Biogeosciences Discuss., 11, 17255–17298, 2014 www.biogeosciences-discuss.net/11/17255/2014/ doi:10.5194/bgd-11-17255-2014 © Author(s) 2014. CC Attribution 3.0 License.



This discussion paper is/has been under review for the journal Biogeosciences (BG). Please refer to the corresponding final paper in BG if available.

Reconciling single chamber Mg/Ca with whole test δ^{18} O in surface to deep dwelling planktonic foraminifera from the Mozambique Channel

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Received: 7 November 2014 – Accepted: 10 November 2014 – Published: 12 December 2014 Correspondence to: J. Steinhardt (juliane.steinhardt@nioz.nl)

Published by Copernicus Publications on behalf of the European Geosciences Union.



Abstract

Most planktonic foraminifera migrate vertically through the water column during life, meeting a range of depth-related conditions as they grow and calcify. For reconstructing past ocean conditions from geochemical signals recorded in their shells it is there-

- ⁵ fore necessary to know vertical habitat preferences. Species with a shallow habitat and limited vertical migration will reflect conditions of the surface mixed layer and short- and meso-scale (i.e. seasonal) perturbations therein. Species spanning a wider range of depth habitats, however, will contain a more heterogeneous, intra-specimen variability (i.g. Mg/Ca a δ^{18} O), which is less for species calcifying below the sea-
- sonal mixed layer (SML). Here we present results on single-chamber Mg/Ca combined with single shell δ^{18} O and δ^{13} C of surface water *Globigerinoides ruber*, the thermocline-dwelling *Neogloboquadrina dutertrei* and *Pulleniatina obliquiloculata* and the deep dweller *Globorotalia scitula* from the Mozambique Channel. Species-specific Mg/Ca, δ^{13} C and δ^{18} O data combined with a depth-resolved mass balance model
- ¹⁵ confirm distinctive migration and calcification performs for each species as a function of hydrography. Whereas single specimen δ^{18} but always reveal changes in depth habitat related to hydrography (i.g. temperature), measured Mg/Ca of the last chambers can only be explained by active migration in response to changes in temperature stratification. Since species show different responses to changes in hydrography, their
- ²⁰ shell chemistry can be used to reconstruct different components of the past ocean climate system such as seasonality and depth stratification. Here we present combined single-specimen δ^{18} O and single-chamber Mg/Ca measurements for different species, providing a composite of thermocline and sub-thermocline conditions. These results allow for species-specific reconstruction of calcification depths, using a mass
- ²⁵ balance model, of four species of planktonic foraminifera. This shows that the single chamber Mg/Ca and single test δ^{18} O are in agreement with each other and in line with the changes hydrography induced by eddies. Whereas single chamber Mg/Ca are most affected by frequency, seasonality is reflected more clearly in single test δ^{18} O.



1 Introduction

Most planktonic foraminifera inhabit the upper 200 m of the water column, with exceptions of some species living as deep as 1000 m (e.g. Hemleben, 1989). The average depth habitat of individual species and the range of water depths at which they are

- ⁵ found reflect their ecology (e.g. feeding behavior), ontogeny and seasonal preferences. Stable oxygen isotope values (δ^{18} O) and Mg/Ca ratios (Shackleton et al., 1974; Fairbanks et al., 1980; Ortitz et al., 1996; Elderfield and Ganssen, 2000) have been used to reconstruct upper water column conditions using species with a known depth range (e.g. Ravelo et al., 1992; Patrick and Thunell, 1997; Faul et al., 2000; Cléroux et al.,
- ¹⁰ 2013). For many species, however, application of Mg/Ca as a seawater temperature proxy is complicated by depth migration as a function of ontogeny. Previous studies revealed major Mg/Ca heterogeneity within foraminiferal shells (e.g. Eggins et al., 2003; Hathorne et al., 2009; Kunioka et al., 2006; Jonkers et al., 2012), which were attributed to a combination of vertical migration during their life and vital effects. Nevertheless,
- ¹⁵ species-specific patterns of vertical migration and hence depth of calcification determine which part of the water column can be reconstructed.

Field observations show that most foraminiferal species do not occupy a single depth, but rather calcify at a range of depths. Many species migrate vertically as they grow and, therefore, the chemical composition (e.g. Mg/Ca and δ^{18} O) of their tests changes

- with age. Fairbanks et al. (1982) and Field (2004) suggested that foraminifera may modify their habitat depth depending on hydrographic condition and food supply. However, little is known about the exact controls on depth habitat, termination of shell growth and controls on shell features (e.g. formation of crusts). A better understanding of the vertical calcification pattern of different species is needed to reconstruct past changes
- ²⁵ in vertical structure of the water column by using geochemical proxies, e.g. for temperature (δ^{18} O and Mg/Ca). Using geochemical signals of species with different and well-constrained calcification depths (Emiliani, 1954; Mulitza et al., 1997) changes in water column conditions can be resolved.



Using core top samples from the Indian Ocean, Birch et al. (2013) report δ^{13} C and δ^{18} O measurements made on several species of planktonic foraminifera across a range of tightly constrained size windows. From size controlled δ^{18} O calcite trajectories they inferred depth habitats, using modern vertical temperature profiles. However, by using multiple core-top specimens this data set encompasses not only vertical changes in the water column structure, but also inter- and intra-annual changes therein,

which are both known to vary substantially in this region (McClanahan, 1988; Damassa et al., 2006; Hasenrath et al., 1992). In this study we use sediment trap samples, allowing analyses of specimens that lived during a confined time interval and link in situ hydrographic changes (e.g. temperature) more directly to their test chemistry.

Single-chamber Mg/Ca compositions from specimens with contrasting calcification depths (the surface-dweller *Globigerinoides ruber*, d'Orbigny, 1839, the thermoclinedwelling species *Neogloboquadrina dutertrei*, d'Orbigny, 1839 and *Pulleniatina obliquiloculata*, Parker et al., 1865 and the deep dweller *Globorotalia scitula*, Brady, 1882) reflect temperatures throughout the upper 500 m and were shown to reliably reflect short-term hydrographic changes (Steinhardt et al., 2014). Meso-scale eddies such as observed in the Mozambique Channel (MC) induce variations in temperature and salinity. Anticyclonic (anti-clockwise) eddies in the MC are characterized by

a warm water core and are associated with elevated sea surface heights and large vertical isopycnal excursions. Foraminifera living in the mixed layer of the MC are af-

- fected by eddy-induced changes, which is reflected by the geochemistry of *G. ruber* and *N. dutertrei* (Steinhardt et al., accepted), resulting in higher Mg/Ca ratios and more depleted $\delta^{18}O_{cc}$ values. These short-term changes in vertical water column temperature and $\delta^{18}O_{sw}$ distribution should influence shell $\delta^{18}O$ and Mg/Ca throughout the different ontogenetic stages for any species migrating during its life. Alternatively, foraminifera may respond to altered hydrographic conditions by changing their calcification depth. Here we present combined single-specimen $\delta^{18}O$ and single-chamber
 - Mg/Ca measurements for different species, providing a composite of thermocline and sub-thermocline conditions. Since single chamber Mg/Ca values cannot be compared



one-on-one with whole test δ^{18} O-values we evaluate our results using a mass balance model for depth related carbonate addition of four species of planktonic foraminifera.

