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Sea-level rises at Heinrich stadials of early Marine Isotope Stage 3: Evidence of terrigenous *n*-alkane input in the southern South China Sea

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ABSTRACT

The timing of suborbital-scale sea-level fluctuations within Marine Isotope Stage 3 (MIS 3) remains a matter of debate. We use a set of co-registered signals of the sediment core MD05-2897 from the southern South China Sea (SCS) to evaluate the phase relationship between sea-level fluctuations and climatic events during early MIS 3. During Heinrich Stadials 6, 5a and 5 (HS6, HS5a, HS5), planktonic foraminiferal $\delta^{18}O$ values of core MD05-2897 increased by 0.8–1.0‰ due to an enrichment of $\delta^{18}O$ in precipitation and/or a reduction of monsoon precipitation. The alkenone-derived sea surface temperature ($U^{K'}_{37}$-SST) recorded 1.0–2.0 °C cooling signatures during wintertime of HS6, HS5a and HS5, which were attributed to a stronger influx of cold surface waters from the northern SCS driven by the strengthened winter monsoon. Therefore, a combination of foraminiferal $\delta^{18}O$ and $U^{K'}_{37}$-SST results well documents these Heinrich stadials of the East Asian monsoon climate. Moreover, we find that the terrigenous *n*-alkane abundance of core MD05-2897, which is independent of changes in vegetation types around the southern SCS throughout MIS 3, is potentially an indicator for relative sea-level changes on suborbital timescale. The *n*-alkane abundance was relatively higher during the first half of HS6, HS5a and HS5 and afterward significantly decreased during the second half of these Heinrich stadials. This may suggest relatively lower sea level at the beginning of Heinrich stadials and sea-level rises afterward. Our new results add to the growing body of evidence that the timing of millennial-scale sea-level rises during early MIS 3 was simultaneous with Heinrich stadials.

1. Introduction

Greenland ice core records have revealed that MIS 3 (60,000–25,000 years before present) was a time period of highly climatic instability in the Northern Hemisphere high latitude. It was characterized by a series of alternating warm interstadials (known as Dansgaard–Oeschger events) and cold stadials (e.g. Johnsen et al., 1992; Dansgaard et al., 1993; North Greenland Ice Core Project members, 2004). These substantial millennial-scale climatic oscillations occurred when the global ice sheets were at an intermediate size during MIS 3. However, when the global ice volume reached its maximum size at the Last Glacial Maximum or its minimum size during the Holocene over the last glacial–interglacial cycle, the climate system was relatively stable on millennial-to-centennial time scales. Moreover, the most rigorous stadials recorded in Greenland ice cores were always associated with massive iceberg discharges from the subarctic regions and ice-rafted debris deposition in the northern North Atlantic, the so-called Heinrich events (Hemming, 2004 and references therein). These two lines of evidence imply that a proper size and changes in the accumulation–ablation phasing of ice sheets might have played an important role in triggering and/or amplifying millennial-scale climate variability during MIS 3 (e.g. Schmittner et al., 2002; Flückiger et al., 2006; Clark et al., 2007). Therefore, understanding the dynamics of ice sheets during MIS 3 would favor the decipherment of the forcing mechanisms of millennial-scale climatic instability. As the wax and wane of ice sheets were recorded as the fall and rise of global sea level, respectively, it becomes crucial to constrain the magnitude and the timing of sea-level changes within MIS 3.

