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Sensing Seasonality in the Arabian Sea: a coupled $\delta^{18}O-Mg/Ca$ approach

W. Feldmeijer¹, L. J. de Nooijer², G.-J. Reichart^{2,3}, and G.M. Ganssen¹

¹Faculty of Earth and Life Sciences, Earth and Climate Cluster, VU University Amsterdam, de Boelelaan 1085, 1081 HV Amsterdam, the Netherlands
 ²Department of Marine Geology and Chemical Oceanography, NIOZ Royal Netherlands Institute for Sea Research, P.O. Box 59, 1790 AB Den Burg, the Netherlands
 ³Faculty of Geosciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, the Netherlands

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Correspondence to: W. Feldmeijer (w.feldmeijer@vu.nl)

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Abstract

Millennial scale climate variability punctuates the record of Northern Hemisphere glacials in the form of Dansgaard–Oeschger cycles. The coldest episodes within these cycles have a marked impact on the location of the Inter-tropical Convergence

- ⁵ Zone and thereby the intensity and extent of the Asian monsoon system. Arabian Sea oceanography is closely linked to the monsoon cycle and responds rapidly to changes therein. Seasonally varying upwelling intensity, adhesive mixing and the resulting variability on sea surface temperature and salinity, however, make it challenging to precisely reconstruct the behaviour of the Indian monsoon system through the
- ¹⁰ Dansgaard–Oeschger cycles. To reconstruct impact of millennial-scale changes in the monsoon on the Arabian Sea, paired single-specimen Mg/Ca and stable oxygen isotope analyses were performed on three species of planktonic foraminifera from the northern as well as the western Arabian Sea. Mismatches between Mg/Ca- and δ^{18} Oderived temperatures reflect changes in salinity caused by regional variability in the
- ¹⁵ hydrological cycle. Comparison of Mg/Ca-derived temperatures from *Globigerinoides ruber*, *Globigerina bulloides* and *Neogloboquadrina dutertrei* over Heinrich Event 4 and Interstadial 8 allows for reconstructing the seasonal range in temperatures (minima and maxima) and vertical stratification of the water column during these intervals. Results show that Arabian Sea surface water temperatures were lower during the North Atlantic
- Heinrich Event 4, and that temperatures in the northern and western Arabian Sea differed relatively much. This implies that the north east monsoon (i.e. boreal winter) was enhanced during this interval. In contrast, the summer upwelling related species *G. bulloides* reveals lower temperatures during Interstadial 8 in the western Arabian Sea, showing an enhanced summer monsoon during the warmers stages of millennial-scale
- climate variability. Together, these results show that summer and winter monsoon intensities were thus also anti-phased on a millennial scale. An intensified NE monsoon might have contributed to enhanced mixing of surface waters in the northern Arabian Sea.





1 Introduction

Phases of millennial-scale Pleistocene climate change have been recognised in ice cores since their first description by Dansgaard et al. (1993). The coldest phases of these so-called Dansgaard–Oeschger cycles are characterized by occurrence of layers
⁵ containing large quantities of ice rafted debris (IRD) in the North Atlantic, deposited after sudden collapse of glaciers and arctic sea-ice sheets. These periods are so-called Heinrich Events (HE) (Bramlette and Bradley, 1940; Broecker et al., 1992; Heinrich, 1988) and their equivalent can be recognized in climate records throughout the Northern Hemisphere, including the Arabian Sea. There, they are expressed in a temporal
¹⁰ weakening of the summer monsoon (Anderson and Prell, 1993; Gupta et al., 2003; Ivanochko et al., 2005; Jung et al., 2004; Jung et al., 2002; Kroon et al., 1990, 1991; Naidu and Malmgren, 1996; Reichart et al., 1997; Schulz et al., 2011; Reichart et al., 1998; Schulz et al., 1998). Furthermore, alteration of the climate-ocean system dur-

¹⁵ ing HE's can lead to changes in the formation of oxygen rich Sub-Antarctic Mode and Antarctic Intermediate Water (SAMW-AAIW), also affecting ventilation and bottom water oxygenation of the northern Arabian Sea (Böning and Bard, 2009).

The geochemical signal incorporated within the calcite tests of foraminifera has been a tool to reconstruct past environments and climate states employed for over half a cen-

- tury (Emiliani, 1955). Since the advent of mass spectrometry large improvements in both the sampling methodology and the refinements of the mass spectrometers themselves have allowed analysis of single foraminiferal tests (Ganssen et al., 2011; Haarmann et al., 2011), or even single chambers (e.g. Eggins et al., 2003; Reichart et al., 2003).
- ²⁵ Conventional isotope analysis provides an accurate estimate of the mean δ^{18} O when at least 20 specimens are pooled for one measurement (Schiffelbein and Hills, 1984). Such measurements, however, result in oxygen isotope ratios representing the average temperature of the sampled interval. Using foraminifera from sediment trap samples, for



example, this period is very small and recorded temperatures between specimens will be limited. For pooled fossil foraminifera, however, seasonal, inter-annual, centennial and possibly millennial-scale changes in seawater temperature may not be recognized. To capture temperature changes at a high temporal resolution, single shell oxygen isotope analyses can be used and reveal the seasonal distribution, including minima and maxima of seawater temperatures for the selected time period (Wit et al., 2013).

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The oxygen isotope ratio of carbonates ($\delta^{18}O_c$) depends on both temperature and the oxygen isotope composition of seawater ($\delta^{18}O_{sw}$). Hence, when an independent temperature proxy is available, both temperature and the seawater oxygen isotope composition can be reconstructed (Rohling, 2007). Organic biomarkers like TEX₈₆ and U^K₃₇ may serve this purpose (Brassell et al., 1986; Schouten et al., 2002), although potential differences in the season and water depth at which these compounds and foraminiferal shells are produced add to the uncertainty of reconstructed temperatures. This potential error can be circumvented by combining foraminiferal Mg/Ca with $\delta^{18}O_c$

- ¹⁵ measured on the same specimen. Deriving Mg/Ca from single chambers determined with Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) (e.g. Bolton et al., 2011; Eggins et al., 2003, 2004; Marr et al., 2011, 2013a, b; Sadekov et al., 2009; Bolton and Marr, 2013), leaves sufficient material for subsequent single specimen- δ^{18} O analysis.
- Here we use this approach to reconstruct seasonal ranges in temperature during selected time slices in the northern, as well as western Arabian Sea. By using different species, with specific ecologies we also constrain vertical temperature gradients in the Arabian Sea during Heinrich Event 4 (HE4) and the preceding interstadial 8 (IS8). Comparison of the two areas within the Arabian Sea allows deconvolving impacts of
- ²⁵ summer and winter monsoon and reconstruction of the relation to millennial-scale climate variability and the Indian monsoon system.





