Dear Editor,

Checking once more the calculations presented in our manuscript we noted a mistake in the sign of the correction factor used for calculating the cumulative growth curves (Figure 7e). We have changed this in the manuscript by deleting the sentences that described this correction and instead we added a paragraph to explain the differences in δ^{18}O and Mg/Ca-derived calcification depths (line 442-456). These adjustments do not change our conclusions and only slightly alter the content of our discussion.

We sincerely apologize for any inconvenience caused and hope this addition is still in time.

Also on behalf of all co-authors,

Juliane Steinhardt.

Dear Editor,

We thank the referees for their thorough reviews and used their comments to improve our manuscript. We used all comments to produce a revised version of our manuscript, which we would like to offer you for publication in Biogeosciences. Below, we copied the reviewers' comments and replied to them one by one. Although some of the comments resulted in a substantial reorganization of the text, this did not affect the general structure of the discussion, nor did it affect our conclusions. We think that these changes have clarified the text of the manuscript and we now highlighted the potential of our results for understanding depth habitat distribution of planktonic foraminifera.

Also on behalf of all other authors,

Juliane Steinhardt

Referee#1:

Review paper

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

by J. Steinhardt et al.

General comments

The paper of J. Steinhardt "Reconciling single chamber Mg/Ca with whole test δ18O in surface to deep dwelling planktonic foraminifera from the Mozambique Channel" is supposed to be published in "Biogeosciences". Primary goal of the submitted paper is to reconstruct calcification and migration patterns of various planktonic foraminiferal species based on single-chamber Mg/Ca and single foraminiferal test $\delta^{18}O$ and $\delta^{13}C$. Sample material is from a deep (~2.250 m) sediment trap from the Mozambique Channel. The novel analytical results have been supported by a convincing depth resolved mass balance model. The overall topic is of quite large interest to the paleoceanographic community, which is commonly using foraminiferal tests as biotic carriers for geochemical proxy parameters. The manuscript shows that the authors spent quite a lot of work into this study, and the results for sure deserve publication. The paper is very well-written, concise, and clearly structured, and the figures are mostly of high quality. Error calculation and statistics are exemplary! Nonetheless, I hesitate to recommend this paper for publication without explicit improvement and thorough revision. First, the manuscript is very complex, and it affords very thorough reading. It could gain from shortening by leaving out the last chapters on foraminiferal δ^{13}C. Second, the advantage to infer calcification and migration patterns of planktonic foraminifers from deep (>2000m) sediment trap material raises criticism as long it is not shown that results clearly differ from studies based on sediment surface material directly from below the trap. Sediment surface material should in fact be available in this region! Also and in particular with respect to the foraminiferal Mg/Ca data, it needs at least to be discussed whether and how foraminiferal Mg/Ca could have been altered by calcite dissolution processes during settling from the ocean surface to depths below >2000 m. Overall, the study pinpoints the necessity to strengthen efforts to carry out plankton net studies. Third and similarly important, the author should cautiously avoid any suspicion on plagiarism. Large parts of Chapter 2 (Oceanographic setting) and Chapters 3.1, 3.3, and 3.4 were one-to-one taken from Steinhardt et al., 2014 (Marine Micropaleontology 113, 20-33). Plagiarism in science, in fact, is an important issue and is very precisely defined. Official guidelines should be considered by the author is very precisely defined. Official guidelines should be considered by the author.

Referee: First, the manuscript is very complex, and it affords very thorough reading. It could gain from shortening by leaving out the last chapters on foraminiferal δ^{13}C.

Author´s response: We agree with the reviewer that the paper was somewhat long and that shortening improves the clarity of the discussion. We think that it is still worthwhile to keep the discussion on δ^{13}C in the paper, as this is the only independent data available to cross-validate the proposed calcification depth model based on δ^{18}O. Instead, we shortened our manuscript by deleting parts of sections 5.3.3 and 5.3.4, which described other factors in detail that could potentially affect calcitic δ^{13}C and included a short paragraph summarizing the content of 5.3.3 and 5.3.4 in 5.3.2. Furthermore we deleted the second paragraph of the original section 5.3.4 streamlining this part of the discussion. We also shortened the text of the results section by putting the Mg/Ca and δ^{18}O results in a table (Table 2). Together with several other more modest changes (see below) we think that overall readability of the manuscript has significantly improved.

Referee: the advantage to infer calcification and migration patterns of planktonic foraminifers from deep (>2000m) sediment trap material raises criticism as long it is not shown that results clearly differ from studies based on sediment surface material directly from below the trap. Sediment surface material should in fact be available in this region! Also and in particular with respect to the foraminiferal Mg/Ca data, it needs at least to be discussed whether and how foraminiferal Mg/Ca could have been altered by calcite dissolution processes during settling from the ocean surface to depths below >2000 m. Overall, the study pinpoints the necessity to strengthen efforts to carry out plankton net studies.

