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On the timing and forcing mechanisms of late Pleistocene glacial terminations: Insights from a new high-resolution benthic stable oxygen isotope record of the eastern Mediterranean

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A B S T R A C T

Benthic oxygen isotope records of deep marine sedimentary archives have yielded a wealth of information regarding ice sheet dynamics and climate change during the Pleistocene. However, since they often lack independent age control, these records are generally bound by a fixed phase relationship between orbital forcing and the climate response, e.g. ice volume changes. We present the first long (~1.2 Ma) benthic oxygen isotope record from the eastern Mediterranean, based on ODP Sites 967 and 968, which clearly reflects the behavior of global climate on a glacial–interglacial scale throughout the late Pleistocene time period. The age model for our record is based on tuning the elemental ratio of titanium versus aluminum (Ti/Al) against insolation. The Ti/Al record is dominated by the precession-related changes in northern African climate, i.e. monsoonal forcing, and hence largely independent of glacial–interglacial variability. We found the largest offset between our chronology and that of the widely applied, open ocean stacked record LR04 (Lisiecki and Raymo, 2005) for T_{VII} (~624 ka), which occurred ~9 kyr earlier according to our estimates, though in agreement with the AICC2012 δD_{ice} chronology of EPICA Dome C (Bazin et al., 2013). Spectral cross-correlation analysis between our benthic $\delta^{18}O$ record and 65°N summer insolation reveals significant amounts of power in the obliquity and precession range, with an average lag of 5.5 ± 0.8 kyr for obliquity, and 6.0 ± 1.0 kyr for precession. In addition, our results show that the obliquity-related time lag was smaller (3.0 ± 3.3 kyr) prior to ~900 ka than after (5.7 ± 1.1 kyr), suggesting that on average the glacial response time to obliquity forcing increased during the mid-Pleistocene transition, much later than assumed by Lisiecki and Raymo (2005). Finally, we found that almost all glacial terminations have a consistent phase relationship of ~45 ± 45° with respect to the precession and obliquity-driven increases in 65°N summer insolation, consistent with the general consensus that both obliquity and precession are important for deglaciation during the Late Pleistocene. Exceptions are glacial terminations T_{IIIb}, T_{36} and potentially T_{32} (and T_{VII} T_{24} and T_{34}), which show this consistent phase relationship only with precession (only with obliquity). Our findings point towards an early (>1200 ka) onset of the Mid Pleistocene Transition. Vice versa, the timing of T_{VII}, which can only be explained as a response to obliquity forcing, indicates that the transition lasted until at least after MIS 15.

1. Introduction

The global climate state shifted through the past 1 million years (Myr) of Earth's history from a predominantly obliquity driven glacial–interglacial mode towards a pronounced 100-kyr glacial–interglacial rhythm (Imbrie et al., 1993; Tiedemann et al., 1994; Lisiecki and Raymo, 2005). This transition is known as the Mid Pleistocene Transition (MPT) and its origin is still under debate (e.g Clark et al., 2006; Maslin and Ridgewell, 2005). Part of the discussion relates to the fact that the benthic foraminiferal $\delta^{18}O$ isotope record – reflecting both changes in deep sea water temperatures and the isotopic composition of sea water through the uptake of isotopically light water in ice sheets – behaves inconsistently with respect to the astronomical cycles of precession and obliquity, which are considered as the major forcing mechanisms of the glacial–interglacial variability during this time period (Hays

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et al., 1976; Imbrie et al., 1993; Tiedemann et al., 1994; Lisiecki and Raymo, 2005). The available knowledge of how climate and ice sheets respond to the precession and obliquity-driven insolation usually stems from the last and penultimate glacial–interglacial transitions, which are well constrained by highly detailed records that are readily datable using radiocarbon or other absolute methods (e.g. Lourens et al., 1996; Martrat, 2004; Lemieux-Dudon et al., 2010). This inferred knowledge about climate response to insolation forcing has generally been extrapolated into the past. In other words, a predefined relationship is used to tune the benthic foraminiferal $\delta^{18}O$ isotope record to insolation forcing using a fixed phase lag between the data and the target curve, generally represented by a simple ice-sheet model (e.g. Shackleton et al., 1990; Lisiecki and Raymo, 2005).

With the availability of long and high quality records, Lisiecki and Raymo (2005) established a state of the art marine isotope chronology based on 57 benthic isotope records, spanning the last 5.3 Ma: the LR04 benthic oxygen isotope stack. This high-resolution reconstruction of global climate is the current global standard for correlating marine isotopic records as well as many other climate reconstructions (e.g. Bintanja et al., 2005; Wolff et al., 2006; Parrenin et al., 2007; Tzedakis, 2007). The age model for the LR04 benthic stack was established by tuning the linear components to a simple ice sheet model (Imbrie and Imbrie, 1980). In this model it is assumed that the phase lags in ice sheet response at the frequencies of obliquity and precession are those of a single exponential system (Imbrie and Imbrie, 1980; Imbrie et al., 1984; Lisiecki and Raymo, 2005). The ice-sheet model (1) is forced by the 21 June 65°N insolation curve (Laskar et al., 1993; ‘x’ in equation (1)), taking into account an ice sheet response time (Tm) of 15 kyr and a nonlinearity coefficient b of 0.6. These values are based on radiometric dating of the penultimate glacial cycle (Imbrie and Imbrie, 1980) and kept constant for the last 1500 kyr (Lisiecki and Raymo, 2005).