2 Study area

The Arabian Sea region is characterized by a seasonal reversal of the dominant wind direction. During the southwest-monsoon (boreal summer), this direction is towards the northeast, causing upwelling of cold and nutrient-rich seawater offshore Somalia and

- ⁵ Yemen (Peeters et al., 1999 and references therein). In the northern Arabian Sea, on the other hand, the water column remains stratified during summer (Reichart et al., 1998). During the northeast-monsoon (boreal winter), the dominant wind direction reverses as a result of a change in the position of the inter-tropical convergence zone (ITCZ), resulting in water column stratification in the western Arabian Sea, and convec-
- tive turnover in the northern Arabian Sea. Recorded sea surface temperatures (SST's) in the western Arabian Sea range from > 20 °C during the SW-monsoon to 30 °C during the NE-monsoon. In contrast, in the northern Arabian Sea, SST's range from 30 to 22 °C during the SW- and NE-monsoon, respectively (Fig. 1). Hence the annual temperature contrast in both areas is similar, but opposite between seasons.
- ¹⁵ Cores NIOP478P (24°12.7′ N; 64°39.7′ E; 565 m water depth) and NIOP905P (10°46.9′ N; 51°56.4′ E; 1586 m water depth) were recovered off the coast of Pakistan in 1992 and Somalia in 1993, respectively (Fig. 1). The age model for NIOP905P is based on 24 radiocarbon dates between 0 and 35 kyr (Ivanochko et al., 2005). The age model for NIOP478P is based on correlating the *Neogloboquadrina dutertrei* oxygen
 ²⁰ isotopes to those of NIOP464P, revealing that this core covers the past 68 kyr (Reichart et al., 1998, 2002).

3 Methodology

3.1 Sample preparation

From both cores samples were selected corresponding to time slices equivalent to $_{25}$ IS8 (~ 36.5–38.6 kyr) and HE4 (~ 39–40 kyr; Fig. 2). To promote sample dissociation,



sediment samples were dried overnight at 70 °C, soaked in water for at least half an hour prior to sieving over a 63 µm screen. Subsequently, samples were split into size fractions 63–125 µm, 125–250 µm, 250–300 µm, 300–355 µm and > 355 µm. From the 250–300 µm size fraction, 50 specimens of the surface-dwelling, oligotrophic species

- Globigerinoides ruber, the relatively cold, nutrient-dependent species Globigerina bulloides and the thermocline dweller *N. dutertrei* were picked for NIOP905P and 25–30 specimens of all three species from NIOP478P. Less specimens were taken from the latter, as the higher sedimentation rate at this location limited the number of specimens available. All specimens were placed in an ultrasone bath for 10 s in ethanol to remove adhered particles. Specimens were then inspected under a light microscope
- and if necessary, sonification was repeated until foraminifera appeared free of these particles.

3.2 Seasonal and vertical foraminiferal distributions in the Arabian Sea

In the western Arabian Sea, abundances of *G. ruber* are relatively constant throughout the year (Curry et al., 1992). This species inhabits the upper 50 m of the water column (Peeters et al., 2002), implying that their average value and range in δ^{18} O and Mg/Ca ratio reflect average and seasonal variability in sea surface temperatures (SST's) in the Arabian Sea (Conan and Brummer, 2000; Zhang, 1985).

The thermocline dweller *N. dutertrei* peaks in abundance at \sim 50–200 m water depth (Ravelo et al., 1990; Fairbanks et al., 1982) and shows maximum shell fluxes during

- (Ravelo et al., 1990; Fairbanks et al., 1982) and shows maximum shell fluxes during the upwelling season in the western Arabian Sea (Conan and Brummer, 2000). In the northern Arabian Sea, low abundances of *N. dutertrei* have been attributed to relatively low nutrient concentrations (Guptha et al., 1997; Zhang, 1985). With the absence of a clear seasonality in nutrient levels in the northern Arabian Sea (Madhupratap et al.,
- ²⁵ 1996; Qasim, 1982), single specimen- δ^{18} O and Mg/Ca values likely reflect year-round thermocline temperatures.

More pronounced than for *N. dutertrei*, shell fluxes of *G. bulloides* are positively correlated to nutrient levels, which in the western Arabian Sea are promoted by summer





upwelling intensity (Conan and Brummer, 2000). Like G. ruber, G. bulloides inhabits the surface layer (i.e. upper \sim 50 m) of the water column in this area (e.g. Peeters et al., 2002). For NIOP905P, temperature reconstructions based on this species will therefore primarily reflect the cold, summer sea surface temperatures. Seasonal variability in 5 nutrient load in the northern Arabian Sea (NIOP478P) is less pronounced compared to the western Arabian Sea but both advection of nutrient rich water during the summer monsoon and convective mixing of the water column during the NE-monsoon brings nutrients to the local surface waters. Therefore Mg/Ca and δ^{18} O of this species will reflect SST's from both monsoon seasons, with relative contributions depending on productivity in each season.

3.3 **Trace metals**

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Specimens were analysed for Mg/Ca using Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) at Utrecht University (Reichart et al., 2003). Single foraminiferal chambers were ablated in a helium atmosphere with a 5 Hz pulse repetition rate, using a laser spot diameter of 80 µm (Fig. 3) at an energy density of ~ 1 J cm^{-2} . Masses monitored included ²³Na, ²⁴Mg, ²⁶Mg, ²⁷Al, ⁴³Ca, ⁴⁴Ca, ⁵⁵Mn and ⁸⁸Sr. A NIST SRM610 glass standard was used for calibration and ablated three times with a laser power density of $\sim 5 \,\mathrm{J\,cm^{-2}}$ after every 10–12 for a miniferal samples. Calibration of element/calcium ratios in calcium carbonate samples using a NIST glass standard has been demonstrated to be accurate for many elements when us-20 ing a 193 nm laser and not affected by switching between energy densities (Hathorne

- et al., 2008). The precision of the technique is $\sim 4\%$ (1 σ) for Mg/Ca based on multiple spot analyses of powder pellets of carbonate reference materials (e.g. Raitzsch et al., 2011). Time resolved signals were selected for integration, background subtracted, and calibrated with the signals from the NIST SRM610 using ⁴³Ca as an internal stan-25
- dard and element concentrations reported by Jochum et al. (2011). Reproducibility of single chamber Mg/Ca was determined for every species using 30 specimens by ablating the final chamber three times with a smaller laser spot diameter ($40 \,\mu m$; Fig. 3)





and average standard deviation is $0.35 \text{ mmol mol}^{-1}$. For conversion of Mg/Ca ratio's to temperature we used calibrations by Bolton et al. (2011) for *G. ruber*, Marr et al. (2011) for *G. bulloides* and Von Langen et al. (2005) for *N. dutertrei*.

