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History and Prediction of the Asian Monsoon and Glacial Terminations, Based on Records from the South China Sea

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1. Introduction

What caused the global ice sheets to come and go? Knowledge of this question is crucial for understanding global climate evolution and predicting future climate changes. Since the 1840s, when geologists firstly noted the expansion and retreat of ice sheets on land, scientists have been trying to solve this question. Although at present it is generally thought that the glacial cycles are driven by changes in solar insolation due to subtle variations in Earth's orbit parameters (Milankovitch, 1941; Hays et al., 1976; Imbrie et al., 1992), the mechanism by which and the degree to which insolation plays a role on the glacial terminations remains unclear. For example, if glacial cycles vary directly in response to insolation, why do glacial terminations not occur at every time of increasing insolation?

The benthic $\delta^{18}O$ in the ocean is known to increase with glaciation and thus can be used to estimate the global ice-volume changes (Hays et al., 1976; Imbrie et al., 1984; Ruddiman, 2003). Therefore, precise timing of the benthic $\delta^{18}O$ records is crucial for testing the exact relationship between glacial terminations and changes in insolation. Generally, a record of benthic $\delta^{18}O$ versus depth was transformed into a record versus time by tuning the benthic $\delta^{18}O$ record to the Earth's orbital parameters (e.g. Imbrie et al., 1984; Ruddiman et al., 1986; Raymo et al., 1989; Shackleton et al., 1990; Lisiecki and Raymo, 2005). However, it is problematic to discuss the linkage between glacial termination and solar insolation based on the astronomical chronology because of the risk of circular reasoning. In the present study, therefore a different procedure independent of orbital tuning was adopted to establish the timescale for the late Quaternary benthic $\delta^{18}O$ record retrieved from Ocean Drilling Program (ODP) Site 1143, southern South China Sea (Fig. 1). On the one hand, Zhang et al. (2007) recently published a high-resolution Asian summer monsoon record over the last 600 kyr using the ratio of hematite to goethite contents (Hm/Gt) from this site. On the other hand, the high-resolution (from orbital down to millennial) variations in Asian summer monsoon in South China over the last 350 kyr are now available from the $\delta^{18}O$ of stalagmites from caves, which were accurately dated by high-resolution U-series analyses (Wang et al., 2001, 2005, 2008; Yuan et al., 2004; Zhang et al., 2008; Cheng et al., 2009). The stalagmite $\delta^{18}O$

