04 stack) and the Hm/Gt curve to the 65 \^{}N summer insolation curve is a particularly useful approach to obtain refined timescales. Hence, it constitutes the basis for our effort. Our proposed modifications result in a more accurate and robust chronology than the existing astronomical timescale for the ODP Site 1143. This updated timescale further enables a detailed study of the orbital variability of low-latitude Asian summer monsoon throughout the Plio-Pleistocene. Comparison of the Hm/Gt record with the \( \delta^{18}O \) record from the same core reveals that the oscillations of low-latitude Asian summer monsoon over orbital scales differed considerably from the glacial–interglacial climate cycles. The popular view that summer monsoon intensities during interglacial stages and weakens during glacial stages appears to be too simplistic for low-latitude Asia. In low-latitude Asia, some strong summer monsoon intervals appear to have also occurred during glacial stages in addition to their increased occurrence during interglacial stages. Vice versa, some notably weak summer monsoon intervals have also occurred during interglacial stages next to their anticipated occurrence during glacial stages. The well-known mid-Pleistocene transition (MPT) is only identified in the benthic \( \delta^{18}O \) record but not in the Hm/Gt record from the same core. This suggests that the MPT may be a feature of high- and middle-latitude climates, possibly determined by high-latitude ice sheet dynamics. For low-latitude monsoonal climate, its orbital-scale variations respond more directly to insolation and are little influenced by high-latitude processes, thus the MPT is likely not recorded. In addition, the Hm/Gt record suggests that low-latitude Asian summer monsoon intensity has a long-term decreasing trend since 2.8 Ma with increased oscillation amplitude. This long-term variability is presumably linked to the Northern Hemisphere glaciation since then.

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\section{1. Introduction}

The Asian monsoon system is an important component of the global climatic system (Webster, 1994), which controls much of the Asian climate changes (Sun and Wang, 2005; Wang et al., 2005a; Clift and Plumb, 2008). Knowledge of the long-term spatial and temporal evolution of the Asian monsoon would aid in understanding of its underlying forcing mechanisms. This would in turn enable a better prediction of future climate change scenarios with regard to the Asian monsoon. The Asian monsoon is characterized by seasonal reversal of winter and summer monsoons, which results in cold/dry winters and warm/wet summers over the Asian mainland (Wang et al., 2005a; Clift and Plumb, 2008). The Asian summer monsoon evolution in South China during the Holocene and the late Pleistocene (i.e. from 387 ka to present) can be reflected in detail (from orbital down to millennial variations) from the \( \delta^{18}O \) record of stalagmites from South China, which are dated by high-resolution U-series analyses (Wang et al., 2001, 2005b, 2008; Yuan et al., 2004; Cheng et al., 2006, 2009; Zhang et al., 2008), although measuring stalagmite \( \delta^{18}O \) is
not the same as (directly) measuring summer monsoon intensity. Note that the summer monsoon intensity contains not only the monsoon precipitation, but also other issues, such as temperature and wind speed. The Chinese loess-paleosol sequences offer a good opportunity to trace the Asian monsoon evolution in north China during the Pleistocene (e.g., An et al., 1990, 2001; Liu and Ding, 1998; An, 2000; Ding et al., 2002, 2005; Sun et al., 2006). Up to now, however, published high-resolution records that reveal orbital changes in the Asian monsoon extending back to the pre-Pleistocene periods are rare.

Recently, Zhang et al. (2007, 2009) established a high-resolution Asian summer monsoon record throughout the last 5 Myr using the ratio of hematite and goethite contents (Hm/Gt) from the Ocean Drilling Program (ODP) Site 1143 in the southern South China Sea (Fig. 1). Generally, a weaker summer monsoon would result in decreased humidity and subsequently higher Hm/Gt ratios, whereas a stronger summer monsoon would lead to increased humidity with related lower Hm/Gt ratios, because dry and humid conditions are more favorable for the formation of hematite and goethite, respectively (Harris and Mix, 1999; Ji et al., 2004; Zhang et al., 2007, 2009). The Plio-Pleistocene part of the ODP Site 1143 is 190 m long. As suggested by presently accepted chronology of this ODP site, which was generated by tuning the benthic δ¹⁸O record to the orbital obliquity (41-kyr) and precession (23-kyr) cycles. The stalagmite δ¹⁸O record is the most accurately dated in the ODP Site 1143 by considering the structures of both Hm/Gt and benthic δ¹⁸O records (Tian et al., 2002) (from now on referred to as the T2002 timescale), the 190-m deposits span the last 5 Myr. Inferred from the T2002 timescale, the resolution of Hm/Gt record is as high as 2 kyr, which enables a detailed study of the orbital and millennial as well as long-term changes of Asian monsoon during the last 5 Myr.