3.4 Stable isotope measurements

- ⁵ Foraminifera used for LA-ICP-MS were subsequently analysed individually for their stable isotope composition. Samples were analysed on a Thermo Finnigan Delta⁺ mass spectrometer equipped with a GASBENCH II preparation device. Samples were placed in a He-filled 3 mL exetainer vial and digested in concentrated H₃PO₄ at a temperature of 45 °C. Four ~ 2 mm glass beads were added to each sample vial to limit potential isotopic fractionation due to the heat retaining capacity of the beads, and thus not allowing the acid to cool before contact with the foraminiferal test, and reduce sample
- loss when brought into contact with the acid and thus make sure the foraminifer is dissolved. Subsequently the CO₂-He gas mixture was transported to the GASBENCH II by use of a He flow through a flushing needle system where water was removed from the gas using a NAFION tubing. Stable isotopes of the CO₂ were analysed in the mass spectrometer after separation of other gases in a GC column. Stable oxygen isotope values, $\delta^{18}O_c$, are reported as per mil deviation relative to the V-PDB standard. Reproducibility for $\delta^{18}O_c$ of routinely analysed lab CaCO₃ standards is within 0.1 ‰ (1 σ) for regular analysis and within 0.12 ‰ (1 σ) for small quantities (i.e. comparable to single foraminifera). Kim and O'Neil (1997) was used for conversion of $\delta^{18}O_c$ to temperature with a glacial $\delta^{18}O_c$ correction of 0.7% for the time period from which samples were
- with a glacial $\delta^{18}O_{sw}$ correction of 0.7 ‰ for the time period from which samples were taken (Bintanja and Van de Wal, 2008).



4 Results

4.1 Mg/Ca

Single-specimen Mg/Ca ratios of all species and of both locations are significantly different between HE4 and IS8. Except for ratios from specimens of *G. ruber* from the western Arabian Sea (NIOP905P) which were similar for both time intervals (Fig. 4).

- western Arabian Sea (NIOP905P), which were similar for both time intervals (Fig. 4). For both HE4 and IS8, differences exist between species' average Mg/Ca from each of the core locations, whereas in most cases, oxygen isotope values are similar (Fig. 5). Species' average Mg/Ca values are also often significantly different between HE4 and IS8 (e.g. for *G. bulloides* from both locations), while oxygen isotopes for these pairs are often similar (Fig. 5). Additionally, calculated temperatures based on average Mg/Ca
- ratios for *G. bulloides* and *N. dutertrei* show occasional large discrepancies from those calculated using the average δ^{18} O for the same specimens as seen in the samples from HE4 for both sites (Figs. 4 and 5).

Variability in Mg/Ca from specimens within one sample varies between species.
For *G. ruber*, it is relatively small (on average standard deviation = 1.24 mmol mol⁻¹) compared to that in *G. bulloides* and *N. dutertrei* (on average standard deviation of 2.00 and 1.47 mmol mol⁻¹, respectively). Comparison of Mg/Ca retrieved from chambers within one specimen shows that ratios decrease with chamber number in *G. ruber* and *G. bulloides*, i.e. the final chamber often has the lowest Mg/Ca. This is in line with previously reported intra-specimen variability in Mg/Ca (Bolton et al., 2011; Marr et al., 2011, 2013b). Contrastingly, Mg/Ca is highest in the ultimate chambers of *N. dutertrei*, which is on average 3.08 mmol mol⁻¹ compared to 1.87 and 1.50 mmol mol⁻¹ for the penultimate and antepenultimate chamber, respectively.

4.2 Oxygen isotopes

²⁵ Despite oceanographic differences between the western and northern Arabian Sea, average δ^{18} O values measured on single shells are similar for IS8 and HE4 for all three





species at both locations (Fig. 5). The range in obtained temperatures, i.e. reflecting the seasonal temperature variability, varies between the two locations (Table 1). In the western Arabian Sea (NIOP905P), the δ^{18} O-based seasonal temperature range is similar between IS8 and HE4. Furthermore, for *G. ruber* and *G. bulloides* this range is smaller to that of *N. dutertrei* during HE4. In the northern Arabian Sea (NIOP478P) all three species have a larger seasonal temperature range during HE4 compared to IS8.

- For *G. ruber*, δ^{18} O values are similar for IS8 and HE4, whereas the other two species have more depleted isotope ratios during HE4. Between the two regions, the difference in δ^{18} O is highest for *G. bulloides* (more depleted in NIOP905P) during HE4.
- ¹⁰ There is a weak, but significant correlation between the single-chamber Mg/Ca and single-specimen δ^{18} O ($R^2 = 0.07$; n = 331) due to the large number of data points. When using each species' and location's average Mg/Ca and δ^{18} O there is a stronger significant correlation between the two ($R^2 = 0.37$; n = 12; Fig. 6).

5 Discussion

15 5.1 Mg/Ca

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Sea surface temperatures based on Mg/Ca from *G. ruber* are very similar for both sites (Fig. 4) yet specimens from IS8 in the northern Arabian Sea are about 5 °C warmer (Fig. 1). Those based on *Globigerina bulloides* are 4-9 °C lower in the western than in the northern Arabian Sea (Fig. 4), likely reflecting upwelling of deep, cold waters in summer caused by the SW monsoon. For *N. dutertrei*, the trend is similar (Fig. 4), with a difference of ~ 3 °C between IS8 and HE4, indicative of this species' year round abundance at both sites and the decrease in thermocline temperature during HE4.

On average, Mg/Ca-based temperatures differ between 2 and 5 °C between the two intervals. However, *G. ruber* in the western Arabian Sea reveals similar sea surface temperatures for IS8 and HE4 (Fig. 4). This suggests that surface water-cooling in this region is a seasonal phenomenon (*G. bulloides* and *N. dutertrei*), as it is not seen in





reconstructed annual averages (*G. ruber*). A strong seasonal cooling of Arabian Sea (surface) waters during HE4 is in line with previous records (e.g. Reichart et al., 2004). In the northern Arabian Sea, temperature contrasts between the sea surface (*G. ruber*) and the mixed layer (*N. dutertrei*) are similar in the two intervals, while at NIOP905P

- ⁵ the vertical temperature gradient (i.e. the difference between *G. ruber* and *N. dutertrei*) during HE4 is almost double (8.2 °C) that of IS8 (4.5 °C; Fig. 4). This suggests that during the studied interval the northern Arabian Sea is affected to depths of at least the mixed layer whereas in the western Arabian Sea, impacts are confined to the surface layer.
- The ranges in Mg/Ca for all three species in both periods (Fig. 4) are relatively large (5.5–2.9, 6.6–6.8 and 4.8–2.8 mmol mol⁻¹ in the northern Arabian Sea and 3.2–4.5, 3.7–3.7 and 5.0–4.4 mmol mol⁻¹ (IS8–H4) in the western Arabian Sea, for *G. ruber*, *G. bulloides* and *N. dutertrei*, respectively). The measured ranges from our study compare well to those found in previous studies applying LA-ICP-MS (Bolton et al., 2011; Marr at al., 2011). For *G. ruber* and *N. dutertrei* from both sites there are large offsets
- between the ranges in temperature in IS8 and HE4, although for *G. bulloides*, the ranges are similar.