2 Oceanographic setting

The Mozambique Channel (MC) (Fig. 1) is an oligotrophic region with spece water chlorophyll *a* concentrations between 0.30 mgm⁻³ in summer and 0.25 mgm⁻³ in winter. Sea surface temperatures (SST) in the MC vary seasonally and with eddy-induced transport (Fallet et al., 2011) The seasonal temperature change is associated with the monsoon system and shows SSTs ranging from 25 to over 30 °C with an annual mean of 27.6 °C. With the onset of Austral summer rainfall increases, caused by the seasonal migration of the ITCZ and sea surface salinities decrease slightly from 35.2 in winter to 34.9 in summer (Fallet et al., 2010). The main water masses of the upper part of the MC include the Tropical Surface Water (TSW), Subtropical Surface Water (STSW) and Indonesian Throughflow Water (ITFW). The warm, fresh surface water (TSW) forms in the tropics and is transported westward within or north of the South Equatorial Current (SEC; New et al., 2007). Close to the western margin, where the SEC bifurcates,

- warm surface waters are transported poleward, either east of Madagascar, or through the MC (e.g. Gründlingh, 1995; Swallow et al., 1988). The STSW is characterized by relatively high salinities and a subsurface maximum, with salinities of 35.2–35.5, at approximately 200 m below sea surface, at which depth the surface water subducts below
- the fresher TSW (Wyrtki, 1973). Southward migration of anticyclonic meso-scale eddies, originating at 10° S north off the Comoros Islands, affects the hydrography in the MC (Fig. 1). Eddies pass through the MC at a mean frequency of about four to seven per year (at a southward propagation speed of 3–6 kmd⁻¹) before joining the Agulhas Current. An eddy passage is associated with vertical movement of isopycnals, which
- ²⁵ can occasionally exceed 40 m day⁻¹ in the upper layer (Ullgren et al., 2012). Backeberg and Reason (2010) suggested that formation of meso-scale eddies in the Mozambique Channel is related to variability in SEC transport (Fig. 1).



3 Material and methods

3.1 Sediment trap and mooring array

Ongoing hydrographic observations in the MC started in November 2003, as part of the Long-term Ocean Climate Observations (LOCO) program, with an array of eight moor-

- ⁵ ings across the narrowest part of the channel, providing continuous current velocities, temperature and salinity measurements at fixed depths. Technicap PPS 5 sediment traps were deployed at 16.8° S and 40.8° E in the central MC (Fig. 1). Equipped with a 24-cup automated sampling carousel and a baffled collecting area of 1 m², the trap was positioned 250 m above the channel floor at 2250 m water depth. In total, four
- sediment trap deployments took place between November 2003 and February 2009, each programmed to a 17, 21 or 23 days sampling interval. Prior to deployments, sample cups were filled with an HgCl₂-poisoned and borax-buffered solution of seawater collected from the deployments depth (Loncaric et al., 2007). Sediment trap samples were wet-split, sieved and foraminiferal tests were cleaned as previously described (Fallet et al., 2009, 2010).

We selected the sediment trap intervals during which the complete sediment cup collection took place under either full eddy or full non-eddy conditions (Steinhardt et al., 2014; Supplement). For the selected collecting intervals, temperature and salinity observations from the mooring (Imc5a) are compiled and daily means were used to calculate eddy and non-eddy temperature profiles.

3.2 Temperature and salinity data

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For this study, we used temperatures recorded at 110, 200 at 400 m water depth by a CTD deployed on mooring Imc5A (16.8°S, 41.1°E, Fig. 1), which is closest to the sediment trap site. Moored salinity and temperature data, collected during the selected intervals of eddy and non-eddy conditions (Table S1 in the Supplement), was spline fitted in Analyseries 1.1.6 68 K to achieve meter-wise data resolution. Sea sur-



face temperatures were retrieved from the 4 km daytime MODIS/AQUA dataset around trap site (16–17° S and 40–41° E) for the period of the selected collecting intervals (http://podaac-tools.jpl.nasa.gov/las). Surface salinity data is not available for the complete deployment period and instead, CT assed salinity-depth profiles taken during the deployment/recovery cruises were used (Ullgren et al., 2012). Based on the trend observed in the moored salinity data at 100 m water depth (Ullgren et al., 2012; less saline during eddy condition) we use CTD minimum surface salinities to represent eddy surface salinities and maximum surface salinities to represent non-eddy conditions. Since salinity mooring data was nonexistent between 400 and 1525 m, we have chosen two more "anchor points" at 700 and 1000 m water depth from the CTD depth

sen two more "anchor points" at 700 and 1000 m water depth from the CTD depth profiles in order to better capture the Red Sea Water (RSW) advection at these depths and to achieve a more accurate salinity fitting curve for the upper 1000 m.

3.3 Planktonic foraminiferal species and ontogeny

From the sediment trap samples, we selected four species according to the depth stacking of their habitat as reported in previous studies. *Globigerinoides ruber* white is a shallow, surface mixed layer dwelling species (0–50 m), often used to reconstruct paleo-SST (Hemleben et al., 1989). The subsurface-dwellers *Neogloboquadrina dutertrei* and *Pulleniatina obliquiloculata* have been associated with a calcification depth of 0–100 and 60–150 m in the upper and middle thermocline, respectively
(Erez and Honjo, 1981; Fairbanks et al., 1982; Ravelo and Fairbanks, 1992; Spero et al., 2003; Field, 2004; Kuroyanagi and Kawahata, 2004; Huang et al., 2008). We included the deep-dwelling species *Globorotalia scitula* to analyse responses to deep water conditions (Bé, 1969; Ortiz et al., 1996; Itou et al., 2001; Fallet et al., 2011).

Measurements on *G. ruber* were usually performed on specimens in the 250–315 μ m size fraction. In a limited number of samples, abundances for of this species were low in this size fraction, and geochemical analyses were performed on specimens from a larger size fraction (315–400 μ m). Analyses on *N. dutertrei*, *P. obliquiloculata* and *G. scitula* were generally done on the size range > 315 μ m, with additional measurements



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on the 250–315 μm size fraction depending on the specimen abundance within the sample.

3.4 Mg/Ca measurements

Most of the Mg/Ca ratios of single chambers used in this study were previously published (Steinhardt et al., 2014) and was expanded Wh Mg/Ca values of the final chambers (F-0), determined by Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) at Utrecht University (Reichart et al., 2003). A GeoLas 200 Q Excimer 193 nm deep ultra violet laser (Lambda Physik) was used to ablate craters of 60 or 80 µm in diameter depending on the surface area of the chambers. Energy density at the sample surface was approximately 1 J cm⁻² and all samples were ablated with a repetition rate of 7 Hz in a He atmosphere. The sector field mass spectrometer (Element 2, Thermo Scientific) was run in low-resolution mode and masses monitored included ²³Na, ²⁴Mg, ²⁶Mg, ²⁷Al, ⁴³Ca, ⁴⁴Ca, ⁵⁵Mn, ⁸⁸Sr, ¹¹⁴Cd, ¹³⁸Ba and ²³⁸U. Calibration was performed against SRM NIST610 glass standard (using values from Jochum et al., 2011), using ⁴³Ca as an internal standard. The glass standard was ablated 15 at higher energy density (5 J cm⁻²), 3 times between every 10–12 foraminiferal samples. A matrix-matched, homogenous calcite crystal (Icelandspar) with known Mg/Ca and Sr/Ca (Raitzsch et al., 2010) was ablated to check for possible matrix dependent fractionation caused by the different energy densities when switching between glass and calcium carbonate (Dueñas-Bohórquez et al., 2011). Concentrations of Mg 20 in the foraminiferal shell were calculated using count rates for ²⁴Mg. Concentrations of Mg and confidence intervals for each individual measurement were calculated us-

ing the software package Glitter (Maquarie Research Limited, 1999–2000). The matrix matched in-house standard showed average relative SDs (SD) of 3.7% for Mg/Ca.

²⁵ Measurements were performed on intact specimens and always proceeded from the outside towards the inside. In total, 695 single-chamber element/Ca values were obtained for 373 specimens. Values deviating more than twice the SD from the averous of the total dataset were regarded as outliers (n = 28) and removed from the dataset.