Although the T2002 timescale was established based on orbital tuning, the Hm/Gt record plotted on the T2002 timescale shows poor orbital periodicities, which cannot be matched with the ETP curve (Fig. 2). Here the ETP curve is the sum of normalized eccentricity (E, ~100-kyr), obliquity (T, 41-kyr) and reversed precession (P, 19- and 23-kyr), which reflects the characteristics of the Earth’s orbital elements. A good tuning should result in high coherencies between climate and ETP curves, generally above the 95% confidence (Brüggemann, 1992). Since the precession cycles are quite weak in the Plio-Pleistocene benthic δ¹⁸O record, the tuning of precession signal in the benthic δ¹⁸O record to orbital precession as adopted by Tian et al. (2002) would result in considerable uncertainties of the assignment of short-term sedimentary precession cycles. The stalagmite δ¹⁸O record is the most accurately dated monsoon record on the relevant 100-kyr timescale, with errors of mere decades (Wang et al., 2001, 2005b, 2008; Yuan et al., 2004; Cheng et al., 2006, 2009; Zhang et al., 2008). When comparing the Hm/Gt record in the T2002 timescale with the composite Chinese stalagmite δ¹⁸O record (from the Sanbao, Linzhu, Dongge and Hulu caves, see their locations in Fig. 1) during the past ~390 kyr (Wang et al., 2001, 2008; Cheng et al., 2009), the correlation between the two timescales appears to be less consistent as well (Fig. 3). A rearrangement of these tie points (dashed lines) could result in a more plausible correlation between the Hm/Gt and stalagmite δ¹⁸O records that with the current timescale shows a rather variable sedimentation rate (Fig. 3). The shifts in sediment accumulation rate when compared to the speleothem timescale (cf. Fig. 3) and the rather poor assignment of precession cycles in the T2002 timescale suggest that it is appropriate to re-assess this timescale for the ODP Site 1143. Especially the summer monsoon record inferred from the Hm/Gt ratio is now available for the last 5 Myr for that site. The Hm/Gt record has strong short-term oscillations related to precession cycles, which in principle would enable a better assignment of the sedimentary precession cycles allowing a more precise timescale. These observations motivated us to construct an improved timescale for the Plio-Pleistocene part of the ODP Site 1143 by considering the structures of both Hm/Gt and benthic δ¹⁸O records. A series of major events, such as the final closure of the Panama Isthmus and the Indonesian seaway, the final uplift stage and expansion of the northern edge of the Tibetan

Fig. 1. Location map of the ODP Site 1143 (modified from Zhang et al., 2007). Gray dashed line represents the 100 m isobaths (approximate position of the coastline during glacial sea level low stands) in the South China Sea. Back dashed line represents the Molengraaff paleo-river. The arrow represents the Asian summer monsoon direction.

Fig. 2. Cross-spectral comparisons of the ETP curve with the Hm/Gt record (Zhang et al., 2007, 2009) expressed on the T2002 timescale (Tian et al., 2002). The shaded areas represent the coherency between Hm/Gt and ETP, and the horizontal dashed line indicates 95% confidence limit for coherence peaks. Here the ETP curve is the sum of normalized eccentricity (E), obliquity (T), and reversed precession (P). The cross-spectral analyses were performed with Arand software developed by Brown University. Bandwidth we used is 0.007 kyr⁻¹.
Plateau and the onset of Northern Hemisphere glaciations, which are closely linked to the appearance of the current patterns in the climate system, are within the Plio-Pleistocene period (Raymo, 1994; Zheng et al., 2000; An et al., 2001; Cane and Molnar, 2001; Schmittner et al., 2004; Clift and Plumb, 2008). In addition, the South China Sea area was also under the influence of Asian monsoon during the Plio-Pleistocene and may thus contain important monsoonal information. Therefore, a refined timescale for the ODP Site 1143 will enable a better understanding of the orbital variations of low-latitude Asian and global climate as well as of the paleoceanographic history of the South China Sea throughout the Plio-Pleistocene.

Using the recently published Hm/Gt (Zhang et al., 2007, 2009) and benthic δ18O records (Tian et al., 2002), we present here an improved timescale for the ODP Site 1143 throughout the last 5 Myr. We calibrate firstly the benthic δ18O record to the stack of 57 globally distributed benthic δ18O records (LR04 stack) (Lisiecki and Raymo, 2005) and secondly the Hm/Gt record to the 65°N summer insolation curve (Laskar et al., 2004). Because of more robust tuning, our new timescale (hereinafter referred to as A2011 timescale) appears to be more consistent than the T2002 timescale. A smoother sediment accumulation is the result in line with a continuous monsoon-derived riverine input to the depositional environment. Particularly within the time interval between 5 and 3.2 Ma, the new timescale shows considerable improvement. Based on the A2011 timescale, we further employ the Hm/Gt record to discuss the variations of low-latitude Asian monsoon throughout the last 5 Myr over short-term orbital scales and long-term trends as well as the possible relationship with variations of global ice volume.

2. Geological setting and materials

ODP Site 1143 (9°21.72′N, 113°17.11′E; 2777 m water depth) was drilled in a depression on the carbonate platform that forms the southern continental shelf of the southern South China Sea (Fig. 1). As a semi-enclosed deep-sea basin, the South China Sea is the largest marginal sea of the western Pacific, covering an area of ~3.5 × 10^6 km^2. The seasonally reversed circulations of the Asian winter and summer monsoon result in cold/dry winters and warm/wet summers over the South China Sea. Due to strong monsoon precipitation and intrusion of low-salinity water from along shore of Borneo, the sea surface salinity in the southern South China Sea is quite low, ranging from ~31–34.3‰ (Tian et al., 2004). The sea surface salinity in the open western Pacific is as much as 35–35.5‰ throughout the upper 560 m of the water column (Tian et al., 2004). The deposits at the ODP Site 1143 mainly consist of terrigenous quartz, feldspar and clay minerals, with only a minor biogenic component (~2%) (Wan et al., 2006). Perhaps rather surprising in an overall detrital setting, only the Brunhes/Matuyama (B/M) paleomagnetic reversal was identified at a depth of ~42.5 m; other paleomagnetic reversals were not found (Fig. 4) (Tian et al., 2002).
**Fig. 4.** First-order correlations of the benthic δ^18O record (Tian et al., 2002) of the ODP Site 1143 to the LR04 stack of benthic δ^18O (Lisiecki and Raymo, 2005). B, Brunhes; M, Matuyama; FO, first occurrence; LO, last occurrence; LCO, last common occurrence. The ages of panktonic foraminiferal events refer to the magnetostratigraphic dating of these events from other ODP sites (Berggren et al., 1995). The age of B/M boundary refers to the astronomically tuned Neogene timescale (Lourens et al., 2004). Numbers arranged on the benthic δ^18O curves represent the marine isotope stages. Dashed lines show the typical correlations between the benthic δ^18O records of the ODP Site 1143 and LR04 stack.
This makes it impossible to establish a chronology for the ODP Site 1143 based on magnetostratigraphy. The reason for the poor paleomagnetic record is presumably related to poor demagnetization of the characteristic remanent magnetization (ChRM) or diagenetic removal of magnetite which dissolves more quickly than hematite and goethite (Shipboard Scientific Party, 2000; Larrasoñã et al., 2003a, b; Liu et al., 2004; Ao et al., 2010a), but a full account is beyond the scope of this paper.