Author´s response: The main advantage of using sediment trap material is that we can link the chemistry of the shells to actual ambient *in situ* measurements from the moorings and from real-time satellite derived observations. Therefore we are able to link short time changes in hydrography (i.e. eddies) to the differences in shell chemistry. This is now added to the manuscript (section 3.1). The reviewer is correct in that dissolution of (the surface of) foraminiferal shells might potentially affects their geochemistry. However, a previous study of Fallet et al. (2012) showed that in the Mozambique Channel, foraminiferal shells are not affected by dissolution by comparing size-normalized weights from specimens from core-tops and from sediment trap samples (~2000 meters). This indicates that dissolution did not affect our foraminifers and therefore their Mg/Ca, δ^{18}O and δ^{13}C reflect the original signal. This is in line with excellent preservation of foraminifera from core tops at ~3000 meters in the northern part of the Mozambique Channel (Birch et al., 2013). This information has been added to the revised version of our manuscript (section 3.3, p.17263 after original line 2).

Referee: Third and similarly important, the author should cautiously avoid any suspicion on plagiarism. Large parts of chapter 2 (Oceanographic setting) and Chapters 3.1, 3.3, and 3.4 were one-to-one taken from Steinhardt et al., 2014 (Marine Micropaleontology 113, 20-33). Plagiarism in science, in fact, is an important issue and is very precisely defined. Official guidelines should be considered by the author.

Author´s response: Sections 2, 3.1, 3.3 and 3.4 appear indeed very similar to corresponding sections from Steinhardt et al. (2014). The reason for this is that we used similar material for this and our previous study. Some repetition of e.g. description of methods and oceanographic settings is therefore hard to avoid. For example, the first sentence of section 3.4 already referred to Steinhardt et al. (2014) to point out the similarly between the introductory parts of these papers. However, we agree with the reviewer that we should avoid even the suggestion of duplication of sections of previous publications. Therefore, we cautiously reconsidered the text of sections 3.1 and 3.3. Moreover, we deleted the previous section 3.4 to avoid unnecessary overlap with Steinhardt et al. (2014). Instead, we added a sentence at the beginning of section 3.5 (3.4 in the new version of our manuscript) to refer to our previous paper regarding the laser ablation measurements. We have also referenced Steinhardt et al. (2014) throughout sections 3.1 and 3.3 to explicitly indicate similarity of parts of the approach between these two studies.

Few comments and suggestions:

Referee: Abstract: The abstract needs to be shortened and focussed. Avoid “too long” introductory passages. Avoid repetitions as “Here we present….”.

Author´s response: We have condensed our Abstract, which now measures 228 words instead of 317 words in the previous version.

Referee: Methods Chapter, p. 17265, line 4: Provide exact information on δ18Osw database from the South Indian Ocean: chart, table, e.g. in supplement.

Author´s response: We added a supplementary table with $\delta^{18}O_{sw}$ information. This contains salinity, temperature and seawater $\delta^{18}O$ with a depth resolution of approximately 20 meters. The data as such was already referenced in the original submission.

Referee: Chapter 4.1: Although the Mg/Ca data were already published in Steinhardt et al. (2014), a diagram summarizing those results would have been helpful.

Author´s response: We added a table (Table 1) summarizing the Mg/Ca results of Steinhardt et al. (2014) and added a summary of the newly measured $\delta^{18}O$ and $\delta^{13}C$ of the same specimens.

Referee: Conclusions: Change the ordering of conclusions. First, describe $\delta^{18}O$ and Mg/Ca, then $\delta^{13}C$, in accordance with the structure of the paper.

Author´s response: We agree with the author and changed the ordering of the conclusion. We now describe $\delta^{18}O$ and Mg/Ca, then $\delta^{13}C$, in accordance with the structure of the paper.

Detailed comments:

Referee: Fig. 1: I would suggest to present a detailed chart showing eddies in the Mozambique Channel in much higher resolution, e.g. as sea surface height anomaly map or so. The overview chart could then be taken as inlet. Also, the exact positions of the sediment trap PP5 and the CTD location lmc5A need to be shown in detail. Provide info on: How large is the distance between both: 0.3° = 20 nm? How is that in relation to the diameter of an eddy (~300 km?).

Author´s response: Figure 1 has been changed and now includes a detailed mooring array with the location of the sediment trap as well as a sea level anomaly snapshot showing the passing of an eddy during the deployment.

Referee: Fig. 2: Provide regression line for *G. scitula.*

Author´s response: Figure 2 has been changed and includes now the regression for *G. scitula*.

Referee: Fig. 4: I would recommend to use different symbols for different species. The author should clarify in the figure caption whether the data – at least parts - were published elsewhere. Add an introductory sentence summarizing the intention of the figure.

Author´s response: Figure 4 has been changed accordingly, using different symbols for different species and reference to original publication of the Mg/Ca data has been added.

Referee: Fig. 5: The figure caption should appear more self-explanatory and should provide more information on how the temperatures were calculated. Refer to the text or provide equations/references. Legend could be taken out, if the according information would be included into the figure caption. Add an introductory sentence on the intention of the figure.