3.5 Stable isotope analyses

All data shown here are measured on single shells. Whole shell δ^{18} O and δ^{13} C analyses were carried out on the same specimens used for LA-ICP-MS, after microscopic removal from the ablation stub with ethanol and inspection for possible contaminations.

- ⁵ Measurements were performed at the Universitat Autònoma de Barcelona on a Thermo Finnigan MAT253 mass spectrometer coupled to a Kiel IV device for CO₂ sample gas preparation. External reproducibility (1 σ) of δ^{13} C standards NBS19 and IAEA-CO was 0.04 ‰ and for δ^{18} O 0.08 ‰.
- Single shells from part of the sample set were analyzed using a Thermo Finnigan Delta Plus mass spectrometer equipped with a Gas Bench II preparation device at the VU University Amsterdam. Single specimens were loaded into round-bottom vials, which were subsequently flushed with He. The samples then reacted with phosphoric acid (H_3PO_4) injected into the vial producing CO_2 gas, which is transported in a helium stream to the mass spectrometer. Traps are used to remove residual H_2O from the
- ¹⁵ sample gas and the CO₂ is separated from other possible contaminant gases on a poraplot Q GC column. Reproducibility (1 σ) of δ^{13} C standards NBS19 and was 0.07‰ and for δ^{18} O 0.12‰. Values measured on the Kiel IV and the GASBENCH-II are comparable and species-specific δ^{18} O_{CC} are in good agreement. Measurements with the GASBENCH-II have a somewhat wider SD inherent to continuous flow mass spec-
- ²⁰ trometry. In total, 391 single test stable isotope values were obtained. Values deviating more than twice the SD from the ave \bigcirc of the total dataset were regarded as outliers (*n* = 23) and removed from the dataset.

The $\delta^{18}O_{sw}$, expressed on the SMOW scale is converted to Pee Dee Belemnite (PDB) scale by subtracting 0.27‰ (Hut, 1987). Various $\delta^{18}O$ -temperature equations have been proposed and discussed in detail in other studies (Bemis et al., 1998; Regenberg et al., 2009), without clear consensus on the most appropriate equation. Here, we integrated calcification depth for each species calculated by matching the foraminiferal calcite $\delta^{18}O_{CC}$ with the calculated calcite $\delta^{18}O_{eq}$ following Eq. (1) from



Kim and O'Neil (1997) for the temperature dependent fractionation of calcite by inorganic precipitation (assuming calcification in equilibrium with the ambient seawater).

$$\delta^{18}O_{eq} = 25.778 - 3.333 \times \sqrt{43.704 + 7} + \left(\delta^{18}O_{sw} - 0.27\right)$$
(1)

We extracted $\delta^{18}O_{sw}$ values from the South Indian Ocean for the upper 2000 m (4.5– 120.2° E; 0–32.9° S, N = 154) from the Global Seawater Oxygen-18 Database (http: //data.giss.nasa.gov/o18data/). Additionally we included in situ $\delta^{18}O_{sw}$ measurements from the MC, near the sediment trap location (41.08° E; 16.74° S) in order to determine the regional relationship between $\delta^{18}O_{sw}$ and salinity (Eq. 2)

$$S = 0.463 \times \delta^{18} O_{sw} - 15.9, r^2 = 0.87$$

¹⁰ This linear relationship (see Eq. 2) is subsequently used to generate $\delta^{18}O_{sw}$ values based on salinities measured in the proximity of the trap by moored T-S sensors during eddy and non-eddy conditions for depths ranging from 0 to 1000 m.

Seawater temperature and $\delta^{18}O_{sw}$ profiles for eddy or non-eddy conditions are used to compare the $\delta^{18}O$ data depending on the time interval sampled by the sediment trap. We used averaged $\delta^{18}O_{sw}$ from the depth range suggested by previously measured

¹⁵ We used averaged $\delta^{10}O_{sw}$ from the depth range suggested by previously measured single chamber Mg/Ca analyses (Steinhardt et al., 2014), to compare to the isotopic temperature of calcification (T_{iso}), which is calculated using the following equation:

$$T_{\rm iso} = 16.1 - 4.64 \times \left(\delta^{18} O_{\rm CC} - \left(\delta^{18} O_{\rm SW} - 0.27 \right) \right) \\ + 0.09 \times \left(\delta^{18} O_{\rm CC} - \left(\delta^{18} O_{\rm SW} - 0.27 \right) \right)^2$$



(2)

(3)

4 Results

4.1



The Mg/Ca data of the single chamber analyses were published previously in Steinhardt et al., 2014. In summary, average single-chamber Mg/Ca values of G. ruber are highest, followed by those of N. dutertrei and P. obliquilocuata, low-5 est values are observed in specimens of G. scitula. Average Mg/Ca values for *N. dutertrei* (2.6 mmol mol⁻¹, standard error: (SE): 0.06 mmol mol⁻¹, N = 228) correspond to lower temperature (22.5 °C) compared to ratios from G. ruber (average Mg/Ca = 5.32 mmol mol⁻¹, SE: 0.09 mmol mol⁻¹, N = 176). Average Mg/Ca values of N. dutertrei and P. obliguiloculata (2.29 mmol mol⁻¹, SE: 0.1 mmol mol⁻¹, N = 47) are similar and those of G. scitula are notably lower (on average 1.5 mm ol mol⁻¹, SE: 0.07 mmol mol⁻¹, N = 100), corresponding to temperatures of 14.4 °C. The inter test variability is highest in G. ruber (SD: $\pm 1.2 \text{ mmol mol}^{-1}$), followed by N. dutertrei (SD: $\pm 1.0 \text{ mmol mol}^{-1}$), *P. obliquiloculata* (SD: $\pm 0.6 \text{ mmol mol}^{-1}$), and is lowest in *G*. scitula (SD: ± 0.4 mmol mol⁻¹). Whereas most species show no trends in Mg/Ca in 15 subsequently build chambers, those in N. dutertrei increase towards the final chamber. Analysis of variance on ranks (Kruskal-Wallis One Way analysis) showed that the differences are significant at the P < 0.001 level. A pairwise Multiple Comparison Procedure was used to show that all chambers in N. dutertrei differ in Mg/Ca (Dunn's Method, P < 0.05). Generally, Mg/Ca values of the pre-penultimate chamber 20 (F-2; 2.40 ± 0.88 mmol mol⁻¹) are lowest and increase towards the final chamber (F-0; 3.30 ± 0.9 mmol mol⁻¹). This difference is most pronounced under non-eddy condition $(F-2 = 2.14 \pm 0.83; F-0 = 3.44 \pm 0.73 \text{ mmol mol}^{-1}).$

4.2 Oxygen isotopes

²⁵ Single specimen values of $\delta^{18}O_{CC}$ range from -3.50% to 2.65‰. Although the values measured on individual specimens clearly overlap, each species has a different aver-



age $\delta^{18}O_{CC}$ and $\delta^{13}C_{CC}$ (Figs. 2 and 3). The $\delta^{18}O_{CC}$ values are most depleted for *G. ruber*, somewhat more enriched in comparison to *G. ruber* for *P. obliquiloculata* and *N. dutertrei*, with most enriched values in *G. scitula* (Figs. 2 and 3). The relationship between temperature and $\delta^{18}O_{CC}$ is generally described with more depleted $\delta^{18}O_{CC}$ values indicating higher temperatures and thereby shallower calcification depths. Thus, each species has a distinct whole test- $\delta^{18}O$ signature, reflecting their different mean calcification depth. *G. ruber* (-2.57 SD : ±0.24‰, SE: ± 0.04‰), *N. dutertrei* and *P. obliquiloculata* record positive $\delta^{18}O_{CC}$ values between -2.52‰ (SD: ±0.42‰, standard error (SE): ±0.03‰) and -1.13‰ (SD: ±0.24‰, SE: ±0.04‰), more noticeable positive values are found for *G. scitula* with 1.47‰ (SD) (Fig. 3). No significant trend between size and stable isotopes was observed for any of the analyzed species over the size range we used, as confirmed by ANOVA tests (Kruskal–Wallis One Way Analysis of Variance on Ranks) of $\delta^{18}O_{cc}$ between the size fractions (*G. ruber*; p = 0.774, *N. dutertrei*; p = 0.500, *G. scitula*: p = 0.373).