Hematite (Hm) and goethite (Gt) contents over the last 5 Myr (from 0 to 190 m) were assembled by Zhang et al. (2007, 2009) for 2122 samples from the ODP Site 1143 using a Perkin Elmer Lambda 900 diffuse reflectance spectrophotometer in the Surficial Geochemistry Institute of Nanjing University, China (see Zhang et al., 2007 for a detailed description of the measuring method). Subsequently, the Hm/Gt ratio is calculated and interpreted as a proxy for changes in Asian summer monsoon intensity in South China (Zhang et al., 2007, 2009). This published Hm/Gt record is an important ingredient for our tuning. Another key component is the published benthic δ18O record from the same core (Tian et al., 2002). Within the interval of our tuning, a total of 1992 samples of benthic foraminifera were measured for stable oxygen isotopes using a Finnigan MAT252 mass spectrometer in the Marine Geology Laboratory of Tongji University, China (Tian et al., 2002). The benthic δ18O values are from the benthic foraminifera Cibicidoides wuellerstorffii and Uvigerina peregrina. The values of U. peregrina are adjusted by subtracting 0.64‰ (Tian et al., 2002).

The sensitivity of the Hm/Gt ratio to precipitation has been demonstrated by its correlation with topography: generally soils with relatively higher hematite concentrations occur on the drier slopes in the landscape while higher goethite concentrations are noted in the wetter depressions (Curi and Franzmeier, 1984; Santana, 1984; da Motta and Kampf, 1992). In an overall wetter climate the proportion of comparatively dry slopes is therefore lower while the expression of wetter depressions is restricted in drier climate. The Hm/Gt ratio has been used in a number of areas of sedimentary basins (e.g. Harris and Mix, 1999; Ji et al., 2002; Clift, 2006). For example, the Hm/Gt ratio record retrieved from Ceara Rise sediments in the western tropical Atlantic Ocean was used to estimate the Pleistocene variability of the precipitation in the Amazon Basin (Harris and Mix, 1999). The Hm/Gt ratio record retrieved from the Chinese loess deposits was used to estimate the Asian summer monsoon evolution, which has high values at loess layers (comparatively dry climate, weak summer monsoon interval) and low values at paleosol layers (comparatively humid climate, strong summer monsoon interval) ( Ji et al., 2004). Clift (2006) used the Hm/Gt ratios of the ODP Site 1148 from the northern South China Sea to infer the Asian summer monsoon variations for the past 25 Myr. As already adopted by Zhang et al. (2007, 2009), the Hm/Gt ratios of the ODP Site 1143 can be used as an indicator of summer monsoon intensity because of the following four reasons. (1) The terrigenous deposits, including the hematite and goethite, at the ODP Site 1143 were mostly derived from the Mekong Basin (Fig. 1) through fluvial and marine transportation (Wan et al., 2006), with a discharge of ~160 × 106 t of sediment per year (Milliman and Meade, 1983). Other rivers such as the Baram River from northwest Borneo and the Chao Phraya River from western Indochina have a combined annual sediment discharge of ~23 × 106 t to the southwest South China Sea. These therefore were not an important source of the ODP Site 1143 sediments compared with the Mekong River (Milliman and Syvitski, 1992; Hiscott, 2001). The dominant surface current during interglacial periods from the southwest makes terrigenous input from the Red River and Pearl River insignificant as well. During glacial periods with lower sea levels, however, the Molengraaff River may have transported some additional sediments from the Paleo-Sunda shelf to the ODP Site 1143 (Molengraaff and Weber, 1920) (Fig. 1). (2) Hematite and goethite in the ODP Site 1143 are not significantly affected by pore-water reduction after burial (Zhang et al., 2007, 2009) as suggested by following evidence. A commonly used sign for strongly reductive alteration is the presence of pyrite in sediments (Berner, 1981, 1984). However, pyrite was not found in the ODP Site 1143 (Wang et al., 2001). This implies that anoxic diagenesis was not significant here. Furthermore, unlike the low-coercivity magnetite, the high-coercivity hematite and goethite are rather resistant to pore-water reduction processes (Snowball, 1993; Nowaczyk et al., 2002; Demory et al., 2005). Prolonged diagenesis generally requires abundant (reactive) organic matter (Berner, 1984; Robinson et al., 2000; Demory et al., 2005), however, the so-called green layers in the ODP site 1143 sediments have a low total organic carbon (TOC) content (Tamburini et al., 2003). (3) The relative abundance of goethite to hematite on the paleo-Sunda shelf and in the Mekong Basin varies with climatic conditions: dry and humid conditions are more favorable for formation of hematite and goethite, respectively (Curi and Franzmeier, 1984; Santana, 1984; da Motta and Kampf, 1992; Zhang et al., 2007, 2009). (4) The dry and humid conditions over the South China Basin are mainly modulated by Asian summer monsoon (Tian et al., 2004, 2005, 2006; Wang et al., 2005a; Zhang et al., 2007, 2009), although it is debatable whether the climate in Borneo is significantly affected by the monsoon circulations (Cobb et al., 2007). Therefore, the strong summer monsoon periods would result in more goethite deposition in the South China Sea, whereas the weak summer monsoon periods would result in more hematite deposition. So, for this region low and high Hm/Gt ratios would imply strong and weak summer monsoons, respectively.