The average sea level during the first and the second half of MIS 3 was estimated to be 60 m and 80 m lower than the present, respectively (Siddall et al., 2008). The first unambiguous evidence regarding millennial-scale sea-level fluctuations within MIS 3 was derived from a deep-sea sediment core in the North Atlantic (Shackleton et al., 2000). In this core planktonic foraminiferal $\delta^{18}O$ remarkably resembles climate records from Greenland, which was thus aligned to Greenland ice core records to develop an age model. Parallel benthic foraminiferal $\delta^{18}O$ from the same core, however, shows strong similarities to climate records from Antarctic ice cores. Millennial-scale variability of benthic foraminiferal $\delta^{18}O$ during MIS 3 was found coincident with Antarctic climate events A1–A4 (e.g., EPICA Community Members, 2006). Although benthic foraminiferal $\delta^{18}O$

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possibly included signals of bottom-water temperature variations, it suggests that MIS 3 sea level might have undergone substantial changes on millennial timescale, following an Antarctic-style rhythm and timing (Shackleton et al., 2000). Sea-level rises on suborbital timescale occurred during Antarctic warm periods, which thus corresponded to the Northern Hemisphere cold periods due to the bipolar seesaw pattern between Greenland and Antarctic climate records (Blunier and Brook, 2001).

This observation was subsequently confirmed by absolute-dating results on coral terraces from Huon Peninsula (Yokoyama et al., 2001; Chappell, 2002). Fossil coral records further corroborated four sea-level rises within MIS 3; each was at an order of 10–15 m and lasted for 1000–2000 years, corresponding to a Heinrich event in the North Atlantic. A sea-level reconstruction from the central Red Sea reproduced these four millennial-scale sea-level fluctuations, which superimposed on long-term sea-level changes during early–middle MIS 3 (Siddall et al., 2003). However, sea-level rises were estimated to be up to 35 ± 12 m but also synchronous with Northern Hemisphere Heinrich Stadials 6, 5a, 5 and 4 (HS6, HS5a, HS5, HS4), respectively (Siddall et al., 2003, 2008; Rohling et al., 2008). Some indirect evidence reach a similar conclusion, e.g., salt marsh vegetation along the coast of Cariaco Basin significantly expanded during Heinrich stadials of early–middle MIS 3, which was considered to be induced by rapid sea-level rises (González and Dupont, 2009). Observations and model studies suggested that the melt-water accounted for sea-level rises over Heinrich stadials dominantly originated from the Northern Hemisphere ice sheets (Knutti et al., 2004; Hill et al., 2006; Clark et al., 2007), or was equally contributed by the Northern Hemisphere and the Antarctic ice sheets (Rohling et al., 2004).

Although an increasing number of evidence support the idea that suborbital sea-level rises within MIS 3 were coeval with Heinrich stadials, other reconstructions suggest a different phase relationship between climatic events and sea-level changes during MIS 3. Based on radiocarbon dating results and geomagnetic paleointensity correlations, Arz et al. (2007) developed an independent age model for a sea-level reconstruction from the northern Red Sea. They found that a number of pronounced sea-level rises on millennial timescale during MIS 3 were concurrent with warm interstadials recorded in Greenland ice cores rather than cold stadials (Arz et al., 2007). A recent high-resolution record from the Mediterranean continental shelf also recognized five sea-level rises during MIS 3, which corresponded to the five warmest Greenland interstadials, respectively (Sierro et al., 2009). Therefore, the conflicting evidence demonstrates that a convincing timing for millennial-scale sea-level fluctuations within MIS 3 has not yet been established.

Due to limits of the accuracy of age models, it is difficult to establish millennial-scale phase relationships between different climate parameters, based on proxy records from different archives and locations. One solution is to develop proxy records representing sea-level changes and other climate parameters, respectively, from the same paleoclimate archive. Therefore, the evaluation of phase relationships between different climate parameters could be independent of age models through use of this kind of co-registered signals (e.g., Rohling et al., 2008). In this manuscript we present a set of parallel climatic proxy records of a sediment core MD05-2897 from the southern South China Sea (SCS). We find that both planktonic foraminiferal $\delta^{18}O$ and alkenone-derived sea surface temperature ($U^{K'}_{37}$-SST) records of core MD05-2897 well characterize a few Heinrich stadials of the East Asian monsoon climate during early MIS 3, while the terrigenous *n*-alkane abundance from the same core seems to be an indicator for local sea-level fluctuations in the past. By comparing millennial-scale variations in different proxy records, we attempt to evaluate the phase relationship between climatic events and sea-level changes during MIS 3.

