



New Arabian Sea records help decipher orbital timing of Indo-Asian monsoon

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ABSTRACT

A recent study suggested that Indian monsoonal proxies commonly used in the Arabian Sea, in general productivity proxies, could be impacted by changes in the Atlantic overturning rate (AMOC) throughout a control on the nutrient delivery into the euphotic zone. This oceanic mechanism could lead to a misunderstanding between the Indian summer monsoon (SM) and orbital forcing and could confuse a direct comparison with other archives derived from other monsoonal sub-systems (such as East-Asian or African records). Here we analyze three independent proxies (bromine, foraminifera assemblages and grain size) extracted from a marine sediment core (MD04-2861) covering the last 310 ka, and retrieved in the northern Arabian Sea near the Makran margin, an area influenced by summer and winter Indian monsoon. The grain size proxy deals with the regional continental climate through fluvial and eolian processes. It cannot be linked to changes in nutrient content of AMOC and present the same phase relationship (timing) than the other SM proxies. This demonstrates that the productivity signals (Bromine) in the northern Arabian Sea are mainly controlled by SM dynamics and not AMOC modulated nutrients at orbital scale changes. We thus build a multi-proxy record of SM variability (i.e. SM stack) using statistical tools (principal component analysis) further compiled on an age model constructed independently from orbital tuning. We find that strong SM lag by 9 ± 1 ka the NH summer insolation maximum (minimum of precession, June 21 perihelion and obliquity maximum) in the precession band, and by 6 ± 1.3 ka in the Obliquity band. These results are consistent with previous studies based on marine and terrestrial records in both Indian and Asian regions, except Asian speleothems. Our study supports the hypothesis that internal climate forcing (decreased ice volume together with the increase of latent heat export from the southern Indian Ocean) set the timing of strong Indo-Asian summer monsoons within both the precession and obliquity cycle. The external forcing (direct sensible heating) initiate monsoonal circulation. Strong Indian winter monsoon (WM) occurs between ice maxima and northern hemisphere sensible heat minima, indicating that both act to strengthen WM circulation. The summer and winter monsoons are in antiphase in the precession band suggesting that the two systems are dynamically linked.

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1. Introduction

The Indo-Asian monsoon represents the strongest expression of the monsoon modern dynamics, allowing important transfers of moisture at a large geographical scale and deeply affecting human populations. Monsoon strength and variability is crucial for the economical prosperity of regions.

The forcing/response relationship of the Indo-Asian monsoon at orbital scale during the Quaternary period is still debated in the literature. This lack of understanding how of the monsoon responds to the most fundamental of boundary conditions at this time scale

(insolation, ice-volume, greenhouse gasses, ocean–atmosphere energy exchange) does not bode well for predicting monsoon response to future climate change. Two different hypotheses exist and are based upon observed timing.

- (1) Clemens and Prell (2003) and Clemens et al. (2008, 2010) focussed their studies on wind-derived proxies within sedimentological archives from the Owen Ridge, northern Arabian Sea. They proposed that strong events of Indo-Asian summer monsoon lag by ~ 8 ka the maximum northern hemisphere (NH) summer insolation (minimum of precession, June 21 perihelion).
- (2) From the analysis of Chinese cave speleothems (Cheng et al., 2009; Dykoski et al., 2005; Wang et al., 2001; 2008), a shorter lag of only ~ 3 ka was observed between strong summer monsoon and maximum NH summer insolation.

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The recent study of Ziegler et al. (2010a) conducted in the Arabian Sea proposed that the summer monsoonal proxies, in general productivity-based proxies, could be influenced by other processes not only related to monsoon forcing. This recent study casts some doubt on the interpretation of the 8 ka lag between precession minima and strong summer monsoons as driven by latent heat export from the southern hemisphere (Ziegler et al., 2010a–b). Indeed, Ziegler et al. (2010a) have proposed that biological productivity and OMZ intensity at the precession frequency band are mainly controlled by changes in the intensity of the Atlantic meridional overturning circulation (AMOC) which controlled the nutrient delivery in the euphotic zone of the Arabian Sea.

The aim of our study is to carry new insights about Indo-Asian monsoon forcing and response (phase relationship). We used a sedimentary core located in the northern Arabian Sea, close to the Makran margin. To complete previous works which generally focus their interpretations on the monsoon processes with productivity-based proxies, we have analyzed tools linked to productivity, but also foraminifera assemblages together with grain size parameters dealing with the regional continental climate. Based on our new results and the comparisons with previous published data, we discuss the orbital forcing and response of the Indo-Asian monsoon system.

2. Environmental setting

The studied core MD04-2861 is located in the Arabian Sea, off the tectonically-active Makran margin (24.13 N; 63.91 E; 2049 m depth) (Bourget et al., 2011; Ellouz-Zimmermann et al., 2007; Kukowski et al., 2001; Fig. 1A). This core was retrieved on the little Murray Ridge, northward of the Murray Ridge where Ziegler et al. (2010a) have studied cores NIOP463 and MD04-2876. Sites investigated by Clemens and Prell (2003) are located southward in the Arabian Sea, on the Owen Ridge (Fig. 1A).