¹⁵ No significant differences in δ^{18} O values for *G. ruber* and *N. dutertrei* were found between eddy and non-eddy conditions. As for the deeper dwelling species *P. obliquiloculata* (U = 54, P = 0.04) and *G. scitula* (U = 80, P = 0.021), most depleted δ^{18} O values were found during eddy conditions and non-eddy conditions, respectively (Fig. 3).

4.3 Carbon isotopes

Values for δ¹³C range from -1.5‰ to 2.0‰. Most enriched δ¹³C values are found in *N. dutertrei* (δ¹³C = 0.52‰, SD: ±0.44‰, SE: ±0.042‰), whereas values for *P. obliquiloculata* are most depleted (δ¹³C = 0.04‰, SD: ±0.21‰, SE: ±0.037‰). Individuals of *G. ruber* reflect a relatively large range in δ¹³C_{cc} values (0.39‰, SD: ±0.53‰, SE: ±0.06‰), whereas *G. scitula* (0.27‰, SD: ±0.22‰, SE: ±0.04‰) displays a much more limited variability in δ¹³C_{cc} (Fig. 3). Species specific δ¹³C-δ¹⁸O relationships (Fig. 2) differ and only *G. scitula* showed a go ive correlation between



single specimen carbon and oxygen isotope ratios (Fig. 2, $r^2 = 0.388$, p < 0.001).

Moreover, values for *G. scitula* differ from those of other species, with relatively depleted δ^{13} C (0.27 ‰, SD: ±0.22 ‰) and relatively enriched δ^{18} O values (1.47 ‰, SD: ±0.87 ‰).

From the four investigated species, only *G. scitula* (*N*) did not show a significant difference in δ^{13} C between eddy and non-eddy conditions. *G. ruber* (*N* = 200; Mann– Whitney rank sum test *U* = 3373, *p* = 0.002), and *P. obliquiloculata* (*N* = 33; *U* = 52, *p* = 0.032) showed significantly more positive δ^{13} C values during non-eddy conditions. During non-eddy condition however, *Dutertrei* (*N* = 118; *U* = 939.5, *p* = 0.002) recorded more negative δ^{13} C values (Fig. 3).

10 4.4 Calcification temperatures

The calculated multi-specimen T_{iso} from Eq. (4) and the single chamber Mg/Ca are positively, exponentially correlated (Fig. 4). Variability in this relationship is highest at higher (> 25 °C) temperatures. Mg/Ca-derived calcification temperatures, for *G. ruber* are on average 28.1 ± 2.8 °C, based on the calibration of Fallet et al. (2010) for this species in this region. Calcification temperatures for *N. dutertrei* and *P. obliquiloculata* are 21.8 ± 4 °C and 21.2 ± 3.1 °C, respectively, both based on species-specific calibrations from Anand et al. (2003). Mg/Ca ratios of *G. scitula* were transformed into temperatures using the equation for *G. hirsuta* (Anand et al., 2003) resulting in an average

- temperature of 14.9 ± 2.5 °C (Fig. 5). Calcification temperatures based on δ^{18} O result in markedly different values, ranging from 29.4 ± 4.3 °C for *G. ruber* to 24.6 ± 4.7 °C for *N. dutertrei*, 22.2 ± 2.3 °C, for *P. obliquiloculata* and 9.7 ± 7.4 °C for *G. scitula* Since *P. obliquiloculata* and *G. scitula* showed significant differences for $\delta^{18}O_{CC}$ between eddy and non-eddy conditions, we separately calculated temperatures for eddy and noneddy condition. Mean $\delta^{18}O$ from Eq. (4) for eddy intervals yield 23.1 ± 1.9 °C for *P. obliquiloculata* and 8.6 ± 2.1 °C for *G. scitula*. For non-eddy intervals calcification tem-
- ²⁵ *obliquiloculata* and 8.6 ± 2.1 °C for *G. scitula*. For non-eddy intervals calcification temperatures are 22.8 ± 1.9 °C for *P. obliquiloculata* and 12.2 ± 4.1 °C for *G. scitula* (Fig. 5).



5 Discussion

5.1 Single specimen isotope temperatures

The average, single-specimen $\delta^{18}O_{CC}$ of G. ruber reflect SSTs of 27.0 ± 2.2 °C-28.4 ± 2.1 °C (based on sediment-trap calibrations from Fallet et al., 2010 and Wilke 5 et al., 2009, respectively), which are close to satellite-derived annual mean SST of 27.6°C (Fallet et al., 2010). When only applying the equation of Kim and O'Neil (1997) for conversion of $\delta^{18}O_{CC}$ into temperature, however, SSTs are considerably higher $(29.4 \pm 2.3 \degree C)$. This discrepancy, may be caused by the fact that the calcite-water calibration of Kim and O'Neil (1997) is based on inorganic precipitation experiments, free of vital effects and therefore \bigcirc be offset compared to the temperature- $\delta^{18}O_{CC}$ relationship of biogenic carbonates. The shallow depth habitat of G. ruber in the MC is in line with previous studies showing that this species is confined to the photic zone (Deuser et al., 1981; Loncaric et al., 2006; Peeters and Brummer, 2002), because of the light requirement of its symbionts. Based on its relatively narrow preferred depth habitat, this species is a suitable tracer for (sub)tropical surface-water (0-100 m, mixed layer) conditions (e.g. Deuser, 1987; Anand et al., 2003; Field, 2004; Fallet et al., 2010). Birch at al. (2013) show that test size of specimens of G. ruber is not correlated to $\delta^{18}O_{cc}$, confirming that this species occupies a narrow calcification depth during its life. In addition to its shallow living depth, G. ruber is known to occur relatively equally throughout the year (e.g. Deuser, 1987; Mohtadi et al., 2006; Tedesco et al., 2007), whereas in other 20 areas, including the MC, they occur at highest densities during summer months (Tolderlund and Bé, 1971; Duplessy et al., 1981; Ganssen and Sarnthein, 1983; Deuser and Ross, 1989; Equchi et al., 2003; Loncaric et al., 2006; Fallet et al., 2010). This seasonal preference results in SST's that are slightly biased towards summer conditions when

²⁵ using fossil specimens of this species.

Based on an average $\delta^{18}O_{CC}$ -derived temperature of 21.8±4^C, calcification depths of *N. dutertrei* are in the range of 20–100 m (Fig. 6) with an average of 58 m. For eddy conditions, the average calcification depth is approximately 80 m, for non-eddy condi-



tion it is approximately 37 m. Previous studies using *N. dutertrei* from Indian Ocean core top samples and Mozambique Channel sediment traps have reported similar depth ranges of (40–150 m; Kiefer et al., 2006) and similar average depths (80 m; Fallet et al., 2011), respectively. Both of these studies used pooled specimen for their sta-

- ⁵ ble isotope analysis and hence provided the population's average calcification depth. Moreover, pooling of specimens from sediment core samples (Kiefer et al., 2006) does not allow for resolving short-term variability in calcification temperatures as do single specimens (e.g. seasonality). The inferred calcification depth for *N. dutertrei* is in line with its characterization as an intermediate deep dwelling species, living preferentially
- ¹⁰ in the seasonal thermocline (e.g. Fairbanks et al., 1982; Curry et al., 1983; Eguchi et al., 2003; Farmer et al., 2007), coinciding with a deep chlorophyll maximum (Fairbanks et al., 1980; Ravelo et al., 1990). Overall living depth of this species is confined to the upper 200 m (Farmer et al., 2007; Kroon and Darling, 1995). Variability in Mg/Ca within single specimen test walls of *N. dutertrei* from the Timor Sea suggested temper-
- atures be the number of the entire thermocline (Eggins et al., 2003). However, most calcification seems limited to a much smaller depth interval and the extremes in Mg/Ca might reflect upper and lower depth limits occupied by this species. Moreover, banding of Mg/Ca in she calcification events (Elderfiel et al., 1996; Erez et al., 2003) Plankton tow
 studies (Fairbanks et al., 1980) showed oxygen isotope equilibrium calcification for *N. dutertrei* and *P. obliguiloculata*.