3. Calibration of the astronomical timescale

Astronomical calibration is a powerful approach to construct timescales which, in principle, have a higher resolution and better accuracy than conventional timescales based on linear interpolation between geomagnetic reversals and/or radiometrically dated calibration points. This approach has been widely used to construct age models for deep-sea sediments (e.g. Raymo et al., 1989; Ruddiman et al., 1989; Shackleton et al., 1990; Hilgen, 1991a,b; Lisiecki and Raymo, 2005; Hüssing et al., 2010), Chinese loess (e.g. Ding et al., 1994; Lu et al., 1999; Heslop et al., 2000; Sun et al., 2006), and other continental deposits (van Vugt et al., 1998; Aziz et al., 2003, 2004; Ao et al., 2010b).

For the construction of an astronomical timescale, the selection of suitable target curves is crucial. In this study, we selected the 65 N summer insolation (Laskar et al., 2004) for the tuning of the ODP Site 1143, because it is a major forcing factor of the orbital-scale changes in the Asian summer monsoon in South China (Wang et al., 2008; Cheng et al., 2009). The orbital solution of La2004 (Laskar et al., 2004) computed with present-day input values for the dynamical ellipticity of the Earth and tidal dissipation in the evolution of the Earth-Moon system, is demonstrated to have an accurate solution with respect to the geological records (Pälike et al., 2006a,b; Tian et al., 2008; Ao et al., 2010b; Hüssing et al., 2010). Before starting the tuning procedure, the phase relationship between orbital forcing and Asian monsoon responses must be known. As proposed by Ruddiman (2006a), the Asian monsoon should respond to the Northern Hemisphere summer insolation with a near-zero phase lag. This is recently confirmed by the comparison of the δ18O sea record retrieved from the well-dated Chinese stalagmites with the 65 N summer insolation (Wang et al., 2008). Further, the in-phase correlation between the precession (23-kyr) signal in the stalagmite δ18O (Wang et al., 2001,
and the orbital precession signal (Laskar et al., 2004) supports a zero phase lag as well (Supplementary Fig. 1). Thus during the present tuning procedure, we utilized a zero time lag between the insolation forcing and the monsoon response. This differs from Tian et al. (2002) who used the then generally accepted 8-kyr lag for the obliquity curve and 5-kyr lag for the precession curve in their tuning.

Unlike the T2002 timescale that uses a single isotope curve for tuning, the A2011 timescale was formulated by visual correlation of the benthic δ18O record to the LR04 benthic stack (Lisiecki and Raymo, 2005) and the Hm/Gt monsoon record to the 65°N summer insolation (Laskar et al., 2004). The LR04 stack was selected over other marine benthic δ18O records because it is constructed by averaging 57 globally distributed sites. It thus has an increased signal-to-noise ratio, which would better remove regional variability and better capture the global ice volume signal (Lisiecki and Raymo, 2005). This cross-correlation with several proxies (here two) is generally more robust than tuning with only a single climate proxy. The visual tuning carried out here was similar to the procedure adopted by Hilgen (1991a, b) and Hilgen et al. (1995, 2006), Ruddiman and Raymo (2003) and Heslop et al. (2000). For example, Hilgen et al. (1995) extended the astronomical (polarity) timescale into the Miocene based on the correlation of characteristic sedimentary cycle patterns in marine sections in the Mediterranean to the 65°N summer insolation. By correlation of CH4 to insolation, Ruddiman and Raymo (2003) constructed a new timescale for the Vostok ice core. Heslop et al. (2000) formulated a refined timescale for the Chinese loess deposits by correlation of the unfiltered grain-size (a proxy of Asian winter monsoon in north China) and magnetic susceptibility (a proxy of Asian summer monsoon in north China) records to the insolation and marine δ18O curves.

Fig. 5. Second-order correlations of the Hm/Gt cycles (Zhang et al., 2007, 2009) of the ODP Site 1143 to the 65°N summer insolation curve (Laskar et al., 2004). Hm/Gt maxima (weak summer monsoon) and minima (strong summer monsoon) were correlated with regional minima and maxima in insolation, respectively. The precession (21-kyr) cycle filtered from the Hm/Gt record expressed on the A2011 timescale is also used to promote a better correlation between the Hm/Gt and insolation records. Dashed lines show the detailed correlations between the Hm/Gt and the insolation records. The red points on the Hm/Gt curves represent the final tie-points we adopted to establish the A2011 timescale. These tie-points are selected from feature correlated specifies maxima (minima) in Hm/Gt record and minima (maxima) in 65°N insolation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
As a first step in our tuning, the magnetostratigraphic (i.e. the B/M boundary) and biostratigraphic data provided 9 initial tie points between the benthic δ18O records of the ODP Site 1143 and the LR04 stack (Fig. 4). Next, we attempt to correlate the benthic δ18O record of the ODP Site 1143 to the LR04 benthic stack, because benthic δ18O is globally correlative during the Plio-Pleistocene (Lisiecki and Raymo, 2005). The characteristics of the benthic δ18O records retrieved from different sites are quite similar, therefore, the correlation of the large-scale δ18O cycles is relatively straightforward. The outcome of this first-order tuning is presented in Fig. 4. The validity of this tuning is supported by the cycle-by-cycle correlation between the two benthic δ18O records and their similar amplitude modulation. This first-order large-scale tuning is crucial to avoid over-correlation of the data during the following second-order tuning. Unlike us, however, Tian et al. (2002) did not use such a visual correlation of the benthic δ18O record to constrain their orbital tuning. Keep in mind that the ages of the B/M boundary and biostratigraphic events we selected to establish our initial timescale as well as the ages from the first-order tuning, are not fixed (generally with a relaxed age less than 40 ka) during our following second-order tuning that focuses on fine-scale features. So, after the first-order tuning, we then further correlate the small-scale Hm/Gt cycles to the 65°N summer insolation. During