Author´s response: The figure caption has been changed accordingly, adding information on how temperatures were calculated.

Referee: Fig. 6: Symbols are difficult to distinguish! Make larger. Enlargen fond! Indicate in figure caption, which symbol belongs to which species (squares = N. dutertrei?). Indicate what the large boxes mean: calcification depth ranges, color-coded for different species (green = G. scitula?)? Colored frames of boxes should be thicker. Check figure captions for typos. Add a introductory/summarizing sentence, e.g., “Apparent calcification depths of species are generally shallower during non-eddy conditions”.

Author´s response: Figure 6 has been changed. Font and symbols were enlarged and boxes are now more clearly indicated. Figure caption was checked for typos and changed accordingly. An introductory sentence has been added.

Referee: Fig. 7: Although this figure is very complex, it nicely brings together the major outcome of this paper. Unfortunately, the figure/labels/symbols are much too small and the authors need to find a way to considerably improve the figure. The many legends may be taken out and explained in the figure caption.

Author´s response: We have attended the figure size issue by separating it into different parts, with the first part being applicable to all species considered, and the species all having a separate box. We also changed the fonts and made some room for the legends.

Referee: Reference list: The list is not yet complete and should be checked (e.g., Hut et al., Regenberg et al.). The list would gain from additions of still missing important contributions of others to the topic. The paper should include a statement, in which databank the data will be electronically stored.

Author´s response: Reference list has been checked and missing references were added accordingly. We added a reference to indicate that the data is now given in a supplementary file.

Referee: Page 17268, line 11: Must be Eq. 3 instead of Eq. 4

Author´s response: Has been changed accordingly.

Referee: Page 17268, line 21: Full stop missing after G. scitula.

Author´s response: Has been changed accordingly.

Referee: Page 17268, line 24: Must be Eq. 3 instead of Eq. 4

Author´s response: Has been changed accordingly

Referee: Page 17268, line 11: Consistently use the term Tiso or δ18O-derived temperature in text and figures.

Author´s response: We changed the term to δ^{18}O-derived temperature consistently throughout the manuscript.

Referee: Page 17269, line 27: If I interpret Fig. 6 correctly, the calcification depths of *N. dutertrei* range between ca. 20 m and 130 m (blue squares????). Overall, the specifications of calcifications depths in the text should be congruent to what is shown in Fig. 6.

Author´s response: This has been changed accordingly.

Referee: Page 17272, line 10: check wording of sentence!

Author´s response: We have checked the wording and changed it accordingly.

Referee: Page 17273, lines 22-24: Support these results by figure or reference. It is not obvious from where these results originate from.

Author´s response: We have added the according reference for these results at line 24.

Referee: Page 17273, line 27: Check for typo.

Author´s response: Has been changed accordingly.

Referee: Page 17274, line 14: Check for typo.

Author´s response: Has been changed accordingly.

Referee: Page 17276, line 7: Check wording.

Author´s response: Has been changed accordingly

Referee: Page 17279, line 7: Check for typo.

Author´s response: Has been changed accordingly

Referee: Page 17279, line 13: Check for typo and wording.

Author´s response: Has been changed accordingly

Referee: Page 17282, line 17: Change FS into R/V.

Author´s response: Has been changed accordingly

Referee: Entire text: Stay consistent with wording: either foraminiferal “test” or “shell”.

Author´s response: This has been changed accordingly throughout the manuscript to the wording “shell”.

Referee#2:

Review paper

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

by J. Steinhardt et al.

This paper contains a significant amount of geochemical data (d18O, d13C, and Mg/Ca) generated on four species of planktic foraminifera. The authors should be commended for this. I would be willing to review a revised version after significant editing, response to comments within attached pdf, and a careful check of whether the references are appropriate.

General comments

Referee: The paper badly needs editing. Many paragraphs lack cohesiveness and lack a topic sentence making a clear point followed by supporting observations or arguments. There are also missing words, typos, etc. I highlighted some of these but not all. It would be easier to read and to follow the arguments made if data were summarized in tables within the text instead of sentences containing multiple means, standard errors, etc.

Author´s response: We have done our best at cross-checking the text for typos and trying to make the paragraphs as cohesive as possible. The data has now been summarized in a table, which should help in making the text easier to read. Several changes were also made in response to reviewer #1 (see above).

Referee: In general, if the data generated are from individual foraminifera, I think analytically sound "outliers" should not be excluded since they reflect the actual variability within the population. Whenever possible show all the data in figures; if it's necessary to summarize, show the range and quartiles (including outliers).

Author´s response: We show all data we think are analytically sound. Still, to our opinion this requires the removal of outliers deviating more than 2 SDs from the calculated mean Mg/Ca or δ^{18}O. These values clearly result in unrealistically high seawater temperatures and are therefore probably incorrect. As a compromise we have retained these data within the data set as such, to be uploaded as a supplementary file (Tab. S3).