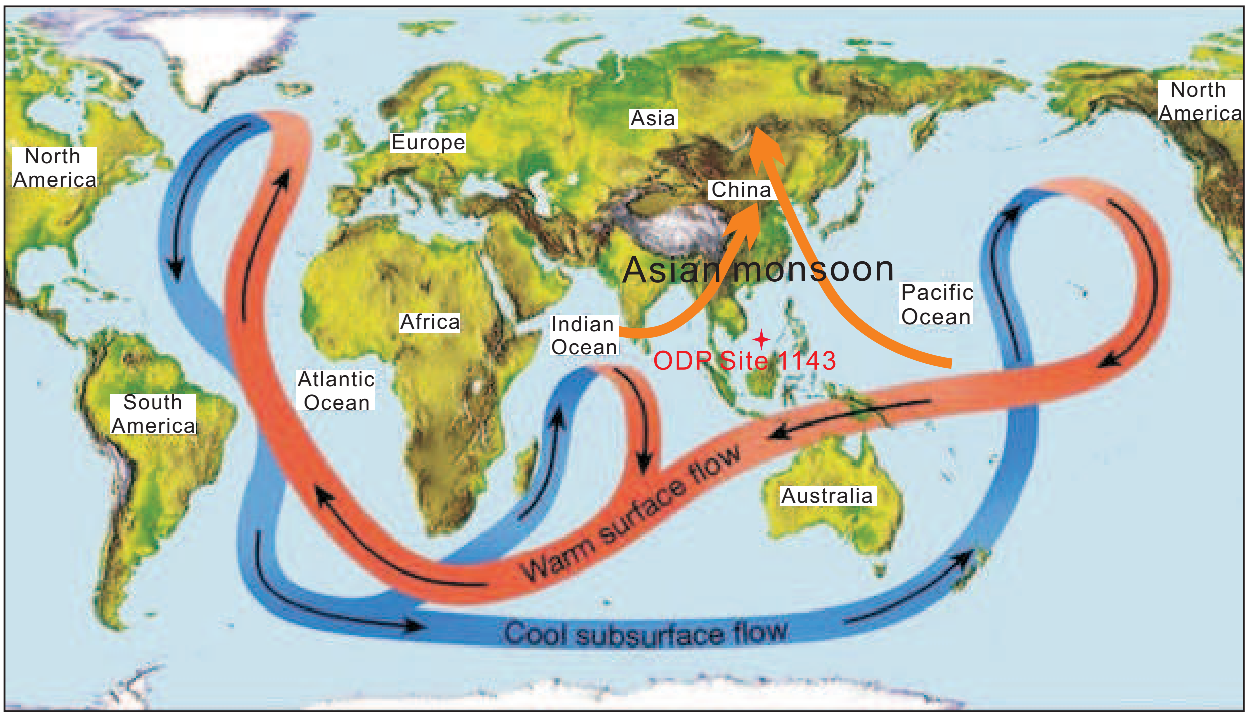

Fig. 1. Map showing the ocean circulation, Asian monsoon and ODP Site 1143 (modified from Friedland (2010)). The orange arrows represent the directions of the Asian summer monsoon.

record is the most accurately dated monsoon record on the relevant 100-kyr time scale, with errors of mere decades. Since both the Hm/Gt record from South China Sea and the stalagmite $\delta^{18}O$ record from South China are good estimates of variations in Asian summer monsoon with similar orbital cycles, we formulate a timescale for ODP Site 1143 over the last 350 kyr by calibrating the Hm/Gt record to the Chinese stalagmite $\delta^{18}O$ record (Wang, et al., 2001, 2008; Cheng, et al., 2009) instead of the orbital parameters as usual. In particular, we test the extent to which the last four terminations as well as the Asian monsoon are linked to solar insolation, based on this orbital-independent timescale without involving in circular reasoning. In addition, the observed late Quaternary relationship between insolation and climate further provide clues for predicting further climate changes.

2. General setting

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). The South China Sea is the largest marginal sea of the western Pacific, covering an area of ~3.5×10^{6} km^2. The seasonal reversal of Asian winter and summer monsoon circulations results 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 Borneo, the sea surface salinity (SSS) in the southern South China Sea is rather low, ranging from ca. 30‰ to 34‰ (Tian et al., 2004). The SSS 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 ODP Site 1143 mainly consist of terrigenous quartz, feldspar and clay minerals, with only a minor biogenic component (<2%) (Wan et al., 2006).

3. Monsoon proxies and chronology

Hematite (Hm) and goethite (Gt) contents over the last 600 kyr (from 0 to 34 m) were assembled by Zhang et al. (2007) for 315 samples from ODP Site 1143 using a Perkin Elmer Lambda 900 diffuse reflectance spectrophotometer in the Surficial Geochemistry Institute of Nanjing University (China). The average resolution of the iron oxides record is ~2 kyr. For the present study of interest, our age calibration is just based on the interval spanning the last 350 kyr (from 0 to 22.1 m) (Fig. 2). The Hm/Gt ratios of ODP Site 1143 can be used as an indicator of summer monsoon intensity because of the following reasons. (1) During chemical weathering, the relative abundance of goethite to hematite varies with climatic conditions: dry and humid conditions are more favorable for the formation of hematite and goethite, respectively (Curi and Franzmeier, 1984; da Motta and Kampf, 1992; Harris and Mix, 1999; Thiry, 2000; Ji et al., 2004; Zhang et al., 2007). (2) The terrigenous deposits, including hematite and goethite, in ODP Site 1143 are mainly derived from the paleo-Sunda shelf and Mekong Basin through fluvial and marine transportation, with a discharge more than 160×10^6 tons of sediment per year (Milliman and Meade, 1983; Wan et al., 2006). Other rivers such as the Baram River from northwest Borneo and the Chao Phraya River from western Indochina have a combined annual sediment discharge less than 23×10^6 tons to the southwest South China Sea (Wan et al., 2006). (3) Hematite and goethite in ODP Site 1143 are little affected by diagenesis after burial (Zhang et al., 2007, 2009; Ao et al., 2011a). (4) The dry and humid conditions over the South China Sea are mainly modulated by Asian summer monsoon precipitation (Tian et al., 2004, 2005; Wan et al., 2006; Zhang et al., 2007; Clift and Plumb, 2008). 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.