The δ¹⁸O_{CC}-based calcification depths for *P. obliquiloculata* reported here (55–112 m, with an average of 74 m, Fig. 6) are in close agreement with those reported previously (e.g. between 60 and 80 m; Mohtadi et al., 2009). Indeed, in plankton tows
²⁵ from the central equatorial Pacific the largest abundance of adult *P. obliquiloculata* with a terminal cortex was found below 60 m (Watkins et al., 1996). All specimens used in this study had the distinctive smooth outer cortex that envelops the final whorl in the adult as well as an arched aperture (Watkins et al., 1996). Non-corticated *P. obliquiloculata* ("juveniles") are confined mostly to the mixed layer (Watkins et al., 1996), indicat-



ing migration to greater depths at the time of cortex formation during the terminal stage of its life cycle (Erez and Honjo, 1981; Hemleben et al., 1989; Ravelo and Fairbanks, 1992).

Previous studies indicated that δ^{18} O-derived temperatures of *G. scitula* are associated with a vital effect of -1.16 % positively off-setting temperatures by approximately 4 °C (Kahn and Williams, 1981). Subtracting the suggested vital effect, the actual ambient seawater temperature at the inhabited depth would be 14.3 ± 3.9 °C, which elevates the inferred average calcification depth to 300 m (ranging between 175 and 500 m). Without such an offset, as used in this study, the average $\delta^{18}O_{CC}$ for *G. scitula* yields a calcification temperature of 10.3 ± 3.9 °C, suggesting that this species calcifies between 300 and 1000 m (Fig. 6) with an average of approximately 500 m.

Birch et al. (2013) support previous findings of a distinct positive correlation between δ^{18} O and size in *G. scitula* (e.g. Friedrich et al., 2012), which is linked to a substantial ontogenetic vertical migration through the water column. Largest individuals have been inferred to live below the thermocline, consistent with the supposed absence of symbionts in this species. This is in line with our observations, showing higher interspecimen variability in δ^{18} O_{CC} for *G. scitula*, than in the other species.

5.2 Habitat depth vs. calcification depth

Planktonic foraminifera collected by sediment traps might record $\delta^{18}O_{cc}$ signals com-²⁰ prising calcification at various depths and thus document an *apparent* average calcification depth by integrating the entire calcification history of the specimen. Given changes in seawater temperature with water depth, even minor changes in the upper or lower range of the depth at which planktonic species calcify, can have a profound effect on the average $\delta^{18}O_{cc}$ and reconstructed temperature. Since evidence is accumulating that some species have a flexible calcification range (e.g. due to seasonality or local hydrography; Loncaric et al., 2006; Wilke et al., 2009), interpretation of down core stable isotope data in terms of thermal structure may be challenging. Therefore, it is crucial to accurately quantify the impact of environmental factors on depth prefer-



ences of planktonic foraminifera. Contrasting eddy and non-eddy conditions, a short-term feature, allow to disentangle seasonal and other short-term local hydrography changes and their effect on foraminiferal calcification depth.

- Using the paleo-temperature equation (Eq. 1; Kim and O'Neil, 1997) and fitting $\delta^{18}O_{calc}$ with $\delta^{18}O_{cc}$, we find that *G. ruber* calcifies on average at the sea surface (down to 7 m during non-eddy conditions and down to 18 m under eddy conditions) (Fig. 6). *N. dutertrei* calcifies on average between 12 and 120 m during eddy conditions (average calcification depth 81 m) and between 17 and 58 m under non-eddy conditions (average 37 m). During eddy conditions, *P. obliquiloculata* calcifies between
- 89 and 124 m (average 107 m), whereas it calcifies a shallower calcification depth during non-edd ndition between 20 and 77 m is being inferred (average calcification depth 60 m). Largest changes in calcification depth in this study is inferred from *G. scitula*. From a calcification range between 503 to 1098 m and an average calcification around 716 m during eddy condition it shifts to a calcification range from 168 to 745 m
 and an average calcification depth of 343 m (Fig. 6). If we apply the suggested 4°C
- offset for *G. scitula* calcification depth of 54311 (Fig. 6). If we apply the suggested 4 C offset for *G. scitula* calcification depth ranges shoal during eddy condition to 303 to 515 m (average 387 m) and during non-eddy to 95 to 350 m (average 178 m).

While Mg/Ca-based temperatures of *G. ruber* and *N. dutertrei* record eddy induced changes in upper water column stratification, δ^{18} O-based temperatures suggest relation relations and the stratification of the strategiest relation of the strategiest relation.

- atively similar calcification depths for both species (Fig. 6). Conversely, while $\delta^{18}O_{cc}$ suggests a significant change in average calcification depth for *P. obliquiloculata* and *G. scitula*, the Mg/Ca of the last formed chambers of *P. obliquiloculata* indicate similar calcification depth. Mg/Ca inferred calcification temperatures, representing the depth occupied at the later stages of the foraminifer's life, were similar between eddy and
- non-eddy conditions. Nonetheless, temperature mooring data show a steep temperature gradient, coinciding with the habitat depth of *G. scitula*, and thereby revealing a wide range of calcification depth for this species, changing significantly with deepening of the thermocline during eddy passage.



Inferred higher variability in calcification temperature for G. ruber presented in this study com a to observed satellite SST likely results from the spatial resolution employed hele. Inter-individual differences in depth migration add to the variability in isotopes and element/Ca ratios when measuring single specimens. Potential effects of ontogeny on stable isotope composition are minimized by using narrow size fractions, as confirmed by the lack of ontogenetic trends with test size in our measurements. Russell and Spero (2000) concluded that natural variability in oxygen isotopes is species specific. Measuring single specimen $\delta^{18}O_{cc}$ of *G. ruber* shells from sediment traps in the eastern equatorial Pacific, they show that over a 1.5-3 day period, the SD of δ^{18} O results in a temperature variability of ±0.87 °C. Such a variability could explain between 12 and 38 % of the variability in δ^{18} O-based temperatures in our samples. Another cause of natural variability might be differences in depth at which an individual calcifies. In laboratory cultures, the addition rate of new chambers in G. sacculifer ranges from 1.6 to 6.2 days (Bé, 1981), while chamber formation in G. hirsuta and G. truncatulinoides takes about 5 to 6 h (Bé, 1979). Considering that our sample dura-15 tion ranges between 17 and 21 days δ^{18} O variability is likely to be affected by other parameters (e.g. temperature). Therefore, the observed variability in δ^{18} O-based temperatures caused by species specific natural variability in $\delta^{18}O_{CC}$ (e.g. Russell and Spero, 2000) during the time it takes to add new chambers, which might be calcified

²⁰ under different conditions or water depth.