Referee: In several places, the references cited are not appropriate and/or do not say what the sentence claims they say. I highlighted these where I saw them.

Author´s response: The suggestions by the reviewer were used to improve citing.

Referee: It is not clear why the Kim and O'Neill paleotemperature equation was used if it does not generate temperatures reflective of actual conditions (section 5.1). This discrepancy was noted in section 5.1 but the remainder of the paper still uses K & O'N. If the different paleotemp equations give such different results it's hard to have confidence in the data interpretation.

Author´s response: We noted that using species-specific equations for *G. ruber* by Fallet et al. (2011) and Wilke et al. (2009) result in SSTs slightly closer to those based on satellite observations. Difference between them and those based on the calibration of Kim and O'Neill (1997) are, however, very small and, more importantly, result in similar estimated depth habitats. Using a different equation for the other species (e.g. that of Erez and Lutz, 1977 for *N. dutertrei*) would result in only a slightly different inferred depth habitat at which 95% of the shell would have been precipitated (~10 meters). The choice for any of these equations, therefore, does not appreciably change the outcome and conclusions of our calculations. The fact that these different calibrations give such similar results gives us confidence in the inferred depth habitats, opposite to the reviewers' suggestion. This misunderstanding comes probably from the differences in using actual in situ temperatures versus annual averages. We have now made this clearer in the manuscript.

Detailed comments

Referee: Shouldn't this read "below the thermocline"? Species living below the mixed layer but within the thermocline would show more variability than either mixed layer dwellers or deeper dwellers.

Author´s response: We agree with the referee that the sentence should rather state that these species calcify mostly below the thermocline. We changed the sentence accordingly.

Referee: Marked paragraph referring to comment c) not appropriate references…

Author´s response: To our opinion the Eggins, 2003, Hathorne, 2009 and Kunioka papers are all highlighting Mg/Ca heterogeneity, being measured with different approaches. In this case we, therefore, think that these references are appropriate.

Referee: Given the spatial and temporal patchiness of phytoplankton blooms I would consider these chl-a values to be the same (ie no seasonal variability).

Author´s response: We used these numbers to underline the fact that the MC is an oligotrophic area, but indeed they are not in line with a seasonal contrast. Still, as this seasonal contrast is well-known we have omitted specific numbers and only state that the MC is generally an oligotrophic area.

Referee: p. 17261, line 24: The mooring location is NOT shown in Figure 1 - needs to be added

Author´s response: This Figure has been changed accordingly and now includes the mooring transect and the trap location.

Referee: p. 17262, line 3- 6: How well does the timing of these cruises match up with the sediment trap collection times (based on presence/absence of eddies)? How much difference in the reconstructed d18O temperatures would it make if you were wrong? This could be addressed with a single sentence.

Author´s response: The method for eddy-detection and the matching of eddy intervals with the sediment trap intervals has been described in Steinhardt et al., 2014 in detail. We have now added the appropriate reference into the method section 3.2 (p. 17261, at line 25).

Referee: p. 17263, line 4-7: reword; perhaps 2 sentences.

Author´s response: We agree and rephrased the sentence to "The Mg/Ca ratios of single chambers used in this study were previously published (Steinhardt et al., 2014)".

Referee: p. 17263, line 26-28: Does this screening refer to the laser ablation data for each individual spot? Or does "dataset" refer to the values obtained from the 695 ablation spots, or the data from the 373 individuals? Be more specific here. If data from individual foram outliers are excluded you are losing information about the population variability of that species by excluding them.

Author´s response: We refer to a previous paper, Steinhardt et al., 2014.

Referee: p. 17264, line 20-23: Same comment: If the analyses are sound (ie the reason for the >2s offset is not analytical) you are losing information about population variability if you exclude outliers from further interpretation. I suggest you at least include them in the data table. The actual range of values obtained from a large sample set is important to preserve - you might pass on the impression to other researchers that the population variability is less than it actually is.

Author´s response: We follow the reviewer's suggestion to add these points to the data table. We chose to remove the outliers (i.e. values deviating more than 2 SDs from the calculated mean Mg/Ca or δ^{18}O) from the figures, see also above.

Referee: p. 17265, line 9: This intercept suggests that the source of the fresh-water end member is quite depleted in O-16, possibly indicating a contribution from AA. Did you try developing this relationship for eddy vs non-eddy conditions? I wonder if the fresh-water end member differs under different eddy conditions. How would an error in the S-δ^{18}Ow relationship propagate through into the final δ^{18}O-T?

Author´s response: We did consider changes in $\delta^{18}O_{sw}$, based on the salinities measured by the moorings into the $\delta^{18}O_{eq}$ calculations for eddy vs non-eddy. This is still an approximation as salinity and $\delta^{18}O_{sw}$ are not one to one coupled, but in this area it will be very close. Hence, although we agree, that measured $\delta^{18}O_{sw}$ for eddy and non-eddy intervals would improve the model the difference expected is very limited. Since we do not have $\delta^{18}O_{sw}$ during specific eddy or non-eddy intervals it is not possible to further expand on this.