$$dy/dt \;=\; (1 \pm b)/Tm\,(x - y) \tag{1}$$

The change in ice volume over time (dy/dt) therefore depends on the insolation forcing × versus present ice volume y, with nonlinearity constant b switching signs: it is negative while ice is growing and positive when the ice sheets decay (i.e. when dy/dt is negative). Together this describes the slow buildup and fast ablation of the ice sheets with a delay in ice sheet response of 4.2, 5.0 and 7.9 kyr in the 19 and 23 kyr components of precession and the 41 kyr component of obliquity, respectively. The constants Tm and b are generally assumed to be invariant with time even though the accumulation rate and size of the ice sheet varied continuously (Shackleton et al., 1990). One objection to the above methods is that we have insufficient possibilities to verify the outcome of such tuned age models. In a limited number of cases a reversal of the earth's magnetic field or radiometrically datable tephra layers generates some control on the tuning, but in most situations the astronomical age model is more precise and deviations fall within error margins of possible secondary age control (Shackleton et al., 1990). Lisiecki and Raymo (2005) used sedimentation rate as a control on their age model. They labored under the reasonable assumption that their stack cannot exhibit overly large variations in sedimentation rate. Therefore, they restrict the algorithm's freedom to compress or stretch their record in tuning it to insolation. This conservative approach however still overrides any natural variability in system earth's response to insolation forcing by aligning the record to a model with predefined response times.

The broadly accepted astronomically-based tuning approach was tested by Huybers and Wunsch (2004), who used only sedimentation rate as an estimate with radiometrically dated geomagnetic boundaries as age markers. With this approach they produced independent age constraints for isotopic shifts, and argued that tuning to insolation suppresses weak non-linear interactions, i.e. climate variability with periodicities of 70 and 29 kyr. Also, the role of eccentricity-modulated precession is often criticized, with obliquity suggested as the dominant late Pleistocene climate forcing (Huybers and Wunsch, 2004; Maslin and Ridgewell, 2005; Huybers, 2007, 2011). Note that late Pleistocene is used here to express the last ~900 kyr, whereas ‘early Pleistocene’ indicates the period before 900 ka (contrast the Late Pleistocene, formally defined to be 0–125 ka; Gradstein et al., 2004). Unfortunately, letting sedimentation rates dictate the age model entirely introduces large uncertainties in the estimates. Adding a different form of age control is the best way to improve this valuable approach.

Better estimates of the phase relation between insolation forcing and the benthic $\delta^{18}O$ response are necessary to improve our understanding of the timing and nature of climatic shifts, such as the MPT and glacial terminations. Outside the realm of deep sea coring there is a variety of settings offering the possibility of climate reconstruction, sometimes with the advantage of additional age control, like radiometric dating. Reconstructions of sea level in relation to ice volume changes have been based on the coral reef growth of Barbados (Harmon et al., 1978, 1983; Bard et al., 1990) using ^{14}C dating and U/Th dating for the last 250 kyr. Dutton et al. (2009) used a set of U/Th-dated speleothems from Italy to reconstruct the sea level of MIS 7 in detail. Also of very high resolution is the speleothem-derived monsoon activity reconstruction of Sanbao-Hulu (Wang et al., 2008; Cheng et al., 2009). The speleothem $\delta^{18}O$ record reflects changes in the strength of the East Asian summer monsoon. The record is dated by U/Th dates back to ~390 ka with average dating errors within ~0.5 kyr (Cheng et al., 2009). It is a highly precise, highly accurate paleoclimate record displaying fast climate shifts such as the Dansgaard-Oeschger millennial scale variability, with rapid transitions between stadial and interstadial periods (Wang et al., 2008; Cheng et al., 2009).

While all of these reconstructions provide valuable insights in paleoclimate behavior over the course of the Pleistocene, they lack some of the benefits typical for deep sea coring. The sea level reconstructions based on corals and speleothems depend on specific finds of suitable archives. Such climate archives often only cover a limited time period, which makes these reconstructions discontinuous. The ice core records, while providing detailed and long sequences of paleoclimate, mostly reflect local circumstances like temperature (Jouzel et al., 2007). The Sanbao-Hulu speleothem record reflects the East Asian Monsoon. Neither of these provides an integrated signal of global climate, as it is provided by benthic $\delta^{18}O$ (Hays et al., 1976; Imbrie et al., 1984). In this study we present the first high resolution, long-term (1.2 Myr) benthic oxygen isotope record from the eastern Mediterranean. Our record is uniquely located in a setting that allows us to date the record without tuning the isotopes to insolation or a reference curve. We arrive at our chronology by tuning a geochemical signature of the sediment directly to insolation. Therefore, no assumptions for the response time of ice volume to insolation are required. This approach builds upon earlier work by Ziegler et al. (2010), who reconstructed the last 350 kyr using sediments from ODP Site 968. With this non-standard age model we test the age and duration of all the major isotopic stages and transitions of the last ~1.2 Ma.

2. Materials and methods

2.1. ODP sites 967 and 968

Our study uses data from the adjacent ODP Sites 967 and 968 in