5.3 Reconciling δ^{18} O and Mg/Ca-derived calcification depths

Mg/Ca-derived temperatures indicate that calcification depths of *N. dutertrei* ranges between 42–169 m (average depth: 81 m) under non-eddy conditions and between 13 and 196 m (average depth: 98 m) during eddy conditions. Thus, the shoaling in average calcification depth from 98 m during eddy conditions to 81 m during non-eddy conditions, indicated from the whole shell $\delta^{18}O_{cc}$ is less as that inferred from Mg/Ca, derived from the calcification of the last chambers. A more pronounced trend is present in Mg/Ca of *P. obliquiloculata*, shifting between 70 and 90 m (average 75 m) during



non-eddy conditions, to depths between 147 and 244 m (average 150 m) during eddy conditions. The Mg/Ca-derived shift is hence bigger than the shift inferred from $\delta^{18}O_{CC}$ (eddy: 107 m and non-eddy: 60 m). Mg/Ca-derived calcification temperatures for *N. dutertrei* and *P. obliquiloculata* are hence cooler and indicative of deeper calcification

- ⁵ of the final chambers compared to that of the whole shell (based on $\delta^{18}O_{cc}$). Calcification temperatures derived from Mg/Ca for *G. scitula* (Fig. 5), indicate an opposite trend, shifting between 257 and 320 m (average 340 m) during eddy conditions to shallower depths between 265 and 287 m (average 230 m) during non-eddy conditions. Depth range based on vital effect corrected $\delta^{18}O_{CC}$ of mid to large (adult) specimens
- ¹⁰ of this species in our study shoal from eddy condition (between 303 and 515 m with an average of 387 m) to non-eddy conditions (between 95 and 350 m with an average of 178 m). Thus, applying the 4°C offset to the δ^{18} O inferred temperatures shifts calcification depth closer to those inferred from Mg/Ca for *G. scitula*. Both, Mg/Ca and δ^{18} O-derrived calcification depth indicate a shoaling for this species. The range of un-
- ¹⁵ certainties related to a species' average calcification depth results from the relatively large natural inter-specimen variability in Mg/Ca. Since we focus on relative differences within species between hydrographic conditions, the uncertainty in calcification temperature resulting from errors in the applied Mg/Ca-temperature calibration does not affect the absolute temperature differences between the eddy- and non-eddy condi-
- tions. Instead, uncertainties in the calculated difference in calcification depths between species will be caused by the inter-specimen variability in Mg/Ca.

5.3.1 Cumulative calcification model

We used a conceptual oxygen isotope mass balance model (Wilke, 2005), applying the temperature fractionation from inorganic calcite precipitation of Kim and O'Neil (1997)

to our measured $\delta^{18}O_{CC}$. The model equation describing foraminiferal migration as a function of depth used here is known as the cumulative form of the Weibull function (Weibull, 1939). It is a continuous probability function (Eq. 5), relating the shell mass 'M'



to depth (z) using two constants (α and β) determining the shape of this relationship:

 $M(z) = 1 - \exp(-1 \times (z/\beta)^{\alpha})$

Since test size of planktonic foraminifera is thought to increase with water depth (Hemleben and Bijma, 1994; Peeters and Brummer, 2002) shell mass must also in-⁵ crease with depth. The isotopic composition of a single shell thus represents the weighted sum of equilibrium calcite precipitated over a depth range of the productive zone (i.e. where primary calcite formation takes place).

Based on Eq. (5), the expected stable isotope composition of a specimen for a discrete water depth interval can be calculated as follows:

$${}_{10} \quad \delta^{18} O_{\text{model}} = \sum_{i}^{n} \frac{(M_i - M_{i-1}) + \delta^{18} O_{\text{eq},i}}{M_i}$$
(5)

Given the $\delta^{18}O_{eq}$ profile in the water column and the measured $\delta^{18}O_{cc}$ of the planktonic foraminifera it is possible to model the mass development (growth pattern) by using the determined Mg/Ca calcification der of the last chambers, indicating the base of the calcite production zone. In Eq. (6), $O_{eq,i}$ denotes the interval averaged

 δ^{18} O of equilibrium calcite for the specified depth interval. For convenience, shell mass at the sea surface was taken as zero and modelled $\delta^{18}O_{cc}$ was done by adapting the variables " α " and " β " in Eq. (5).

Increasing the value of " α " results in a growth curve with a narrow calcification range. Higher values for " β " result in a deepening of the growth curve, thereby determining the

²⁰ position of the base of the productive zone. In contrast to Wilke's (Wilke et al., 2006) approach, we have determined the calcification temperatures of the last three to four chambers, which were used to constrain the base of the calcification range and hence constrained values for " β ".

In this model, it is assumed that shell growth always follows the same function, which is continuous and does not differ between species. Offsets between $\delta^{18}O_{CC}$ and



(4)

 $\delta^{18}O_{sw}$ from expected equilibrium ("the vital effect"), is assumed to be constant over the temperature range in which the species calcifies. We have adapted $\delta^{18}O_{cm}$ in meter steps as calculated from in situ salinity measurements, which where interpolated for the upper 2000 m. We have used expected $\delta^{18}O_{eq}$ values of eddy and non-eddy condition to compare depth distributions for all four species of planktonic foraminifera. 5 Calcification depths inferred from the cumulative δ^{18} O model (Fig. 7) match previously published calcification depths and associated temperatures for the each species relatively well (e.g. Cléroux et al., 2008, 2013; Wilke et al., 2009; Fallet et. 2010, 2011; Birch et al., 2013). In three species, measured $\delta^{18}O_{CC}$ values reflect shallower calcification depths than do single-chamber Mg/Ca-based calcification depths, which is 10 consistent with the general model of migration to greater depth during growth. In case of the deep dwelling G. scitula, however, δ^{18} O-based calcification depth is below that of the final chambers as derived from Mg/Ca-temperatures. Without applying a temperature correction for δ^{18} O-based calcification temperatures of *G. scitula*, calcification depth based on $\delta^{18}O_{CC}$ can deviate up to 300 m from the Mg/Ca based depths. This 15 would suggest that the majority of the previously formed calcite was precipitated deeper in the water column. For our calcification model we corrected $\delta^{18}O_{CC}$ for the vital effect

(Kahn and Williams, 1981). The model shows that species modulate their calcification pattern depending on the hydrographical conditions they live in (e.g. eddy, non-eddy condition). For *G. ruber*, our results show that this species seems to be an exclusive surface dweller and hence an application of the cumulative calcification model only confirms that the majority of the calcite is formed at the sea surface.

For the thermocline dwelling species *N. dutertrei* we find that this species calcifies most of its calcite in a narrow depth range. Our model indicates that calcification during eddy conditions is more intense in the deeper part of the thermocline ($\alpha = 8.8$; $\beta = 85$), whereas calcification during non-eddy condition is more equally distributed over the entire thermocline ($\alpha = 1.9$; $\beta = 47$). It is noteworthy that *N. dutertrei* appears to intensify its calcification efforts during eddy conditions deeper in the thermocline, matching well with the deepening of the isopycnals and hence a narrower range of optimal calci-



fication conditions (Steinhardt et al., 2014). This calcification response is also reflected in more enriched δ^{13} C values during eddy conditions. For *P. obliquiloculata* modelled α and β values are relatively high, particularly during eddy conditions ($\alpha = 5.25$; $\beta = 133$, compared to $\alpha = 3.1$; $\beta = 63$ for non-eddy conditions). This indicates that most of the

- ⁵ calcification in *P. obliquiloculata* takes place at a water depth around 125 m during eddy conditions, and around 50 m during non-eddy conditions. The range at which *G. scitula* calcifies is well below the seasonal thermocline, reflected by high values for α and β (Fig. 7) and does not vary considerably during eddy and non-eddy conditions.
- In general, we conclude that temperature changes within the thermocline induced by eddies affect non-symbiotic species mostly. Also, changes in cumulative calcite addition 10 with depth seem to be species-specific. We modified the model's equation by including a component to account for "ontogenetic effects". This allows to predict expected $\delta^{18}O_{eq}$ for different species and shell sizes (Spero et al., 1997; Bijma et al., 1999; Itou et al., 2001; Peeters et al., 2002). The extended version of the model does not distinguish between calcite deposited during chamber formation (primary calcite) and 15 calcite added as a result of wall thickening due to gametogenic calcite or the precipitation of crust (secondary calcite, Bé, 1980; Duplessy and Bé, 1981; Lohmann, 1995; Jonkers et al., 2012). Secondary calcification might play an important role for deeper dwelling species such as G. scitula, which could explain the offset (0.48%) between $\delta^{18}O_{model}$ and $\delta^{18}O_{CC}$ during non-eddy conditions. This suggests that relatively more 20 calcite is formed deeper in the water column, or secondary calcite is precipitated with a fundamentally different calcification mechanism.