The present timescale for the last 350 kyr as recorded in ODP Site 1143 was established by calibration of the Hm/Gt record to the composited Chinese stalagmite $\delta^{18}O$ record (Wang et al., 2001, 2008; Cheng et al., 2009), because both of them are interpreted as a summer monsoon proxy in South China. This calibration involves downward matches between the Hm/Gt record and the stalagmite $\delta^{18}O$ record (Fig. 2). The strong precession signal in both Hm/Gt and stalagmite $\delta^{18}O$ records guarantees a precise age determination for ODP Site 1143. After our final calibration, the Hm/Gt record was correlated almost cycle-by-cycle with the stalagmite $\delta^{18}O$ record (Fig. 2A–C). Their filtered precession cycles also matched well (Fig. 2D).

4. Discussion

Like the Chinese stalagmite $\delta^{18}O$ record, the Hm/Gt record plotted on our resulted timescale has a good correlation with the solar insolation (Fig. 3 A–C). This is consistent with the response of the Asian summer monsoon in South China to the insolation forcing (Kutzbach, 1981; Wang et al., 2008; Ao et al., 2011b). As indicated by maxima in the benthic $\delta^{18}O$ record from ODP Site 1143, the onsets of the major glacial terminations IV, III, II and I are around 340, 250, 135 and 20 ka, respectively (Fig. 3D). These ages are generally consistent with the recent astronomical estimates for these terminations (Lisiecki and Raymo, 2005). Comparison of the benthic $\delta^{18}O$ record to the summer insolation indicates that all the last four glacial terminations occurred when insolation rose from an outstanding minimum to a prominent maximum (Fig. 3). This is consistent with the primary forcing of glacial