<table>
<thead>
<tr>
<th>Planktonic foraminiferal events</th>
<th>Depth (m)</th>
<th>Age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A2011</td>
<td>T2002</td>
</tr>
<tr>
<td>FO pink Globigerinoides ruber</td>
<td>25.0</td>
<td>0.41</td>
</tr>
<tr>
<td>LO Globigerinoides fistulosus</td>
<td>83.4</td>
<td>1.73</td>
</tr>
<tr>
<td>FO Globorotalia truncatulinoides</td>
<td>96.1</td>
<td>1.99</td>
</tr>
<tr>
<td>LO Dentoglobigerina altispira</td>
<td>134.8</td>
<td>3.03</td>
</tr>
<tr>
<td>LO Sphaeroidinellopsis seminulina</td>
<td>138.0</td>
<td>3.12</td>
</tr>
<tr>
<td>FO Globorotalia tosaensis</td>
<td>144.4</td>
<td>3.32</td>
</tr>
<tr>
<td>LO Globorotalia plesiotumida</td>
<td>161.1</td>
<td>3.82</td>
</tr>
<tr>
<td>LCO Globorotalia margaritae</td>
<td>166.5</td>
<td>4.06</td>
</tr>
</tbody>
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FO, first occurrence; LO, last occurrence; LCO, last common occurrence.
Fig. 6. Comparisons of the Hm/Gt (Zhang et al., 2007, 2009) and benthic $\delta^{18}O$ (Tian et al., 2002) records expressed on the A2011 timescale and the T2002 timescale (Tian et al., 2002). Hm/Gt (Zhang et al., 2007, 2009) and benthic $\delta^{18}O$ records from the ODP Site 1143 plotted on the (A) original depth, (B) A2011 timescale and (C) T2002 timescale. (D) LR04 benthic $\delta^{18}O$ stack (Lisiecki and Raymo, 2005). Numbers arranged on the benthic $\delta^{18}O$ curves represent the marine isotope stages. Dashed lines show the sedimentary correlations among the original depth, A2011 timescale and T2002 timescale. The arrows show a long-term varying trend of the climate proxies.
Fig. 6. (continued).
this second-order tuning, Hm/Gt maxima (weak summer monsoon) and minima (strong summer monsoon) were correlated cycle-by-cycle with regional minima and maxima in insolation, respectively. This relationship between the Asian monsoon and the insolation has been documented by the $\delta^{18}$O data of the Chinese stalagmites (Wang et al., 2001, 2008; Yuan et al., 2004; Cheng et al., 2009). This astronomical calibration of the small-scale Hm/Gt cycles is unfortunately less straightforward at some intervals, such as at ca 0.6, 0.75, 1.1, 2, 2.95, 3.2, 3.86 and 4.66 Ma. In addition to the correlation between insolation and Hm/Gt curves, therefore, meanwhile the correlation between the insolation cycles and the precession (23-kyr) cycles filtered from the Hm/Gt record was also used to assist the tuning (Fig. 5). The strong precession signals in the Hm/Gt record enabled a detailed correlation between Hm/Gt and insolation records, which constitutes the basis for our refined tuning. An important extra constraint in this second-order tuning, is that the resulting ages should not imply changes in sedimentation rate that are geologically implausible (e.g. too sharp shifts in sedimentation rate), or differ too much from the ages constrained by the magnetostratigraphy, biostratigraphy and first-order tuning. The most likely final correlation is presented in Fig. 5 (see Supplementary Table 1 for the final tie-points we adopted and Supplementary Table 2 for the Hm/Gt and benthic $\delta^{18}$O data expressed on the A2011 timescale). Both the Hm/Gt curve and the precession curve filtered from the Hm/Gt record are well correlated with the insolation curve, with only occasional presence of minor discrepancies (Fig. 5).

During our tuning, we tried various alternative tuning options, which involved different tie-points. However, they did not result in consistent correlations between the benthic $\delta^{18}$O records from the ODP Site 1143 and the LR04 stack on the one hand, or between the Hm/Gt record and the insolation record on the other. These tuning options resulted in either a good correlation between the Hm/Gt record and the insolation record with a rather bad correlation between the ODP Site 1143 and the LR04 stacked $\delta^{18}$O records, or vice versa. Also too sharp shifts in sedimentation rate were the outcome. All these alternatives resulted in correlations which are not convincing and less consistent than the correlations presented in Figs. 4 and 5. Therefore, these alternative tuning options were discarded.

4. Evaluation of the astronomical timescale

After our tuning, the M/B boundary in the ODP Site 1143 has an age of 0.77 Ma, which is consistent with its recent astronomical age of 0.78 Ma (Lourens et al., 2004; Lisiecki and Raymo, 2005). The ages of the planktonic foraminiferal events from the A2011 timescale broadly concur with those of the T2002 timescale (Tian et al., 2002) and with magnetostratigraphic datum levels of other ODP sites (Berggren et al., 1995) (Table 1).