5.3.2 Carbon isotopes - testing the calcification model

The δ^{13} C values found in planktonic foraminifera is primarily a function of the carbon ²⁵ isotope composition of the dissolved inorganic carbon (DIC) in seawater (e.g. Urey, 1947; Epstein et al., 1953; McCorkle et al., 1990). Photosynthesis by symbionts and respiration affect the foraminiferal test δ^{13} C (e.g. Grossman, 1987; Spero and Lea, 1993; Bemis et al., 1998), as do light intensity, foraminiferal size and pH (e.g. Oppo



and Fairbanks, 1989; Spero et al., 1991). The effect of light intensity on test δ^{13} C is attributed to symbionts and their photosynthetic activity, preferentially fixing ¹²C and leaving a ¹³C-enriched DIC pool for calcification. Food availability and foraminiferal diet (Bé et al., 1977; Spero et al., 1991; Ortiz et al., 1996) may have additional, although minor effects, on shell δ^{13} C signatures. Together, these controls result in a decrease in planktonic foraminiferal δ^{13} C with depth from the surface to the deeper parts of the water column (e.g. Fairbanks et al., 1980; Curry and Crowley, 1987).

5.3.3 Ontogenetic effect

In our results, there is no size-related trend in the measured stable carbon isotopes. We thus suggest that the employed size fractions contained only mature (adult) specimens (Brummer et al., 1986, 1987). This is supported by previous findings that larger (adult) foraminifera have a smaller surface to volume ratio, tend to grow more slowly and show decreased metabolic activity and less kinetic fractionation (Berger et al., 1978; Kahn, 1979; Vincent and Berger, 1981; Wefer and Berger, 1991; Ravelo and Fairbanks, 1995; Ortiz et al., 1996; Spero et al., 1997). Additionally, low temperatures and reduced food availability will result in relatively low metabolic rates in deep dwelling species, so that their δ^{13} C likely approaches δ^{13} C_{DIC} values (Birch et al., 2013).

5.3.4 Foraminiferal δ^{13} C vs. seawater δ^{13} C DIC

Using the cumulative mass balance model output of the mass added per meter for each species, we calculated $\delta^{13}C_{expect}$ as the weighted sum of the $\delta^{13}C_{DIC}$ (Wilke et al., 2006). Depth-resolved carbon isotope composition ($\delta^{13}C_{DIC}$), available from locations closest to our study site (locations between 37–43° E and 24.7° S, World Ocean Database 2009) were used to calculate the expected $\delta^{13}C$ of the foraminifera ($\delta^{13}C_{expect}$). Comparing water column $\delta^{13}C_{DIC}$ data (Supplement, Fig. S1) from several stations near the MC reveals that absolute values and depth range over which values



decrease is similar at the different sites. To verify the depth related calcification model we compare measured $\delta^{13}C_{CC}$ with model-based $\delta^{13}C_{expect}$ values (Fig. 8).

Carbon isotope values become more negative from surface dwelling *G. ruber* towards deeper dwelling *P. obliquiloculata* near the upper thermocline. Conversely, δ^{13} C

⁵ of the *Globorotalia scitula* increases with depth. This suggests the involvement of biological controls on the δ^{13} C of the different genera (*Globigerinoides, Neoglobo-quadrina, Pullentiatina and Globorotalia*). All $\delta^{13}C_{expect}$ are higher than the measured $\delta^{13}C_{CC}$.

Our cumulative mass balance shows that the majority of the carbonate of *G. ru-*¹⁰ *ber* is formed in surface waters (Fig. 7). Equal $\delta^{13}C_{expect}$ values for eddy and noneddy conditions are the result of similarly enriched $\delta^{13}C_{DIC}$ in the mixed layer. The measured differences in $\delta^{13}C_{CC}$ (Fig. 8) is likely a consequence of the deepening thermocline during passage of an eddy,-carrying nutrient-depleted waters (Kolasinski et al., 2013). Anticyclonic eddies are characterized by accumulation of warm, nutrient-¹⁵ poor and chlorophyll-depleted water in the center, which implies that also $\delta^{13}C_{DIC}$ is more isotopically enriched. Still, local nutrient enrichment potentially occurs at the outer edge as a result of high turbulence along the isopycnal slope (e.g. Falkowski et al., 1991; Lévy, 2003). The strong response of the Mg/Ca and δ^{18} O of *N. dutertrei* dur-

²⁰ ing eddy conditions (deeper calcification) is also reflected by more depleted $\delta^{13}C_{CC}$ ²⁰ values. Remineralization at greater depth cause enrichment of $\delta^{13}C_{DIC}$, resulting in ²⁰ the incorporation of lighter carbon isotopes into the test of *N. dutertrei* during eddy conditions. Based on samples from a sediment trap in Cape basin, Wilke et al. (2009) showed that the species *N. dutertrei* is an accurate recorder of the $\delta^{13}C_{DIC}$. This is in agreement with previous findings (Mulitza et al., 1999), showing that the carbon ²⁵ isotopic composition of *N. dutertrei* exhibits a constant and temperature-independent off-set from $\delta^{13}C_{DIC}$ of ~ 0.5% over a wide temperature range. This difference is in line with the offset in our dataset between $\delta^{13}C_{expect}$ and $\delta^{13}C_{CC}$ of *N. dutertrei* (0.6%).



The δ^{13} C of the symbiont-barren *G. scitula* significantly deviates from those of the shallower dwelling species as a result of a decrease in $\delta^{13}C_{DIC}$ with water depth (Figs. S1 and S2). The more depleted $\delta^{13}C_{CC}$ of *G. scitula* may also be a consequence of a lower metabolism of this species (Vergnaud-Grazzini, 1976; Kahn, 1977, 1979; Berger et al., 1978; Erez, 1978) compared to that of *G. ruber* and *N. dutertrei*. At high metabolic activity, more isotopically lighter carbon is incorporated and since lower temperatures usually reduce metabolic rates, species inhabiting deeper water depths may incorporate relatively heavier carbon isotopes. Minor changes in $\delta^{13}C_{CC}$ for *G. scitula* during eddy vs. non-eddy conditions are in line with the minor response in calcification depth for this species. Similar to previous conclusions, this suggests that Mg/Ca inferred temperature differences between *N. dutertrei* and *G. scitula* are good indicators for eddies passing (Steinhardt et al., 2014). In addition, the $\delta^{13}C_{CC}$ differ-

ences between these species might very well help to reconstruct eddy frequency in this area. The depth integrated difference between δ^{13} C of *N. dutertrei* and *G. scitula* changes from 0.25 to 0.05 ‰.

Comparing $\delta^{13}C_{expect}$ and $\delta^{13}C_{CC}$ for *P. obliquiloculata* there is a discrepancy between eddy and non-eddy conditions (Fig. 8). Similar to *N. dutertrei*, this species is mostly associated with the thermocline (Anand et al., 2003; Cléroux et al., 2008; Sadekov et al., 2009). Our cumulative calcification model showed a slightly deeper calcification depth for *N. dutertrei* and a minor eddy response in calcification range (Fig. 7). However, $\delta^{13}C$ values indicate a significant difference between eddy and noneddy conditions. Mulitza et al. (1999) showed that *P. obliquiloculata* does not calcify in isotopic equilibrium with dissolved $\sum CO_2$, but the deviation from isotopic equilibrium is a linear function of temperature (Fig. 8). While the mean of the $\delta^{13}C$ cannot be used to infer the actual calcification depth, they argue that the spread and skewness of the in-

 δ^{13} C measurements should still be representative of the range of calcification depths and habitat preferences within the thermocline.