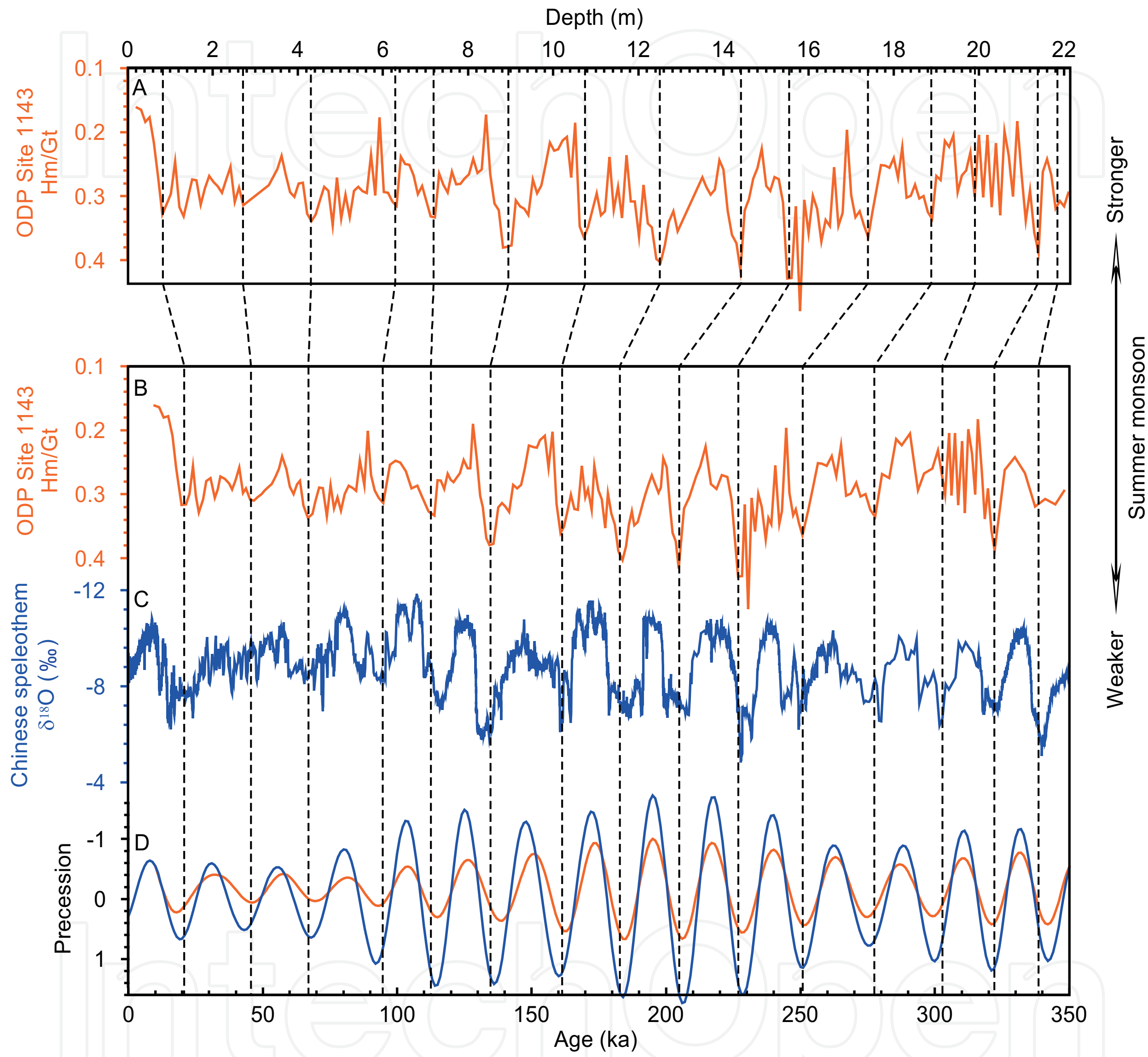

Fig. 2. (A) Hm/Gt record (Zhang et al., 2007) from ODP Site 1143 plotted against depth. (B) Hm/Gt record (Zhang et al., 2007) plotted against our calibrated timescale. (C) Composited Chinese stalagmite $\delta^{18}O$ record (from the Sanbao, Linzhu, Dongge and Hulu caves) (Wang, et al., 2001, 2008; Cheng, et al., 2009). (D) Comparison of filtered precession bands filtered from our calibrated Hm/Gt (orange line) and the composited Chinese stalagmite $\delta^{18}O$ (blue line) records.