Compared to the T2002 timescale, the present A2011 timescale has several features that indicate improvement. Firstly, visual comparison shows that the tuning of the A2011 timescale is more consistent than of the T2002 timescale. For ages younger than 3.2 Ma, the differences are marginal, no more than 40 kyr (Fig. 6). Before 3.2 Ma, however, differences are more prominent, with differences as much as 160 kyr (Fig. 6). These major differences are interpreted to be mainly due to the ‘over-tuning’ in the T2002 timescale. As suggested by the Hm/Gt and benthic $\delta^{18}$O records (Fig. 6), the 3.2–3.7 Ma interval of the T2002 timescale is over-stretched. Following this overstretched interval, there is an ‘over-compressed’ interval at ca 3.8 Ma, with a sedimentation rate close to an order of magnitude higher than that of its neighboring intervals (Fig. 6). Further back in time, another overly stretched and compressed ‘couple’ occurs at ca 4.2–4.5 and 4.5–4.7 Ma in the T2002 timescale (Fig. 6). In contrast, both the benthic $\delta^{18}$O record and the Hm/Gt record indicate that the A2011 timescale shows a more consistent tuning and is more plausible between 3.2 and 5 Ma than the T2002 timescale, without showing any distinct shifts in sedimentation rate for which there is no reason from lithological observation. The sedimentation rate in the A2011 age model varies smoothly between 1 and 6 cm/kyr.

Secondly, the benthic $\delta^{18}$O record is more consistently expressed in the A2011 timescale than in the T2002 timescale before 3.2 Ma (Fig. 6). For example, the LR04 stack suggests that the marine oxygen isotopic stage (MIS) M2 is the coldest glacial period before 3.2 Ma (Lisiecki and Raymo, 2005) (Fig. 6). This is also the case for the A2011 timescale. In the T2002 timescale, however, MIS MG2 becomes the coldest glacial period before 3.2 Ma (Fig. 6). Apparently, MIS M2 was mistakenly tuned to MIS MG2 in the T2002 timescale. The T2002 timescale reveals several sub-glacial and sub-interglacial stages (as suggested by several regional $\delta^{18}$O maxima and minima) within MIS GI11. However, these sub-glacial and sub-interglacial stages are not revealed by the LR04 stack and the A2011 timescale (Fig. 6). As suggested by the LR04 stack and A2011 timescale, glacial MIS GI26 and NS6 should be colder than their neighboring glacial MIS GI28 and SI2, respectively (Lisiecki and Raymo, 2005) (Fig. 6). In the T2002 timescale, however, MIS GI28 and SI2 are colder than MIS GI26 and NS6, respectively (Fig. 6). Unlike the A2011 timescale, the T2002 timescale also results in some other visible inconsistencies of benthic $\delta^{18}$O (e.g. the subtle characteristics of the marine oxygen isotopic stages) compared with the LR04 stack for ages between 3.2 and 5 Ma, in addition to these inconsistencies we pointed out above (Fig. 6).

Thirdly, the A2011 timescale results in a better (almost cycle-by-cycle) correlation between the Hm/Gt record and the composite Chinese stalagmite $\delta^{18}$O record during the past 400 kyr than the T2002 timescale (Fig. 7). The good correlation between the Hm/Gt record and the composite Chinese stalagmite $\delta^{18}$O record also suggests that Hm/Gt is a good proxy parameter of the Asian summer monsoon intensity. Otherwise, a good correlation between the Hm/Gt record and the composite Chinese stalagmite $\delta^{14}$O record after tuning would be non-existent. Summarizing, we are convinced that the proposed revisions to the ODP Site 1143 timescale are essentially correct. It is based on consistent tuning of continuous sedimentary successions. This tuning has resulted in a more accurate timescale for the Plio-Pleistocene part of the ODP Site 1143.

5. Asian monsoon variability during the Plio-Pleistocene

5.1. Orbital-scale variability of the Asian monsoon

It is well-known that the Asian monsoon circulations result from the reversal of the temperature gradient between the Asian continent and the adjacent oceans (Ding and Liu, 1998; Webster et al., 1998; Clift and Plumb, 2008). However, the underlying forcing mechanisms of the changes in this temperature gradient are still an open question. Both ice volume and solar-insolation changes have been proposed to be possible driving forces of this temperature gradient and thus the Asian monsoon circulations (Kutzbach, 1981; Prell and Kutzbach, 1987, 1992; An et al., 1990; Liu and Ding, 1993; Ding et al., 1995; Ding and Liu, 1998; Liu et al., 1999; Clemens and Prell, 2003; Tian et al., 2004; Yuan et al., 2004; Clemens et al., 2008; Kutzbach et al., 2008; Wang et al., 2008; Cheng et al., 2009). According to the ice volume forcing mechanism (Liu and Ding, 1993; Ding et al., 1995; Liu et al., 1999; Tian et al., 2004), insolation is just an initial factor in driving glacial–interglacial cycles, but not a major forcing factor in driving the orbital cycles of monsoon. This mechanism links the monsoon cycles mainly to the ice-volume cycles. In response to an increased ice volume during glacial stages, the winter monsoon would strengthen, whereas the summer monsoon would weaken. In
response to a decreased ice volume during interglacial stages, the winter and summer monsoon would weaken and strengthen, respectively. In contrast, the solar-insolation mechanism (Kutzbach, 1981; Prell and Kutzbach, 1987; An et al., 1990; Yuan et al., 2004; Ruddiman, 2006a; Kutzbach et al., 2008; Wang et al., 2008; Cheng et al., 2009) directly links the changes in the temperature gradient between land and ocean and in turn the Asian monsoon to changes in the Northern Hemisphere summer insolation. According to this view, the summer monsoon would strengthen in pace with increases in insolation rather than only during each interglacial stage. For example, the Chinese stalagmite δ¹⁸O data reveal an intensified monsoon for the late parts of MIS 6, 8 and 10, which correspond to insolation maxima within glacial stages (Fig. 7). Our tuned Hm/Gt and δ¹⁸O records from the ODP Site 1143 reveal significant differences between the Asian summer monsoon cycles and the glacial–interglacial climate rhythms (Fig. 6). Some strong summer monsoon intervals appear to have also occurred during glacial stages in addition to their increased occurrence during interglacial stages. Vice versa, some notably weak summer monsoon intervals also occurred during interglacial stages next to their anticipated occurrence during glacial stages (Fig. 6). This indicates that the ice-volume mechanism to explain summer monsoon intensification during interglacial stages and weakening during glacial stages may be overly simplistic for South China. As indicated by our study, the orbital cycles in low-latitude hydrological/atmospheric circulation are reasonably independent from the waxing and waning rhythms of the global ice volume. This finding may have profound ramifications for understanding of the forcing mechanism of Asian monsoon changes over orbital scales, as well as the monsoon regions’ ecology and hydrology.