Referee: p. 17265, line 15-17: This sentence is convoluted: I think you mean that you used the averaged δ^{18}Osw from the appropriate interval to calculate Tiso (you are not comparing δ^{18}Osw with Tiso; that's comparing apples and oranges).

Author´s response: We changed the sentence accordingly to: "We used averaged $\delta^{18}O_{sw}$ from the depth range suggested by previously measured single chamber Mg/Ca analyses (Steinhardt et al., 2014), to calculate δ^{18}O-calcification temperatures, following the temperature equation of Kim and O'Neil (1997)"

Referee: p. 1726, line 4 - 12: I think the info in this paragraph would be easier to follow and more succinct if included in a table. Also, state that all errors will be reported as standard error unless otherwise stated, and then report mean±SE; this will save space too. And it's consistent with how means/errors are reported later in the paper.

Author´s response: We followed the referee's suggestion and added a table with the Mg/Ca, δ^{18}O and δ^{13}C results. To the manuscript (Tab. 1), including standard errors and standard deviations, as well as calculated calcification temperatures.

Referee: p. 1726, line 4 – 12: The last phrase ("corresponding to...") doesn't follow - is the 14°C a temperature difference? If not, include the temps for all three species - better still, include a table

Author´s response: We followed the referee's suggestion and included a table (Tab.1) with the results.

Referee: p. 17267, line 11-12: Since you determined size by sieving (not by individual size measurements), you should say "no significant trend between size fraction ...". The range of sizes in a given sieved sample is greater than the nominal range of the sieve.

Author´s response: We changed the sentence accordingly.

Referee: p. 17267, line 26-27: I see two groupings in the *G. scitula* data in Figure 2, rather than a linear relationship. The upper group (more depleted $\delta^{18}O$) has more scatter in both $\delta^{18}O$ and $\delta^{13}C$. Is one group from eddy conditions and the other from non-eddy conditions? Do these groups also look different in Mg/Ca?

Author´s response: We agree that the *G. scitula* data looks divided into two clusters. We noted this at an early stage already, but were not able to establish a relation with other parameters, either measured on the same specimens (Mg/Ca) or related to the environment (eddy vs. no-eddy).

Referee: p. 17267, line 26-27: In the caption for Figure 2, say what the error bars represent (analytical error?).

Author´s response: We have added this to the figure caption.

Referee: p. 17268, line 9: I would rather see the actual data points in Figure 3, including analytically sound outliers, rather than a summary measure. If summary is absolutely necessary, show the range and quartiles (box and whiskers plot).

Author´s response: We did not plot the outliers (i.e. values deviating more than 2 SDs from the calculated mean Mg/Ca or $\delta^{18}O$), but maintained the data in the tables. See also discussion earlier in the review.

Referee: p. 17268, line 10: A summary table would be easier to read and would probably save space.

Author´s response: We have added a table with the results to the manuscript.

Referee: p. 17268, line 11:There is no discussion here of the left panel of Figure 4 - I suggest removing it if space is a consideration

Author´s response: We have changed the sentence accordingly, referring now to Eq. 3.

Referee: p. 17269, line 8-11: You don't state which relationship you are finally going to use. If you think the Kim and O’Neill relationship gives inaccurate results, revise section 3 to state that you use Fallet et al or Wilke (one or the other) and stick to it.

Author´s response: We use the Kim and O’Neil equation, which is stated in the method description

Referee: p. 17269, line 19:

*Author´s response:*We followed the referee’s suggestion and rephrased sentence to:
“In addition to its shallow living depth, *G. ruber* is known to occur in some areas relatively equally throughout the year…”

Referee: p. 17269, line 26: Using which paleotemperature equation?

*Author´s response:*We use the Kim and O’Neil equation. This is now stated in line 26.

Referee: p. 17270, line 15-16: This idea is outdated - see Eggins et al 2006 and Spero et al 2015

Author´s response: Spero et al., 2015 is investigating cultured specimens of the symbiont bearing species *O. universa*. This species is generally regarded as atypical, both in terms of

its test development and unusually high bulk Mg/Ca composition (Sadekov et al., 2005). The banding of *O.universa* has been linked to day and night cycles, which is not relevant for deeper dwelling species.
We are not aware of an Eggins et al., 2006 paper dealing with Mg/Ca heterogeneity in planktonic foraminifera. Both Web of Science and Scopus do not show any paper from Eggins et al. in 2006.

Referee: p. 17270, line 19: This paper was written before banding was identified and shouldn't be cited as such. This sentence should be deleted or updated with more recent literature (especially see Spero et al. 2015, EPSL but also Eggins et al. 2006.

Author´s response: The paper cited, "Mg/Ca variation in planktonic foraminifera tests: implications for reconstructing palaeo-seawater temperature and habitat migration" from Eggins et al. (2003) in EPSL is specifically dealing with banding in foraminiferal test walls. This is one of the first papers showing banding in Mg/Ca and although no explanation was given at the time, this is exactly what we are referring to.