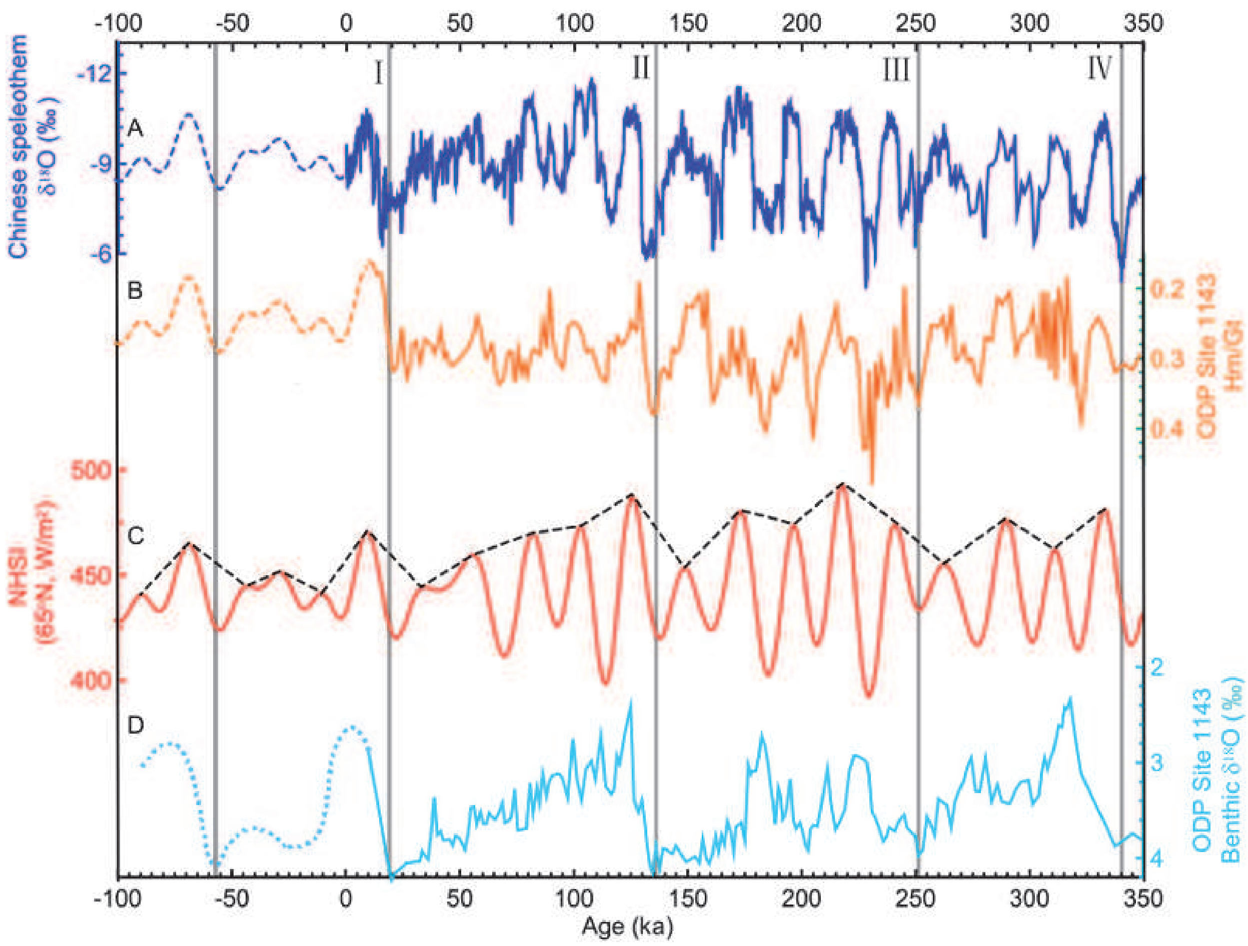

Fig. 3. (A) Composited Chinese stalagmite $\delta^{18}O$ record (from the Sanbao, Linzhu, Dongge and Hulu caves) (Wang, et al., 2001, 2008; Cheng, et al., 2009). (B) Hm/Gt record from ODP Site 1143 (Zhang et al., 2007) plotted against the presently calibrated timescale. (C) 65°N summer insolation (Laskar et al., 2004). The black dashed line joins the maximum of insolation. (D) Benthic $\delta^{18}O$ record (Tian et al., 2002) from ODP Site 1143 plotted on our calibrated timescale. The vertical shaded lines indicate the onset of terminations revealed by the benthic $\delta^{18}O$ record from ODP Site 1143. Terminations are labeled using greek numerals.

terminations by summer insolation, as pointed out by the Milankovitch orbital theory (Milankovitch, 1941). In addition, we noted the following insolation pattern leading up to the glacial terminations: a series of decreased insolation maximum followed by a relatively sharp increase in insolation maximum (Fig. 3). A series of decreased insolation maximum would favor the accumulation of massive ice sheets prior to termination (Broecker, 1984; Peltier, 1994; Raymo, 1997), whose collapse was triggered by a following sharp rise in insolation. This can partly explain why the glacial cycles show a gradual buildup but a rapid collapse. This following insolation maximum, which is generally higher than its nearby insolation maxima, may imply an insolation threshold for triggering a glacial termination (Fig. 3). This is in agreement with the recent view that the amount and rate of insolation rise are important controls on the glacial terminations (Cheng et al., 2009). The insolation maxima may have played a more important role on the ice-age cycles than the insolation minima (Fig. 3C).
In agreement with recent studies (Wu et al., 2005; Cheng et al., 2006, 2009), the Hm/Gt and benthic $\delta^{18}O$ records from ODP Site 1143 suggested that each termination occurred when the

summer monsoon intensity rose from a minimum to a maximum (Fig. 3). This observation implies that the rising summer monsoon intensity may have played a role in driving the termination to completion to some extent, because the summer monsoon, which transports heat from tropical oceans to the Asian mainland, is expected to lead to a rather warm environment and thus promote the snow-cover meltdowns in Asia (Fig. 1). Furthermore, the summer monsoon would favor the vegetation and wetland covers in Asia, which may in turn produce increased greenhouse gases such as CO_2 and CH_4. The feedback effects of the greenhouse gases are widely regarded as a potentially important player in glacial terminations (Petit et al., 1999; Ruddiman, 2003, 2006; Cheng et al., 2009). Likewise, the ocean circulation may have played an important role on the ice-sheet meltdowns as well, because it is considered as a very important heat transport in Northern Hemisphere (Fig. 1). It transports very warm tropical water to the Northern Hemisphere and warms the air during the transportation. Thus it may have an appreciable impact on the ice-cover meltdowns in Northern Hemisphere. Although the Northern Hemisphere summer insolation intensity is the primary trigger of an initial retreat of northern ice sheets, the modulating impacts from the monsoon system (including not only Asian monsoon, but also African and North American monsoons) and ocean circulation may be much more important than the presently thought (Fig. 1), which should be investigated in detail in future studies of the ice-age terminations.