With the T2002 timescale, it is difficult to investigate the orbital changes of the Hm/Gt record during the last 5 Myr (Fig. 2). However, our refined timescale enables an analysis of this issue. The benthic δ¹⁸O records of the ODP Site 1143 and LR04 stack (Lisiecki and Raymo, 2005) show consistent orbital evolution during the last 5 Myr (Fig. 8A and B). Before ca 2.8 Ma the records have a weak obliquity signal (compared to the interval from 2.8 Ma to present), which intensifies significantly after ca 2.8 Ma. Till ca 1 Ma, obliquity is the dominant periodicity, with a notably strong expression of the eccentricity periodicity between 2 and 2.8 Ma. After ca 1 Ma, eccentricity becomes the dominant periodicity instead. Precession signal is very poor throughout the entire last 5-Myr record. Unlike the benthic δ¹⁸O records, the Hm/Gt record from the ODP Site 1143 is characterized by precession cyclicity across the last 5 Myr, with a less important signal of obliquity (Fig. 8C). Both precession and obliquity have slightly stronger power after about 3 Ma, whereas strong eccentricity signals only occur at about 0.7 Ma and between 2.3 and 2.8 Ma (Fig. 8C).
The shift of dominant periodicity from ~41-kyr to ~100-kyr at about 1 Ma revealed by the benthic δ¹⁸O data (Fig. 8A and B) is known as the mid-Pleistocene transition (MPT), which has been widely detected in the marine and continental climate records (see Clark et al., 2006 and references therein). The occurrence of MPT challenges a fundamental tenet of traditional Milankovitch theory, which states that the 65°N summer insolation at the periods of precession and obliquity forces the global climate changes (Milankovitch, 1941; Hays et al., 1976). The enigma of the MPT is that it involved the emergence of ~100-kyr cycles when the insolation does not show a shift of periodicity and the forcing at the eccentricity periodicity is distinctly weaker than the power at precession and obliquity. Therefore, it is difficult to explain the MPT by direct insolation forcing, which is an unresolved issue of Milankovitch theory. It is important that our tuned Hm/Gt record does not show the MPT, with a rather strong precession and a comparatively weak eccentricity during the late Pleistocene instead (Fig. 8C). Consistent with this, low-latitude Asian summer monsoon inferred from the composite Chinese stalagmite δ¹⁸O record (Wang et al., 2001, 2008; Cheng et al., 2009) (Fig. 7D), the pollen record from Lake Biwa in Japan (Nakagawa et al., 2008) and the clay mineral record from the South China Sea (Boulay et al., 2005) were also dominated by precession during the late Pleistocene, with a rather weak eccentricity periodicity. This implies that the MPT may be not recorded in low-latitude Asian monsoon that responds directly to insolation, consistent with the Milankovitch theory. Although the benthic δ¹⁸O record from the same core shows the MPT, it is interpreted as being a signal of high-latitude climate, i.e. the high-latitude ice volume. Our spectral analyses on the terrigenous dust flux in marine sediments from the Arabian Sea (ODP Sites 721/722) (deMenocal et al., 1991; deMenocal, 1995), the subtropical West Africa (ODP Site 659) (Tiedemann et al., 1994) and the eastern Mediterranean Sea (ODP Site 967) (Trauth et al., 2009), which reflect climatic changes in low-latitude Africa during the Plio-Pleistocene, do not reveal a clear MPT as well (Fig. 8D–F). As suggested by the previous studies, the MPT was mostly found in high- and middle-latitude climate records and in (sub-) tropical marine climate records (Ruddiman et al., 1989; Mudelsee and Schulz, 1997; Schmieder et al., 2000; Heslop et al., 2002; Medina-Elizalde and Lea, 2005; Clark et al., 2006; Liu et al., 2008). However, most of the (sub-)tropical marine climate records, such as the records of benthic δ¹⁸O, sea surface temperature and sea level, were actually determined by the high-latitude ice volume dynamics (Hays et al., 1976; Imbrie et al., 1984; Ruddiman, 2003, 2006a,b; Liu and Herbert, 2004). This combined evidence seems to imply that the MPT may reflect processes in high-latitude climate. Its occurrence is therefore possibly restricted to high- and middle-latitude climate records and some climate records retrieved from low-latitudes but which are significantly influenced by high-latitude ice sheet dynamics. In low-latitude monsoonal climate, which varies dominantly and directly in response to changes in insolation with little influence from high-latitude ice dynamics, the MPT likely did not occur. This finding has profound implications for solving the MPT enigma. It supports the proposition that the MPT may be a consequence of long-term cooling of high-latitude climate, especially the increasing global ice volume (Clark et al., 2006; Raymo et al., 2006; Lisiecki and Raymo, 2007).