These ranges cannot be explained solely by temperature and previous studies have shown that even specimens cultured at a set temperature show large variability (Lea

- et al., 1999; De Nooijer et al., 2014). Therefore a large part of the observed variability in single-chamber Mg/Ca can be attributed to intrinsic variability in geochemical composition of the test calcite. Despite the potential bias due to "biological noise" (Wit et al., 2012), Mg/Ca-based temperatures in this study show a clear difference between species, reflecting their depth habitat, a cooling of both surface and mixed layer sea-
- ²⁵ water temperatures at both core locations during HE4 and the effect of relatively strong and persistent upwelling in the western Arabian Sea during both intervals.



5.2 Oxygen isotopes

Despite the similarity in δ^{18} O from specimens of the western Arabian Sea between HE4 and IS8, the δ^{18} O of the three species investigated here from the northern Arabian Sea have different values (Fig. 5). In the western Arabian Sea, δ^{18} O of *G. bulloides*

- ⁵ reflects primarily summer SST's. Since these temperatures remain relatively similar during both HE4 and IS8, it is likely that the strength of the SW-monsoon was similar during both time intervals. In the northern Arabian Sea, *G. bulloides* δ^{18} O values indicate higher temperatures than in the Western Arabian Sea (Fig. 5). Moreover, in NIOP478P, δ^{18} O values are similar for *G. bulloides* and *G. ruber* for both time intervals
- ¹⁰ implying an upper mixed layer throughout the year both during the Heinrich Event and interstadial. Large differences in particle flux in the western and eastern Arabian Sea (Curry et al., 1992; Nair et al., 1989) also suggests a less turbulent water column in the eastern/northern Arabian Sea induced by the NE-monsoon as opposed to the large western upwelling area. The δ^{18} O values of *N. dutertrei* from both sites are relatively similar (Fig. 5) revealing potential depth habitat tracking of this species.
 - Based on average, multi-specimen δ^{18} O values of *N. dutertrei*, both the Western (Ivanochko et al., 2005) and Northern Arabian Sea (Reichart et al., 2004) experienced a 2–3°C warming during the transition from Heinrich Event 4 to Interstadial 8. U_{37}^{K} -based temperatures suggest a similar warming (±2°C) from the cold spell-influenced
- ²⁰ HE4 to IS8 (Reichart et al., 2002). The observed ranges in all species' single shell δ^{18} O values (Fig. 5; Table 1), however, do not reveal this temperature difference between these time slices. Variability in δ^{18} O for all three species in the western Arabian Sea corresponds with a 7–10°C temperature range (Fig. 5; Table 1), which is less than the modern SST range of this area (Fig. 1). Calculated temperatures are similar to modern
- SSTs, suggesting a similar intensity of the SW-monsoon. For the northern Arabian Sea, the calculated range in SSTs for IS8 is similar to the range found today (Fig. 1). The range in SSTs during H4, however, is notably higher (Fig. 5; Table 1), suggesting that





the NE-monsoon caused a relatively strong convective mixing, resulting in a relatively deep mixed layer.

In summary, the δ^{18} O values are in line with previous suggested differences in depth habitat between the three species, similar temperatures are reconstructed for HE4 and

⁵ IS8 in the western Arabian Sea and an average cooling of 1.0–1.5 °C during HE4 in the northern Arabian Sea is derived from the planktonic foraminifera. These results imply a similar summer monsoon intensity, but a stronger winter monsoon during Heinrich Event 4.

5.3 Comparing Mg/Ca and δ^{18} O

- ¹⁰ Foraminiferal shell Mg/Ca ratio is primarily determined by temperature and is minimally affected by salinity and carbonate ion concentration ($[CO_3^{2^-}]$), all of which positively influence Mg/Ca (Arbuszewski et al.; Dissard et al., 2010; Dueñas-Bohórquez et al., 2009; Nürnberg et al., 1996). Calcite oxygen isotope values ($\delta^{18}O_c$) are predominantly influenced by seawater oxygen isotope composition ($\delta^{18}O_{sw}$), temperature and
- ¹⁵ to a lesser degree, $[CO_3^{2^-}]$ (Pearson, 2012). Temperature decreases $\delta^{18}O_c$ by 0.22% for every 1 °C (Kim and O'Neil, 1997; O'Neil et al., 1969). The $\delta^{18}O_{sw}$ and salinity are linearly correlated (Delaygue et al., 2001; Rohling, 2007) and a 1.5 salinity change equals a 0.4% change in $\delta^{18}O_{sw}$ (Rohling, 2007).

With carbonate ion concentrations playing a minor role in foraminiferal geochemistry,
the calculated average SST from Mg/Ca can be used to calculate the δ¹⁸O_{sw}, which in turn, is related to changes in salinity. SST offsets between Mg/Ca and δ¹⁸O for the same species from the same sample are 2–6 °C (Figs. 4 and 5), amounting to a 0.4–1.4 ‰ change in δ¹⁸O_{sw} (Kim and O'Neil, 1997). The global glacial-interglacial (large scale) δ¹⁸O_{sw} fluctuation was ~ 1 ‰ (Berger and Gardner, 1975) with a modelled 0.7 ‰ for IS8-HE4 (Bintanja and Van de Wal, 2008) and therefore cannot fully account for the offsets found in the Arabian Sea data (Fig. 7) given this is a stadial – interstadial (small scale) transition. Local events resulting in increased fresh water input (e.g. enhanced)



precipitation or river run off) could provide an explanation by causing a shifts in $\delta^{18}O_{sw}$ and salinity offsetting both temperature proxies. A change in salinity of 2 units, well within the modern-day Arabian Sea variability (Delaygue et al., 2001; Morrison et al., 1998; Qasim, 1982; Rostek et al., 1993), could explain the difference in Mg/Ca ratio and $\delta^{18}O_c$ calculated average SST's, which may result from enhanced evaporation during IS8 (Reichart et al., 2002).

Assuming that the calculated average Mg/Ca-based temperatures are accurate, foraminiferal δ^{18} O can be calculated by reversing the Kim and O'Neil (1997) temperature equation. The difference between this value and the measured δ^{18} O_c of the same sample then provides the offset from calcification in equilibrium with the ambient environment. Applying the salinity- δ^{18} O_w relationships for this area (Delaygue et al., 2001; Rostek et al., 1993) results in an estimate of the salinity responsible for the observed temperature differences for both locations.