The observed relationship between insolation and climate during the late Quaternary may provide clues for predicting further climate changes. The insolation from now to the future 100 kyr will be similar to the last 100-kyr insolation behavior (Fig. 3C). Since the Asian summer monsoon is correlated cycle-by-cycle to the insolation during the past 100 kyr, a monsoon behavior similar to the insolation is anticipated to occur during the following 100 kyr. Because outstanding insolation maximum during the Holocene has been over and an insolation minimum is coming, a weak summer monsoon interval may come soon instead of the present Holocene strong summer monsoon period (Fig. 3 A–C). An insolation maximum comparable to the Holocene insolation maximum will appear ca. 70 kyr from now, thus a strong summer monsoon interval comparable to the Holocene strong summer monsoon interval will possibly not occur until then (Fig. 3 A–C). Relatively weakened summer monsoon maxima are likely to occur at ca. 10, 30 and 50 kyr from now, which are correlated to less outstanding insolation maxima of these intervals (Fig. 3 A–C).

As suggested by the benthic $\delta^{18}O$ record from ODP Site 1143, we are presently living within an interglacial period (Fig. 3D). The following insolation maxima at 10 and 30 kyr from now are much lower than these during the last 350 kyr. Thus the present interglacial period will possibly continue shorter than the previous interglacial periods (Fig. 3C, D). This shortened interglacial period will be gradually replaced by a glacial period starting from ca. 10 kyr from now. Subsequently, the next glacial termination will occur at ca. 60 kyr from now when the insolation increases from an outstanding minimum to a prominent maximum, which will be followed by an interglacial period comparable to the present interglacial period. This prediction is consistent with the prediction of Raymo (1997) but in contrast to the predictions of Berger and Loutre (1997) and Ledley (1995). Note that the insolation maximum at ca. 70 kyr from now is much higher than its nearby insolation maxima (Fig. 3C), which should be considered as an insolation threshold for triggering this termination.

5. Conclusions

An orbital-independent timescale for ODP Site 1143 over the last 350 kyr was established by calibration of the Hm/Gt record to the Chinese stalagmite $\delta^{18}O$ record. This resulted timescale enabled a detailed study of the Asian monsoon and glacial terminations and their links with solar insolation during the late Pleistocene. Consistent with the insolation forcing of orbital-scale variability of Asian monsoon in South China suggested by recent studies (Kutzbach, 1981; Wang et al., 2008; Ao et al., 2011b), the Hm/Gt record plotted on our timescale has a good correlation with the solar insolation. The glacial terminations, which are determined by independence of orbital tuned results, generally occurred when insolation rises from an outstanding minimum to a prominent maximum, consistent with a classic summer insolation increase trigger for an initial retreat of northern ice sheets or snow covers. In addition to the primary insolation forcing, the monsoon system and ocean circulation may have played a potentially important modulating role on the glacial terminations as well. Combining the late Quaternary relationship between insolation and climate, we predict that the present warm interglacial periods with strong summer monsoon will gradually develop into a cold glacial period with weakened summer monsoon thousands of years later and the next glacial termination will occur ~60 kyr from now. The next interglacial period with a strong summer monsoon period comparable to that of the Holocene will probably occur ca. 70 kyr from now. If this prediction is true, the coming glacial period with weakened summer monsoon is likely to result in a rather cold period thousands of years later, which then may entirely shut down the present global warming. If so, the presently increasing greenhouse gases are probably helpful for human to adapt the following cold glacial period at a long-term timescale such as millennial and orbital timescales, although the current global warming due to accumulation of greenhouse gases is likely to result in some potentially devastating consequences for humans at a short-term timescale such as the next few hundred years. Therefore, using climate-model simulations to test our climate prediction should be a priority in future investigations on this topic.

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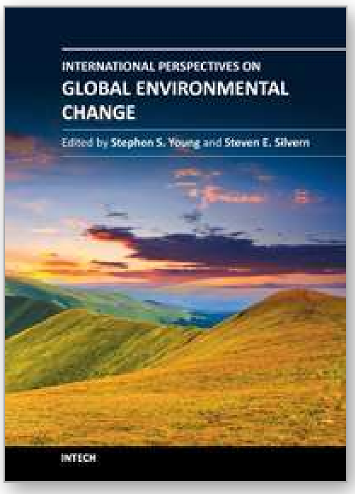

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