Referee: p. 17272, line 4: How does this differ if you use Fallet's relationship*?*

Author´s response: Using the Fallet's relationship, the $\delta^{18}O_{exp}$ are higher than the measured $\delta^{18}O_{CC}$ of *G. ruber* and hence we would overestimate the cumulative $\delta^{18}O_{exp}$. This is related to the fact that mean SST during non-eddy are higher than mean annual SST's used by Fallet et al. (2010) for their empirical calibration. Since we do not refer to annual but in situ conditions our observations are closer to the calculated temperature based on Kim and O'Neil (1997).

Referee: p. 17272, line 9-12*: This sentence is very confusing - reword.*

Author´s response: We rephrased the sentence to: *"*During eddy conditions, *P. obliquiloculata* calcifies between 89 and 124 m (average 107 m), whereas it calcifies at shallower depth, between 20 and 77 m (average calcification depth 60 m) during non-eddy conditions".

Referee: p. 17272, line 20: This entire paragraph is very confusing. The first sentence should clearly state what the main point is, and the remaining sentences should back that up with observations.

Author´s response: We changed the order of this paragraph. "While Mg/Ca-based temperatures of *G. ruber* and *N. dutertrei* record eddy induced changes in upper water column stratification, $\delta^{18}O$-based temperatures suggest relatively similar calcification depths for both species (Fig. 6). Using the paleo-temperature equation (equation (1); Kim and O'Neil, 1997) and fitting $\delta^{18}O_{calc}$ with $\delta^{18}O_{cc}$, we find that…"

Referee: p. 17273, line 3: *or the wrong paleotemp equation - what if Fallet's relationship is used?*

Author´s response: Even if a different temperature equation is applied, the variability will still be larger. Only the absolute values depend on the calibration used, not the variability.

Referee: p. 17275, line 14: Where is equation 6?

Author´s response: We corrected the numbering for the equations.

Referee: p. 17276, line 17-18: The "vital effect" correction should be discussed earlier, with the discussion of the model itself.

Author´s response: We already mentioned vital effects in the earlier section of the discussion (5.1), but restate the issue at the model paragraph.

Referee: p. 17277, line 11-12: Discuss with the discussion of the model itself and show exactly how the original model was changed (ie how the equation was changed).

Author´s response: The Wilke et al. model was followed closely. The main difference was that we use the Mg/Ca value of the F-1 chamber to constrain the 95% calcification level. This is now added to the manuscript.

Review paper

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

by J. Steinhardt et al.

Referee3:

Review of the manuscript "Reconciling single chamber Mg/Ca with whole test d18O in surface to deep dwelling planktonic foraminifera from the Mozambique Channel“ by J. Steinhardt, C. Cleroux, L. de Nooijer, G.-J. Brummer, R. Zahn, G. Ganssen, and G.-J. Reichart. This manuscript presents a large data set of single specimen stable isotopes and single chamber Mg/Ca on four species of planktonic foraminifera from a sediment trap in the Mozambique Channel which is affected by eddies. These lead to slightly different conditions in the water column affecting foram geochemistry. The authors argue that differences in the two sets, i.e. eddy and non-eddy conditions, show that combined stable isotopes and Mg/Ca can be used to reconstruct eddy conditions. Although the data set which is presented is large and very interesting, I’m not convinced that the data show that eddies can be reconstructed with this. For me, the data show how large the variability in single specimen/chamber geochemistry is (which feels more like the main theme of the paper) and that eddy occurrence with different conditions leads to similarly large variations. The range in values for both settings is very large and therewith seems to exclude that it would be possible in a downcore study to make the distinction. The manuscript is generally well-written, but contains many small mistakes giving the feeling that it has been written in a hurry. See below for more detailed comments, but one example is the method section on Mg/Ca. This seems to be copied one to one from a previous paper, the cited papers are missing from the references, and a whole series of elements are mentioned which never show up in the rest of the manuscript. In summary, I recommend that this study is potentially very interesting and fitting in Biogeosciences, but still needs a lot of work. As such I recommend to return the manuscript to the authors with major revisions.

General comments

The authors argue that differences in the two sets, i.e. eddy and non-eddy conditions, show that combined stable isotopes and Mg/Ca can be used to reconstruct eddy conditions. Although the data set which is presented is large and very interesting, I’m not convinced that the data show that eddies can be reconstructed with this. For me, the data show how large the variability in single specimen/chamber geochemistry is (which feels more like the main theme of the paper) and that eddy occurrence with different conditions leads to similarly large variations. The range in values for both settings is very large and therewith seems to exclude that it would be possible in a downcore study to make the distinction. The manuscript is generally well-written, but contains many small mistakes giving the feeling that it has been written in a hurry. See below for more detailed comments, but one example is the method section on Mg/Ca. This seems to be copied one to one from a previous paper, the cited papers are missing from the references, and a whole series of elements are mentioned which never show up in the rest of the manuscript. In summary, I recommend that this study is potentially very interesting and fitting in Biogeosciences, but still needs a lot of work. As such I recommend to return the manuscript to the authors with major revisions.