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During IS8 the largest differences were observed in *G. bulloides* and *G. ruber* in the western Arabian Sea with an average residual of approximately -0.6% (Table 1). This amounts to a salinity imbalance of ~ 2 units (Delaygue et al., 2001; Rostek et al., 1993), possibly indicating a surface water freshening due to a changing evaporationprecipitation balance during the SW-monsoon in the Pakistan area. Off the Somalia coast, *G. bulloides* shows the largest offset (1.32‰; Table 1), implying either more saline waters or enriched $\delta^{18}O_w$ values during this interval. This species calcifies during peak upwelling when denser, more saline water is transported to the surface, pos-

- sibly explaining the observed enrichment in oxygen isotope ratios. Furthermore, the (smaller) offset in *G. ruber* (Table 1) may be explained by strong evaporation in the area as this species calcifies outside of the upwelling season and therefore its ambi-
- ²⁵ ent environment of calcification reflects "normal" conditions for this area. The oxygen isotope signal for *G. bulloides* could therefore reflect a combination of evaporation and upwelling of denser water. It appears that the deeper dwelling species *N. dutertrei* is unaffected, indicating that these salinity changes are confined to the top layer of the Arabian Sea during IS8.





Reconstructed conditions during HE4 are markedly different from those of IS8 with an oxygen isotope residual of ~ 1 ‰ for *G. bulloides* and *N. dutertrei* off Pakistan (Table 1). This may be explained by a strong NE-monsoon inducing enhanced vertical mixing and thereby a reduction in the vertical temperature gradient. *Globigerinoides ruber* from both areas does not show offsets during HE4 (Table 1), implying calcifi-

- cation of this species when the Arabian Sea is well stratified. The difference in temperatures reconstructed from *G. ruber* between IS8 and HE4 may be accompanied by a difference in the evaporation-precipitation balance, resulting in increased evaporation and salinity during the relatively warm Interstadial. In the western Arabian Sea,
- residual oxygen isotopes for *G. bulloides* and *N. dutertrei* are relatively large (1.51 ‰ and 0.77 ‰, respectively; Table 1). These offsets are larger during HE4 than IS8 and may be explained by upwelling of denser water (masses) induced by the global cooling during HE's (Hemming, 2004).

Differences between measured $\delta^{18}O_c$ and those calculated from the Mg/Ca-based temperatures are unlikely the sole result of vital effects. Instead, these results likely reflect differences in the evaporation-precipitation balance during IS8 and HE4 and/or potential changes in intermediate source water brought to the surface of the western Arabian Sea by upwelling. Furthermore, foraminiferal geochemistry in the northern Arabian Sea indicate stronger vertical mixing during HE's due to an enhanced NEmonsoon.

6 Conclusions

In this study we applied combined single specimen Mg/Ca (using LA-ICP-MS) and stable isotope analysis in order to unravel both the temporal (IS8-HE4) and spatial (western and northern Arabian Sea) seasonal contrast in monsoon intensity. Our results show that the western Arabian Sea is only weakly affected by millennial-scale climate variability. In contrast, the northern Arabian Sea experiences increased sea-



sonality during H4 due to intensification of NE-monsoon winds and therefore stronger mixing of the water column.

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References

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- Anderson, D. M. and Prell, W. L.: A 300 kyr record of upwelling off Oman during the late Quaternary: evidence of the Asian southwest monsoon, Paleoceanography, 8, 193–208, 1993.
- ¹⁰ Arbuszewski, J., deMenocal, P. B., Kaplan, A., and Farmer, E. C.: On the fidelity of shell-derived $\delta^{18}O_{seawater}$ estimates, Earth Planet. Sc. Lett., 300, 185–196, 2010.
 - Berger, W. H. and Gardner, J. V.: On the determination of Pleistocene temperature from planktonic foraminifera, J. Foramin. Res., 5, 102–113, doi:10.2113/gsjfr.5.2.102, 1975.
 - Bintanja, R. and van de Wal, R. S. W.: North American ice-sheet dynamics and the onset of 100,000-year glacial cycles, Nature, 454, 869–872, 2008.
 - Bolton, A. and Marr, J. P.: Trace element variability in crust-bearing and non crust-bearing *Neogloboquadrina incompta*, P–D intergrade and *Globoconella inflata* from the Southwest Pacific Ocean: potential paleoceanographic implications, Mar. Micropaleontol., 100, 21–33, 2013.
- Bolton, A., Baker, J. A., Dunbar, G. B., Carter, L., Smith, E. G. C., and Neil, H. L.: Environmental versus biological controls on Mg/Ca variability in *Globigerinoides ruber* (white) from core top and plankton tow samples in the southwest Pacific Ocean, Paleoceanography, 26, PA2219, 21–33, 2011.

Böning, P. and Bard, E.: Millennial/centennial-scale thermocline ventilation changes in the In-

- dian Ocean as reflected by aragonite preservation and geochemical variations in Arabian Sea sediments, Geochim. Cosmochim. Ac., 73, 6771–6788, 2009.
 - Bramlette, M. N. and Bradley, W. H.: Geology and biology of North Atlantic deep-sea cores, Geol. Surv. Prof. Paper., 196-A, 1–34, 1940.

Brassell, S. C., Eglinton, G., Marlowe, I. T., Pflaumann, U., and Sarnthein, M.: Molecular stratig-

³⁰ raphy: a new tool for climatic assessment, Nature, 320, 129–133, 1986.

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- Broecker, W., Bond, G., Klas, M., Clark, E., and McManus, J.: Origin of the northern Atlantic's Heinrich events, Clim. Dynam., 6, 265–273, 1992.
- Conan, S. M. H. and Brummer, G.-J. A.: Fluxes of planktic foraminifera in response to monsoonal upwelling on the Somalia Basin margin, Deep-Sea Res. Pt. II, 47, 2207–2227, 2000.
- ⁵ Curry, W. B., Ostermann, D. R., Guptha, M. V. S., and Ittekkot, V.: Foraminiferal production and monsoonal upwelling in the Arabian Sea: evidence from sediment traps, Geol. Soc. Sp., 64, 93–106, doi:10.1144/gsl.sp.1992.064.01.06, 1992.

Dansgaard, W., Johnsen, S. J., Clausen, H. B., Dahl-Jensen, D., Gundestrup, N. S., Hammer, C. U., Hvidberg, C. S., Steffensen, J. P., Sveinbjornsdottir, A. E., Jouzel, J., and Bond, G.:

- ¹⁰ Evidence for general instability of past climate from a 250-kyr ice-core record, Nature, 364, 218–220, 1993.
 - de Nooijer, L. J., Hathorne, E. C., Reichart, G.-J., Langer, G., and Bijma, J.: Variability in calcitic Mg/Ca and Sr/Ca ratios in clones of the benthic foraminifer *Ammonia tepida*, Mar. Micropaleontol., 107, 32–43, 2014.
- ¹⁵ Delaygue, G., Bard, E., Rollion, D., Jouzel, J., Stievenard, M., Duplessy, J.-C., and Ganssen, G. M.: Oxygen isotope/salinity relationship in the Indian Ocean, J. Geophys. Res., 106, 4565–4574, 2001.
 - Dissard, D., Nehrke, G., Reichart, G.-J., and Bijma, J.: The impact of salinity on the Mg/Ca and Sr/Ca ratio in the benthic foraminifera *Ammonia tepida*: results from culture experiments,

²⁰ Geochim. Cosmochim. Ac., 74, 928–940, 2010.