5.2. Long-term evolution of the Asian monsoon

The ODP Site 1143 Hm/Gt record shows a long-term increasing trend from 2.8 Ma to the present (Fig. 6), which indicates a long-term decreasing trend in low-latitude Asian summer monsoon intensity. This long-term trend in the Asian summer monsoon has also been revealed by mineral magnetic and geochemical studies of the Chinese loess and the Nihewan fluviolacustrine deposits from North China (Chen et al., 2001; Deng et al., 2005, 2006; Ao et al., 2009, 2010c; Ao, 2010). When compared with the benthic δ¹⁸O data from the ODP Site 1143 and the LR04 stack (Fig. 6), the declined trend in the summer monsoon intensity during the past 2.8 Myr is consistent with the onset of Northern Hemisphere glaciation at about 2.8 Ma (Shackleton et al., 1984; Raymo, 1994). Before 2.8 Ma, the global ice volume was dominated by the Southern Hemisphere ice sheets. However, with the occurrence of sustained major Northern Hemisphere glaciation since 2.8 Ma, the Northern Hemisphere ice sheets became dominant instead (Shackleton et al., 1984). In response to the increasing importance of the sustained Northern Hemisphere ice sheets, a long-term decreasing trend in the Asian summer monsoon intensity is expected (Prell and Kutzbach, 1992; An et al., 2001; Clift and Plumb, 2008).

After 2.8 Ma, the Hm/Gt record also has increased amplitudes in its variation upon its long-term increasing trend (Fig. 6), which implies that a larger difference between peaks (stronger monsoon) and troughs (weaker monsoon) is superimposed on the overall weakening trend in summer monsoon intensity. This increased amplitude variability of the summer monsoon may be linked to the occurrence of sustained major ice sheets in the Northern Hemisphere after 2.8 Ma as well, because general-circulation-model simulations suggest that the increased ice volume would increase the sensitivity of the Asian monsoon system, which would in turn increase the oscillation amplitude of the monsoon (Prell and Kutzbach, 1992; deMenocal and Rind, 1993). In addition, the Hm/Gt ratios show an abrupt decrease at ca 2.9–2.8 Ma (Figs. 5 and 6), which presumably suggests an abrupt intensification of the Asian summer monsoon at this time interval.

6. Conclusions

We have formulated a refined 5-Myr astronomical timescale for the ODP Site 1143 by calibration of the benthic δ¹⁸O record to the LR04 stack, and the hematite/goethite ratio, a good estimate of the Asian summer monsoon intensity, to the 65°N summer insolation. It is the strong contribution from the precession signal in the Hm/Gt monsoon proxy that helps to refine the timescale of the ODP Site 1143. In comparison with the T2002 timescale, which was generated by tuning the single benthic δ¹⁸O record to the orbital obliquity and precession (Tian et al., 2002), our combined tuning of monsoon and isotope curves for the development of the present A2011 timescale results in a more accurate and robust chronology.

Fig. 8. Orbital evolution of the Plio-Pleistocene Asian summer monsoon, African climate and global ice volume suggested by evolutionary spectral analysis of the LR04 benthic δ¹⁸O stack and the climate records from the ODP Sites 1143, 721/722, 659 and 967. (A) LR04 stack of benthic δ¹⁸O (Lisiecki and Raymo, 2005). (B) benthic δ¹⁸O (Tian et al., 2002) and (C) Hm/Gt (Zhang et al., 2007, 2009) records from the ODP Site 1143 plotted on the A2011 timescale. (E) Terrigenous dust records from ODP Sites 721/722 (deMenocal et al., 1991; deMenocal, 1995), 659 (Tiedemann et al., 1994) and 967 (Trauth et al., 2009). The evolutionary spectral analysis was performed by the Matlab software package developed by Grinsted et al. (2004). The stronger periodicities have darker red colors (higher intensity), while the weaker periodicities have lighter blue colors (lower intensity). The regions enclosed by thick contours are calculated confidence levels with a significance of >95% using a red-noise process with a lag-1 autocorrelation coefficient. Regions that are influenced by edge effects of the time series are plotted with lighter shades at the beginning and end of the frequency-time plane. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Comparison of the parallel Hm/Gt and δ18O data from the ODP Site 1143 suggests considerable differences between fluctuations in Asian summer monsoon intensity and the glacial–interglacial climate cycles. This indicates that the popular view of summer monsoon intensification during interglacial stages and weakening during glacial stages may be overly simplistic for low-latitude areas. The well-known MPT is only identified in the δ18O record but not in the Hm/Gt record from the same core. This indicates that the MPT may be a feature of high- and middle-latitude climates that is ‘inherited’ in this core. The expression of the MPT is less likely to occur in low-latitude monsoonal climates, in which the orbital variations are more directly forced by insolation. In addition, low-latitude Asian summer monsoon intensity shows a long-term decreasing trend since 2.8 Ma with increased oscillation amplitude, which is presumably linked to the development of sustained major ice sheets in the Northern Hemisphere after 2.8 Ma. The present study has ignored other possible influences on the Hm/Gt record such as the changes in provenance. Future more detailed studies such as reconstruction of long-term high-resolution climate records from South China Sea and other continental areas of low-latitude Asia and climate-model simulations are crucial for testing our conclusions.

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Appendix. Supplementary data
Supplementary data related to this article can be found online at doi:10.1016/j.quascirev.2011.04.009.

References