Major comments

The first proxy in the Abstract mentioned is Mg/Ca, which also starts the methods, but then there are no new results showing up in the rest of the paper. Meanwhile it seems that all relevant information on the Mg/Ca is actually in a previous paper (Steinhardt et al., 2014). We have omitted this section from the manuscript. Initially we added some new data from the F-0 chamber, but ultimately this did not add any new insight. Therefore, and also to avoid any unnecessary overlap, we now refer to the Steinhardt et al 2014 paper for the Mg/Ca data. At the end of the ms d13C comes in, almost as a kind of afterthought. I suggest to make the paper more clear in what it really wants to tell the reader, to make it something which can stand on its own without needing other papers. The Mg/Ca measurements were done by Laser Ablation. Accordingly, test profile Mg/Ca will be representative of the migration of the foram through the water column. In the previous paper it was mentioned that this variability was not considered. Why is this source of information left out? The average of the profiles is taken as indicative for temperature, so the different parts should be too then and thus will give you temperatures of the different depths of calcification. The test profile Mg/Ca data is influenced by many other factors as well. The formation of crust and cortex influences the Mg/ca profile for instance as well. We have for now omitted the Mg/Ca data, whereas detailed shell wall profiles are part of another manuscript.

Comments:

Referee: Section 3.4: If parts are copied from previous papers then at least be precise and include the references into the new reference list. Several references (Reichart et al., Raitzsch et al., Jochum et al., Duenas-Bohorquez et al.) in the methods (3.4) are missing. Is it relevant for the paper that Na, Mn, Sr, Cd, Ba, and U have been measured? “695 values were obtained for 373 specimens”. Please explain, are these averages values for test profiles or single shots on the tests? If new data were measured for this study as written before, then show profiles how the data were generated.

Author´s response: We apologize for this mistake. We have now omitted the entire LA-ICP-MS section, also in response to comments by the other referees. The methods section for the other elements is in fact a remnant of a previous version of the manuscript that somehow escaped the scrutiny of all authors. We have carefully re-checked the reference list and added missing references, when necessary.

Referee: Results, Mg/Ca: This is very confusing! Are new data being presented or not? Ranges and temperatures are being mentioned; and differences in subsequent chambers of dutertrei, but no figures are showing these data. Going back to the Steinhardt et al., 2014 paper it is possible to find these data. But that would suggest that the current manuscript cannot stand on its own, it needs the reader to have the other paper along with it.

Author´s response: Again we apologize for this mistaken. Whereas we initially wanted to present new data on F-0, this provided no new insight. Therefore we have omitted the entire section on la-icp-ms and now refer to the Steinhardt et al., 2014 paper. For completeness we have added the Mg/Ca data to Table 2s, as this allows one-to-one comparison of the data. The table caption refers for the Mg/Ca data to the initial publication.

Minor comments

Referee: Abstract:

“i.g.”: I assume you mean “i.e.” with this?

Author´s response: This has been changed accordingly to “i.e.”

Referee: Page 4, line 7: Ortiz 5-22: Steinhardt et al., accepted?

Author´s response: Changed to Ortiz et al., 1996 and Steinhardt et al., 2014.

Referee: 7-14: “as previously described”; it is not very extensive to include this, it will be helpful.

*Author´s response:*Text has been changed into: according to Barker et al., (2003), modified after Fallet et al., (2009).

Referee: 7-17: how are eddy or non-eddy conditions separated?

Author´s response: Separation of eddy and non-eddy condition was described in detail in Steinhardt et al., 2014. We now include a citation to refer to the explicit to this description in Steinhardt et al., 2014.

Referee: 7-23: the mooring is not present in fig.1.

Author´s response: Figure 1 has been changed and includes now a detailed mooring array with the location of the sediment traps as well as a sea level anomaly snapshot showing the passing of an eddy during the deployment.

Referee: 7-26: how significant is a meterwise resolution?

Author´s response: On the ten-meter scale resolution relevant for planktonic foraminiferal habitats, the one meter resolution seems adequate.

Referee: 8-15: *ruber* s.s. or *ruber* s.l.?

Author´s response: We added a sentence to page 17262 line 17:“To minimize a potential bias associated with the lumping of different morphotypes (Steinke et al., 2005), we used only *G. ruber* sensu stricto, that was by far the most abundant (Fallet et al., 2010).”

Referee: 8-25-27: it is mentioned several times in the text that no size-related trends were present. Was this based on the few specimens mentioned here which were taken from a larger size fraction? In general, size-related effects in forams for isotopes and Mg/Ca are only found when including the more extreme size fractions, i.e. <250 or >400. Anything in-between does not show any trends.

Author´s response: Point appreciated, still we included a paragraph about possible effects to emphasize that differences in our data set cannot be explained with size-related effects.