Dueñas-Bohórquez, A., da Rocha, R. E., Kuroyanagi, A., Bijma, J., and Reichart, G.-J.: Effect of salinity and seawater calcite saturation state on Mg and Sr incorporation in cultured planktonic foraminifera, Mar. Micropaleontol., 73, 178–189, 2009.

Eggins, S. M., de Deckker, P., and Marshall, J.: Mg/Ca variation in planktonic foraminifera tests:

- implications for reconstructing palaeo-seawater temperature and habitat migration, Earth Planet. Sc. Lett., 212, 291–306, 2003.
 - Eggins, S. M., Sadekov, A., and de Deckker, P.: Modulation and daily banding of Mg/Ca in *Orbulina universa* tests by symbiont photosynthesis and respiration: a complication for seawater thermometry?, Earth Planet. Sc. Lett., 225, 411–419, 2004.
- ³⁰ Emiliani, C.: Pleistocene temperatures, J. Geol., 63, 538–578, 1955. Fairbanks, R. G., Sverdlove, M., Free, R., Wiebe, P. H., and Bé, A. W. H.: Vertical distribution and isotopic fractionation of living planktonic foraminifera from the Panama Basin, Nature, 298, 841–844, 1982.





3864

Jung, S. J. A., Ivanova, E., Reichart, G.-J., Davies, G. R., Ganssen, G. M., Kroon, D., and Van Hinte, J. E.: Centennial-millennial-scale monsoon variations off Somalia over the last 35 ka,

- Jochum, K. P., Weis, U., Stoll, B., Kuzmin, D., Yang, Q., Raczek, I., Jacob, D. E., Stracke, A., Birbaum, K., Frick, D. A., Günther, D., and Enzweiler, J.: Determination of reference values for NIST SRM 610-617 glasses following ISO guidelines, Geostand. Geoanal. Res., 35,
- 2004.

- ton, S. G., and Kroon, D.: Variations in tropical convection as an amplifier of global climate 25 change at the millennial scale, Earth Planet. Sc. Lett., 235, 302-314, 2005.
- Ivanochko, T. S., Ganeshram, R. S., Brummer, G.-J. A., Ganssen, G. M., Jung, S. J. A., More-

and their global climate imprint, Rev. Geophys., 42, RG1005, doi:10.1029/2003RG000128,

during the past 130,000 years, Quaternary Res., 29, 142-152, 1988. Hemming, S. R.: Heinrich events: massive late Pleistocene detritus layers of the North Atlantic

ratios of single planktonic foraminifer shells and the potential to reconstruct the thermal seasonality of the water column, Paleoceanography, 26, PA3218, doi:10.1029/2010pa002091, 2011.

Spectrom., 23, 240-243, doi:10.1039/b706727e, 2008.

Ocean, J. Foramin, Res., 27, 5–19, doi:10.2113/gsifr.27.1.5, 1997.

Haarmann, T., Hathorne, E. C., Mohtadi, M., Groeneveld, J., Kölling, M., and Bickert, T.: Mg/Ca

Hathorne, E. C., James, R. H., Savage, P., and Alardc, O.: Physical and chemical character-

Heinrich, H.: Origin and consequences of cyclic ice rafting in the Northeast Atlantic Ocean

istics of particles produced by laser ablation of biogenic calcium carbonate, J. Anal. Atom.

- flux of planktic Foraminifera; sediment trap results from the Bay of Bengal, northern Indian 10
- 357.2003. Guptha, M. V. S., Curry, W. B., Ittekkot, V., and Muralinath, A. S.: Seasonal variation in the
- to 10⁵-vear time resolution, J. Geophys. Res.-Oceans, 102, 26455–26470, 1997. Gupta, A. K., Anderson, D. M., and Overpeck, J. T.: Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean, Nature, 421, 354-

Ganssen, G. M., Peeters, F. J. C., Metcalfe, B., Anand, P., Jung, S. J. A., Kroon, D., and Brum-

000 years, Clim. Past, 7, 1337-1349, doi:10.5194/cp-7-1337-2011, 2011.

5

15

20

30

397-429, 2011.

Geol. Soc. Sp., 195, 341-352, 2002.

Discussion mer, G.-J. A.: Quantifying sea surface temperature ranges of the Arabian Sea for the past 20 Grootes, P. M. and Stuiver, M.: Oxygen 18/16 variability in Greenland snow and ice with 10⁻³-10, 3847–3876, 2014

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Discussion

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CPD

W. Feldmeijer et al.





- Jung, S. J. A., Davies, G. R., Ganssen, G. M., and Kroon, D.: Synchronous Holocene sea surface temperature and rainfall variations in the Asian monsoon system, Quaternary Sci. Rev., 23, 2207–2218, 2004.
- Jung, S. J. A., Kroon, D., Ganssen, G. M., Peeters, F. J. C., and Ganeshram, R. S.: Enhanced
- Arabian Sea intermediate water flow during glacial North Atlantic cold phases, Earth Planet. Sc. Lett., 280, 220–228, 2009.
 - Kim, S.-T. and O'Neil, J. R.: Equilibrium and nonequilibrium oxygen isotope effects in synthetic carbonates, Geochim. Cosmochim. Ac., 61, 3461–3475, 1997.
 - Kroon, D., Beets, K., Mowbray, S., Shimmield, G., and Steens, T.: Changes in northern Indian
- ¹⁰ Ocean monsoonal wind activity during the last 500 ka, Memorie della Societa Geologica Italiana, 44, 189–207, 1990.
 - Kroon, D., Steens, T., and Troelstra, S. R.: Onset of monsoonal related upwelling in the western Arabian Sea as revealed by planktonic foraminifers, Oman Margin/Neogene Package, Proc. Ocean Drill. Program Sci. Results, 117, 257–263, 1991.
- Lea, D. W., Mashiotta, T. A., and Spero, H. J.: Controls on magnesium and strontium uptake in planktonic foraminifera determined by live culturing, Geochim. Cosmochim. Ac., 63, 2369– 2379, 1999.
 - Madhupratap, M., Kumar, S. P., Bhattathiri, P. M. A., Kumar, M. D., Raghukumar, S., Nair, K. K. C., and Ramaiah, N.: Mechanism of the biological response to winter cooling in the northeastern Arabian Sea, Nature, 384, 549–552, 1996.