2. Oceanographic setting and proxy variable used for indicating local sea-level changes

As the largest semi-enclosed marginal basin in the western Pacific Ocean, the SCS is surrounded by vast and shallow continental shelves. Hence, the morphology of the SCS is highly sensitive to the eustatic sea-level changes over glacial–interglacial cycles. For example, during the Last Glacial Maximum when sea level was more than 120 m lower than the present (Hanebuth et al., 2000), the SCS nearly lost its half surface area as a result of shelf exposure. The most prominent change in the paleogeography of the glacial SCS was the emergence of the Sunda Shelf, one of the largest continental shelves in the world (Fig. 1, Hanebuth et al., 2011). The Sunda Shelf is a tectonically stable craton, consisting of the southern shelf of the SCS, the Gulf of Thailand and the Java Sea, covering an area of 1.85×10^6 km^2 with a very low slope gradient (Tjia, 1980).

The modern SCS is also characterized as a catchment for more than ten river systems drained from East Asia and surrounding islands (Fig. 1, Liu et al., 2009). The emerged Sunda Shelf during the last glaciation was also drained by several paleo-river systems, including the East Sunda river, the North Sunda river (= Molengraaff River), the Thai paleo-fluvial systems and the Paleo-Mekong river (Fig. 1, Tjia, 1980; Molengraaff, 1921; Voris, 2000). Most river systems have large drainage areas influenced by strong monsoon precipitation, which discharge immense amounts of sediments to the SCS basin.

Downcore investigations have revealed that the fluvial matter is the main composition of the SCS sediments (Liu et al., 2009), e.g., in the southern SCS below 100 m water depth, the terrigenous input contributes 78.8% and 85.4% to the Holocene and the Last Glacial Maximum sediments, respectively (Liu et al., 2009). The vast majority of the terrigenous input is river-borne sediments from the Mekong River, northern Borneo and Indonesian volcanic arcs (Liu et al., 2009), while wind-blown dust is negligible (Wang et al., 1999). The Last Glacial Maximum sedimentation rates in the southern SCS were nearly 1.5 times as high as during the postglacial time, as the fluvial input increased during the last glacial period while the biogenic carbonate flux nearly remained constant over the last glacial–interglacial cycle (Liu et al., 2009). An increase in the glacial fluvial input is considered to have resulted from the erosion of the newly emerged shelves and a direct transfer of large amounts of fluvial matter to the deep SCS basin during glacial sea-level low (Wang, 1999; Steinke et al., 2003). Accordingly, the input of river-borne sediments to the SCS basin is first orderly controlled by sea-level changes, and fluvial discharge to a specific core location could in turn be used to indicate local sea-level changes.

Long, straight-chain *n*-alkanes in marine sediments mainly originated from leaf waxes of higher-land plants through the transportation of wind and water (Eglinton and Hamilton, 1967). Owing to their water insolubility, chemical inertness and strong resistance to biodegradation, *n*-alkanes are reliable proxies to study terrigenous input to aquatic environments (Eglinton and Eglinton, 2008). In the SCS, *n*-alkane contents in sediments were found to be highly relevant to sea-level changes for the last three glacial–interglacial cycles, with higher concentrations during glacial sea-level low and lower concentrations during interglacial sea-level high (Pelejero et al., 1999a, 1999b; Hu et al., 2003; Pelejero, 2003; He et al., 2008). Moreover, changes in concentrations of *n*-alkanes are able to reflect sea-level fluctuations on shorter time scales, e.g., the dramatic sea-level rise during the melt-water-pulse 1A event of the last deglaciation (at about ~14.6 ka BP) is explicitly expressed as an abrupt and significant decrease in the *n*-nonacosane concentrations both in the northern and southern SCS sediment cores (Pelejero et al., 1999b; Kienast et al., 2003). We therefore attempt to use the *n*-alkane concentration in bulk sediments to indicate millennial-scale sea-level fluctuations in the southern SCS during early MIS 3.