Also changes in the carbonate ion concentration with depth potentially play an important role in the observed differences between species and between eddy and non-eddy



conditions (Figs. S1 and S2). Since the carbonate ion profile is expected to change in accordance with thermocline deepening when an eddy passes we refrained from correcting for this. The observed offsets between species, however, suggest that carbonate ion does play a role there. The deeper living species show an increasing offset with respect to the 1 : 1 line (Fig. 8). The exception is *P. obliquiloculata* which responds to temperature rather than $\delta^{13}C_{\text{DIC}}$ carbonate ion changes (Mulitza et al., 1999).

Overall the here observed relations indicate that interpretation of the foraminifera vertical distribution in the upper water column can be unraveled by coupling various geochemical methods in order to retrieve calcification temperature at different stages

¹⁰ in a foraminifera's life cycle. This in turn can be used to develop new proxies for the thermal and nutrient structure of the upper part of the water column.

6 Conclusions

Documenting changes in upper ocean stratification is essential for understanding past climatic conditions from sediment cores and is commonly estimated by determining the

- ¹⁵ difference in δ^{18} O between thermocline and surface-dwelling planktonic foraminifera (Spero et al., 2003; Cléroux et al., 2007; Farmer et al., 2007; Lin and Hsieh, 2007; Steph et al., 2009). We conducted stable isotope measurements on four species of planktonic foraminifera (*G. ruber*, *N. dutertrei*, *P. obliquiloculata* and *G. scitula*) from selected sediment trap samples, representing eddy and non-eddy conditions in the
- ²⁰ MC. All species analyzed have unique offsets from ambient seawater δ^{13} C. However, comparison of species specific isotopic trajectories with water column δ^{13} C reveals that ambient δ^{13} C_{DIC} may be recorded by the species used in this study. The δ^{13} C of *N*. *dutertrei* and *G. scitula* show eddy related changes in their offsets and can potentially aid to unravel eddy related changes in the nutrient structure.
- ²⁵ Using single shell $\delta^{18}O_{CC}$ paired to single-chamber LA-ICP-MS Mg/Ca measurements we applied a cumulative mass balance model in order to compare growth patterns of the various planktonic species during eddy and non-eddy conditions. The re-



sults indicate that most of the species have somewhat different calcification patterns during eddy and non-eddy conditions. Only Mg/Ca values of *G. scitula* suggest higher calcification temperatures than inferred from δ^{18} O. Furthermore, the results of the δ^{18} O cumulative mass balance model agree with previous findings that thermocline dwelling *N. dutertrei* and deep dwelling *G. scitula* are suitable recorders of eddy induced hy-

drographic changes (Steinhardt et al., 2014). The combination of various proxies (e.g. Mg/Ca, δ^{18} O and δ^{13} C) can thus provide a useful set of geochemical proxies to reconstruct the thermal and nutrient structure of the upper part of the water column.

The Supplement related to this article is available online at doi:10.5194/bgd-11-17255-2014-supplement.

Acknowledgements. We acknowledge funding from the European Commission 7th Framework Marie Curie People program FP7/2007–2013 through funding of the Initial Training Network "GATEWAYS" (http://www.gateways-itn.eu) under the grant number 238512. Furthermore we acknowledge funding from the LOCO programs. Analyses and visualizations of satellite SST used in this paper were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC. We thank the chief scientist Herman Ridderinkhof and the crew of the RRV Charles Darwin, RRV Discovery, FS Meteor, RV Pelagia and FS Algoa. Great thanks to Helen de Waard and Michiel Kienhuis for providing technical support with the trace element analysis at Utrecht University and Suzanne Verdegaal for supporting the measurements at the Vrije Universiteit Amsterdam.

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Figure 1. Hydrography of southwestern Indian Ocean and location of the sediment trap (star). EACC: East African Coastal Current, SEC: South Equatorial Current, AC: Agulhas Current.





Figure 2. Scatter plot of single shell δ^{13} C vs. δ^{18} O. Note the linear relation in *G. scitula* $(r^2 = 0.388, p < 0.001).$

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Interactive Discussion









Figure 4. Scatter plot of Mg/Ca vs. $\delta^{18}O_{cc}$ (left panel). Right panel: single chamber Mg/Ca exponential relationship with $\delta^{18}O$ -derived Temperatures calculated using Kim and O'Neil (1997). Regression: $f = y_0 + a \times x + b \times x^2$, with a = -0.077, b = 0.006, $y_0 = 1.48$, $r^2 = 0.49$ using F-1/2 Mg/Ca from *G. ruber*, F-0 for *N. dutertrei*, *P. obliquiloculata* and *G. scitula* (black circles). F-1 for *N. dutertrei*, *P. obliquiloculata* and *G. scitula* (black circles). F-1 for *N. dutertrei*, *P. obliquiloculata* and *G. scitula* (blue circles).





Figure 5. Inter-species δ^{18} O- and Mg/Ca-derived temperature for eddy and non-eddy intervals. Circles: δ^{18} O-based temperatures, squares represent Mg/Ca-based temperatures. Vertical error bars (SD) for δ^{18} O derived temperatures, horizontal error bars (SD) for Mg/Ca derived temperatures. Red colors: *G. ruber*, blue: *N. dutertrei*, orange: *P. obliquiloculata*, green: *G. scitula*.





Figure 6. Apparent calcification depths for eddy (red) and non-eddy conditions (blue) calculated from single specimen $\delta^{18}O_{cc}$ using in situ temperature and $\delta^{18}O_{w}$. Calcification depth was determined by matching the measured foraminiferal $\delta^{18}O_{cc}$ with the $\delta^{18}O_{eq}$, sing the equation of Kim and O'Neil (1997). We used $\delta^{18}O_{SW}$ from the species calcification depth. Grey box inticates the zone of the close-up on the right (upper 200 m).





Figure 7. Cumulative calcification model for eddy (red) and non-eddy (blue) conditions from left to right: temperature profiles as well as $\delta^{18}O_{equilibrium}$ ($\delta^{18}O_{eq}$) for the upper 1000 m and $\delta^{18}O_{cummulative}$ ($\delta^{18}O_{model}$) for the upper 500 m. On the upper far right, mass development/growth pattern, below cumulative mass of the foraminifera (foram mass) is plotted for the upper 500 m. Bulk $\delta^{18}O_{foram}$ (triangles) Mg/Ca derived single chamber calcification depth (crosses) are indicated in the relevant plots.





Figure 8. Inter-species differences between expected δ^{13} C values, based on the cumulative mass balance model, and measured δ^{13} C values of *G. ruber*, *N. dutertrei*, *P. obliquiloculata* and *G. scitula*. Dashed line indicates the 1 : 1 line of measured and expected δ^{13} C. Red symbols represent values for eddy conditions, blue symbols represent values for non-eddy condition. Thick grey arrows indicate intra-species trends between non-eddy and eddy conditions, thin arrows indicate inter-specific trends. P. obliquiloculata does not calcify in isotopic equilibrium with dissolved $\sum CO_2$, but the deviation from isotopic equilibrium is a linear function of temperature (Mulitza et al., 1999), hence there is no projected $\delta^{13}C_{expect}$, this is indicated by the dotted lines. Open diamond indicates $\delta^{13}C_{expect}$ for *P. obliquiloculata* non-eddy conditions.