20

30

Marr, J. P., Baker, J. A., Carter, L., Allan, A. S. R., Dunbar, G. B., and Bostock, H. C.: Ecological and temperature controls on Mg/Ca ratios of *Globigerina bulloides* from the southwest Pacific Ocean, Paleoceanography, 26, PA2209, doi:10.1029/2010PA002059, 2011.

Marr, J. P., Bostock, H. C., Carter, L., Bolton, A., and Smith, E. G. C.: Differential effects of

- cleaning procedures on the trace element chemistry of planktonic foraminifera, Chem. Geol., 351, 310–323, 2013a.
 - Marr, J. P., Carter, L., Bostock, H. C., Bolton, A., and Smith, E. G. C.: Southwest Pacific Ocean response to a warming world: Using Mg/Ca, Zn/Ca0, and Mn/Ca in foraminifera to track surface ocean water masses during the last deglaciation, Paleoceanography, 28, 347–362, 2013b.
 - Meese, D. A., Alley, R. B., Gow, A. J., Grootes, P. M., Mayewski, P. A., Ram, M., Taylor, K. C., Waddington, E., and Zielinski, G.: Preliminary Depth-Age Scale of the GISP2 Ice Core, US Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, 1994.





- Morrison, J. M., Codispoti, L. A., Gaurin, S., Jones, B., Manghnani, V., and Zheng, Z.: Seasonal variation of hydrographic and nutrient fields during the US JGOFS Arabian Sea Process Study, Deep-Sea Res. Pt. II, 45, 2053–2101, doi:10.1016/S0967-0645(98)00063-0, 1998.
- Naidu, P. D. and Malmgren, B. A.: Relationship between late Quaternary upwelling history and
- coiling properties of *Neogloboquadrina pachyderma* and *Globigerina bulloides* in the Arabian Sea, J. Foramin. Res., 26, 64–70, 1996.
 - Nair, R. R., Ittekkot, V., Manganini, S. J., Ramaswamy, V., Haake, B., Degens, E. T., Desai, B. N., and Honjo, S.: Increased particle flux to the deep ocean related to monsoons, Nature, 338, 749–751, 1989.
- Nürnberg, D., Bijma, J., and Hemleben, C.: Assessing the reliability of magnesium in foraminiferal calcite as a proxy for water mass temperatures, Geochim. Cosmochim. Ac., 60, 803–814, 1996.
 - O'Neil, J. R., Clayton, R. N., and Mayeda, T. K.: Oxygen isotope fractionation in divalent metal carbonates, J. Chem. Phys., 51, 5547–5558, 1969.
- Pearson, P. N.: Oxygen isotopes in foraminifera: overview and Historical review, in: Paleontological Society Short Course, Reconstructing Earth's Deep-Time Climate – The State of the Art in 2012, 1–38, 2012.
 - Peeters, F. J. C., Ivanova, E., Conan, S. M. H., Brummer, G.-J. A., Ganssen, G. M., Troelstra, S., and van Hinte, J.: A size analysis of planktic foraminifera from the Arabian Sea, Mar. Micropaleontol., 36, 31–63, 1999.

20

- Peeters, F. J. C., Brummer, G.-J. A., and Ganssen, G. M.: The effect of upwelling on the distribution and stable isotope composition of *Globigerina bulloides* and *Globigerinoides ruber* (planktic foraminifera) in modern surface waters of the NW Arabian Sea, Global Planet. Change, 34, 269–291, 2002.
- Qasim, S. Z.: Oceanography of the northern Arabian Sea, Deep-Sea Res. Pt. I, 29, 1041–1068, doi:10.1016/0198-0149(82)90027-9, 1982.
 - Raitzsch, M., Hathorne, E. C., Kuhnert, H., Groeneveld, J., and Bickert, T.: Modern and late Pleistocene B/Ca ratios of the benthic foraminifer *Planulina wuellerstorfi* determined with laser ablation ICP-MS, Geology, 39, 1039–1042, doi:10.1130/g32009.1, 2011.
- Ravelo, A. C., Fairbanks, R. G., and Philander, S. G. H.: Reconstructing tropical Atlantic hydrography using planktontic foraminifera and an ocean model, Paleoceanography, 5, 409–431, 1990.





A 225 kyr record of dust supply, paleoproductivity and the oxygen minimum zone from the Murray Ridge (northern Arabian Sea), Palaeogeogr. Palaeocl., 134, 149–169, 1997.

Reichart, G.-J., den Dulk, M., Visser, H. J., van der Weijden, C. H., and Zachariasse, W. J.:

- Reichart, G.-J., Lourens, L. J., and Zachariasse, W. J.: Temporal variability in the Northern Arabian Sea Oxygen Minimum Zone (OMZ) during the last 225,000 years, Paleoceanography,
- bian Sea Oxygen Minimum Zone (OMZ) during the last 225,000 years, Paleoceanography, 13, 607–621, 1998.
 - Reichart, G.-J., Nortier, J., Versteegh, G., and Zachariasse, W. J.: Periodical breakdown of the Arabian Sea oxygen minimum zone caused by deep convective mixing, Geol. Soc. Sp., 195, 407–419, doi:10.1144/gsl.sp.2002.195.01.22, 2002.
- Reichart, G.-J., Jorissen, F. J., Anschutz, P., and Mason, P. R. D.: Single foraminiferal test chemistry records the marine environment, Geology, 31, 355–358, doi:10.1130/0091-7613(2003)031<0355:sftcrt>2.0.co;2, 2003.
 - Reichart, G.-J., Brinkhuis, H., Huiskamp, F., and Zachariasse, W. J.: Hyperstratification following glacial overturning events in the northern Arabian Sea, Paleoceanography, 19, PA2013, doi:10.1029/2003PA000900. 2004.
- Rohling, E. J.: Progress in paleosalinity: overview and presentation of a new approach, Paleoceanography, 22, PA3215, doi:10.1029/2007PA001437, 2007.

15

20

- Rostek, F., Ruhlandt, G., Bassinot, F. C., Muller, P. J., Labeyrie, L. D., Lancelot, Y., and Bard, E.: Reconstructing sea surface temperature and salinity using δ^{18} O and alkenone records, Nature, 364, 319–321, 1993.
- Sadekov, A. Y., Eggins, S. M., de Deckker, P., Ninnemann, U., Kuhnt, W., and Bassinot, F. C.: Surface and subsurface seawater temperature reconstruction using Mg/Ca microanalysis of planktonic foraminifera *Globigerinoides ruber*, *Globigerinoides sacculifer*, and *Pulleniatina obliquiloculata*, Paleoceanography, 24, PA3201, doi:10.1029/2008PA001664, 2009.
- ²⁵ Schiffelbein, P. and Hills, S.: Direct assessment of stable isotope variability in planktonic foraminifera populations, Palaeogeogr. Palaeocl., 48, 197–213, 1984.
 - Schouten, S., Hopmans, E. C., Schefuß, E., and Sinninghe Damsté, J. S.: Distributional variations in marine crenarchaeotal membrane lipids: a new tool for reconstructing ancient sea water temperatures?, Earth Planet. Sc. Lett., 204, 265–274, 2002.
- ³⁰ Schulz, H., von Rad, U., Erlenkeuser, H., and von Rad, U.: Correlation between Arabian Sea and Greenland climate oscillations of the past 110,000 years, Nature, 393, 54–57, 1998.