Nowadays, Arabian Sea environments experience large seasonal variations due to strong monsoonal winds and associated migration of the InterTropical Convergence Zone (ITCZ) (Clemens and Prell, 2003; Luckge et al., 2001; Sirocko et al., 1991; von Rad et al., 1995). The seasonal reversal in the wind direction is also associated with contrasted precipitations, high variability in the sediment inputs and drastic changes in oceanic current strength and direction (Schott et al., 2009; Sirocko et al., 2000; von Rad et al., 1999). During the summer season (SW monsoon) (Fig. 1B), warmer and more humid conditions are observed over Karachi and the Indian subcontinent (Luckge et al., 2001). During the winter season (NE monsoon), precipitations also occur (Luckge et al., 2001) linked to the cyclonic low-pressure systems originating in the eastern Mediterranean which occasionally penetrate the Arabian landmass (Weyhenmeyer et al., 2000). However, arid conditions generally dominate during the winter monsoon, and paleostudies suggest that the origin of atmospheric water vapor changed from a dominantly northern Mediterranean source (modern pattern), to a primarily southern Indian Ocean source during the Late Pleistocene (Weyhenmeyer et al., 2000). Even if the Pakistan region received less than 200 mm of annual precipitation today (Pakistan Meteorological Department), the climate of the region results in intense flash flooding of the drainage system over the Makran region linked to this continental humidity/aridity balance (von Rad et al., 1999). A large number of fluvial systems are distributed along the Makran coast (Fig. 1A) and are associated offshore with the presence of several submarine canyons along the Makran continental slope (Bourget et al., 2010; 2011). Turbidity current activity has been recorded in both slope and abyssal plain areas throughout the Pleistocene and the Holocene (Bourget et al., 2010; Prins and Postma, 2000). However, our core is located on a submarine topographic high, up to ~1000 m above the surrounding sea-floor, preventing our site from any direct influence of turbidity currents on the sedimentary processes. Meanwhile our coring site is located relatively close to the coast (less than 150 km) and thus

could be influenced by sediment supply from the continent, via fluvial and/or aeolian transport and decantation in the water column. Regional dust transport (Sirocko et al., 2000), controlled by both continental aridity and wind strength, is likely to influence the sedimentation at our core site. The increase/decrease of wind allows the development/suppression of a strong coastal upwelling along the Oman margin, which adds a biogenic component to the lithogenic sedimentation (Clemens et al., 1996; Clemens and Prell, 1991; Reichart et al., 1998) (Fig. 1B). Large eddies and filaments generated during the SW monsoon upwelling (as visible at Ras al Hadd; Fig. 1B) are transported north-eastward to the Arabian Sea and affect our site (Fig. 1). Moderate NE wind blowing during the NE monsoon is also driving upwelling and enhanced productivity along the Makran coast (Fig. 1). Supply of oxygen-poor intermediate waters (You, 1998) combined with high surface productivity (linked to upwelling reinforcement) produce an intense oxygen minimum zone (OMZ). Our core site is located below the present day extension of this OMZ (Supplementary Fig. 1).

3. Material and methods

3.1. Bromine measurements

Bromine measurements were performed with an Avaatech XRF core scanner at EPOC laboratory. Each core section was scanned every 2 cm with ionization energy of 30 kv. Bromine counts are exclusively associated to marine organic content (MOContent) in the sediment of Arabian Sea (Ziegler et al., 2008). An increase in Bromine is associated to an increase in MOContent. Further information about the XRF scanning technique and its interest in paleostudies can be found in Richter et al. (2006).

3.2. Grain size analysis

Grain size analysis were performed using a Malvern™ Supersize 'S' at EPOC laboratory every 10 cm in the core. For some additional samples, we have removed carbonate prior to grain size analyses. Carbonate was removed using 20% Acetic Acid (48 h at room temperature).

3.3. Thin section

To obtain high-resolution sedimentological information in core MD04-2861, thin section was performed at EPOC laboratory using the method described in Zaragosi et al. (2006). We realized a thin section at 1930–1940 cm in core MD04-2861. Vertical cross-sections were made in the middle of the sediment/resin sample obtained using a diamond saw. Then, thin-section images were acquired using a fully automated Leica DM6000 B Digital Microscope using analyzed polarized light at EPOC laboratory.

3.4. Foraminifera assemblage

The subsamples were dried, weighed, and washed every 10 cm in the core through a 150 µm mesh sieve. Total assemblages of planktonic foraminifera were analyzed using an Olympus SZH10 binocular microscope following the taxonomy of Hemleben et al. (1989) and Kennett and Srinivasan (1983). About 300 specimens were counted in each level after splitting with an Otto microsplitter.

3.5. Isotopes

Specimens were picked within the 250–315 µm size fraction every 10–20 cm in the core. Benthic isotopic analyses were carried out on the species *Planulina wuellerstorfi* at EPOC laboratory. Those solid, calcium carbonate samples (50 to 100 µg of foraminifer shells) were individually reacted with ortho-phosphoric acid to produce CO₂ gas, which was analyzed with an Optima© stable isotope mass

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