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Singh, A. D., Jung, S. J. A., Darling, K., Ganeshram, R. S., Ivanochko, T. S., and Kroon, D.: Productivity collapses in the Arabian Sea during glacial cold phases, Paleoceanography, 26, PA3210, doi:10.1029/2009PA001923, 2011.

Sirocko, F., Sarnthein, M., Erlenkeuser, H., Lange, H., Arnold, M., and Duplessy, J.-C.: Century-

- scale events in monsoonal climate over the past 24,000 years, Nature, 364, 322–324, doi:10.1038/364322a0, 1993.
 - Stuiver, M. and Grootes, P. M.: GISP2 oxygen isotope ratios, Quaternary Res., 53, 277–284, 2000.

von Langen, P. J., Pak, D. K., Spero, H. J., and Lea, D. W.: Effects of temperature on Mg/Ca

- in neogloboquadrinid shells determined by live culturing, Geochem. Geophy. Geosy., 6, Q10P03, doi:10.1029/2005GC000989, 2005.
 - Wit, J. C., de Nooijer, L. J., Barras, C., Jorissen, F. J., and Reichart, G. J.: A reappraisal of the vital effect in cultured benthic foraminifer *Bulimina marginata* on Mg/Ca values: assessing temperature uncertainty relationships, Biogeosciences, 9, 3693–3704, doi:10.5194/bg-9-3693-2012, 2012.

15

- Wit, J. C., Reichart, G. J., and Ganssen, G. M.: Unmixing of stable isotope signals using single specimen δ^{18} O analyses, Geochem. Geophy. Geosy., 14, 1312–1320, 2013.
- Zhang, J.: Living planktonic foraminifera from the eastern Arabian Sea, Deep-Sea Res. Pt. I, 32, 789–798, 1985.

Core	Species	Period	Mean ∂ ¹⁸ O	δ^{18} O variability	Temp. Range	lce Vol. Corr.	Mg/Ca Mean Temp	Calc. δ^{18} O	Residual
			(‰)	(‰)	(°C) ^a	(‰) ^b	(°C)	(‰) ^c	(‰)
NIOP905P	G. ruber	IS8	-0.60	1.78	8.09	-1.30	20.7	-0.98	0.32
NIOP478P	G. ruber	IS8	-0.47	1.50	6.82	-1.17	25.2	-1.90	-0.73
NIOP905P	G. ruber	H4	-0.47	1.48	6.73	-1.17	21.4	-1.13	0.04
NIOP478P	G. ruber	H4	-0.14	1.92	8.73	-0.84	20.3	-0.90	-0.06
NIOP905P	G. bulloides	IS8	-0.21	2.01	9.14	-0.91	14.5	0.35	1.26
NIOP478P	G. bulloides	IS8	-0.37	1.56	7.09	-1.07	23.3	-1.52	-0.45
NIOP905P	G. bulloides	H4	-0.06	1.48	6.73	-0.76	12.7	0.75	1.51
NIOP478P	G. bulloides	H4	-0.60	2.67	12.14	-1.30	16.9	-0.17	1.13
NIOP905P	N. dutertrei	IS8	0.61	1.79	8.14	-0.09	16.2	-0.02	0.07
NIOP478P	N. dutertrei	IS8	0.34	1.20	5.45	-0.36	17.2	-0.24	0.12
NIOP905P	N. dutertrei	H4	0.57	2.10	9.55	-0.13	13.2	0.64	0.77
NIOP478P	N. dutertrei	H4	0.22	2.22	10.09	-0.48	13.8	0.51	0.99

Table 1. Average and range in δ^{18} O for both locations and all three species.

 a Temperature range is calculated by 1°C = 0.22‰ (Kim and O'Neil, 1997; O'Neil et al., 1969). b 0.7‰ ice volume correction (Bintanja and Van de Wal, 2008). c δ^{18} O calculated by reversing Kim and O'Neil (1997).

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Figure 1. Sea surface temperature map of the Arabian Sea for both monsoon seasons. Cores NIOP905P and NIOP478P are indicated with a star and diamond, respectively. Arrows reflect the dominant wind direction during these seasons.













Figure 3. SEM images of *N. dutertrei* (left) and *G. bulloides* (right). Ablation holes in *N. dutertrei* in three youngest chambers have a diameter of 80 μ m. Three holes in youngest chamber of *G. bulloides* have an ablation diameter of 40 μ m. Scale bar = 100 μ m.





Figure 4. Frequency distribution of Mg/Ca ratio's for *G. ruber, G. bulloides* and *N. dutertrei* for NIOP905P (top row) and NIOP478P (bottom row). Average SST calculated applying Bolton et al. (2011) (*G. ruber*), Marr et al. (2011) (*G. bulloides*) and Von Langen et al. (2005) (*N. dutertrei*) and number of specimens (*n*) measured are indicated in each histogram.





Figure 5. Frequency distribution of δ^{18} O values for *G. ruber, G. bulloides* and *N. dutertrei* for NIOP905P (top row) and NIOP478P (bottom row). Average SST calculated using the equation of Kim and O'Neil (1997) and applying a 0.7 ∞ correction (Bintanja and Van de Wal, 2008). Number of analysed specimens (*n*) is indicated above each histogram.







Figure 6. Cross-plot for average δ^{18} O and Mg/Ca for *G. ruber* (triangles), *G. bulloides* (diamonds) and *N. dutertrei* (circles) for IS8 (open markers) and HE4 (filled markers). Different sites are marked within the symbols with "a" for NIOP905P and "b" for NIOP478P.



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Figure 7. Schematic representation of mean temperature (dashed horizontal line) and temperature range (shaded areas) for δ^{18} O (colour) and Mg/Ca (grey) for *G. ruber* (rub; red), *G. bulloides* (bul; blue) and *N. dutertrei* (dut; green) during Interstadial 8 (IS8) and Heinrich event 4 (HE4). Range for δ^{18} O from Table 1 and Mg/Ca envelope calculated with smallest and largest outlier corrected value using species specific calibration curves for *G. ruber* (Bolton et al., 2011), *G. bulloides* (Marr et al., 2011) and *N. dutertrei* (von Langen et al., 2005).