Referee: **Section 3.4**: see above. Line 5: “expanded”, so extra profiles were lasered on the last chamber? These data should be shown.

Author´s response: Based on the comments of the other referees as well as this comment, we decided to omit the additional Mg/Ca data. See discussion at several points above.

Referee: 10-16: delete “and”;

Author´s response: The sentence was changed accordingly.

Referee: lines 16-18: “are in good agreement”. Be specific, give numbers.

Author´s response: We have now added a table (Tab. 2) into the method section showing the exact numbers.

Referee: Page 11: it is unclear which dataset was used for δ18Osw, from the global dataset or from the measured samples? Is this a new relationship for δ18Osw and salinity? If not, include a reference.

Author´s response: This was mentioned in paragraph on page 17265 line 4-8: “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/]. We also mentioned that we additionally included some one new $\delta^{18}O_{sw}$ measurements from the MC, from near to the sediment trap location (41.08°E; 16.74°S). This one point merely confirmed the regional relationship between $\delta^{18}O_{sw}$ and salinity”. We included now included an additional supplementary table with the $\delta^{18}O_{sw}$ data used here.

Referee: Why did you use the Kim and O’Neil equation and not the species-specific equations?

Author´s response: In our opinion the Kim and O’Neill data set is the most general calibration allowing to compare inter specific differences which are automatically accounted for when using species specific calibrations. We have added this to the manuscript.

Referee: 12-4: add brackets to 2014; which temperature calibrations were used to calculate temperatures? Do these data include the data from the previous paper too or just the new data?

Author´s response: We have changed the sentence accordingly and now state that the temperature equation of Kim and O’Neil was applied. Both previously published Mg/ca and new $\delta^{18}O$ data was utilized to calculate temperatures.

Referee: Intertest variability in *ruber* is highest. This is counter-intuitive if the species is the one which is migrating the least of all, sticking most of its life cycle close to the surface. How can this be explained?

Author´s response: This is explained by the fact that the highest temperature variability is also observed at the sea surface, in contrast to the more stable deeper parts of the water column. This is in fact a very nice observation, in line with our model, which is now added to the discussion. Also differences in symbiont activity are probably highest within the euphotic zone.

Referee: All the numbers in the Results section make it very confusing to read. Please add tables for this to give a much better overview.

Author´s response: We followed this and the other referee's suggestion and now included a table with the results.

Referee: 14-11: "multi-specimen"? and equation 4 should be 3 I guess.

Author´s response: "Multi-specimen" is based on the fact that we here averaged Mg/Ca and δ^{18}O data for all specimen of each species.

Discussion. 5.1:

Referee: what is the message of the first paragraph? It is well-known that *G. ruber* is a shallow dwelling species. This can be shortened considerably.

Author´s response: The main message of this section was the potential role of seasonality on skewing the average temperature recorded in the shells of *G. ruber* towards the warmer season.

Referee: 15-23: Loncaric is spelled incorrect on several occasions.

Author´s response: We have corrected this mistake throughout the manuscript.

Referee: 16-3: remove brackets for 40-150. These ranges in reconstructed depths are the interesting thing in the paper instead of an average depth of 37 m. Apparently even under "stable" conditions you do already get such a large spread. Where does this come from?; "pooled specimen" in general this is not much more than 5 specimens, how representative are those measurements then for the population?

Author´s response: We analysed the complete population present within the sediment trap for each interval, hence it is 100% representative. Still, we agree that the observed variability is considerable and our measurements do underline high intra-specimen variability. Moreover, the data explains some of the variability observed within a population.

Referee: 16-10: why not compare to your own dutertrei Mg/Ca?

Author´s response: We agree with the referee and added now a comparison of the average Mg/Ca-based temperature (22.5±4°C) and the average $\delta^{18}O_{CC}$-derived temperature (24.3±2°C), which are in good agreement.

Referee: 16-15/22: includes a series of typos.

Author´s response: We have carefully re-checked this section for typos and corrected when present.

Referee: 16-23: Mohtadi et al., 2009 is missing from the references.

Author´s response: This reference has been added to the reference list.

Referee: 17-6: this would fit it then with the Mg/Ca; how are the vital effects for the other species?

Author´s response: The vital effect was only obvious for *G. scitula*. The other species are within the ranges previously suggested.

Beginning 5.2:
Referee: any geochemical signal recorded in a foram test is an average of the range over which calcification took place. So all reconstructed calcification depths are apparent.

Author´s response: We agree with the referee and merely used the term ”apparent” to stress this.
Referee: 18, middle paragraph: this belongs in the results and/or a table; last paragraph is confusing, please clarify.

Author´s response: Since we are here discussing “inferred temperature” we think this belongs in the discussion. The last part of the paragraph was rephrased highlighting that the $\delta^{18}O$ was similar, but inferred calcification depths not.

Referee: 19-6: “trends with test size”, see comment before.

Author´s response: This has been changed based on an earlier comment.

Referee: Lines 6-20: what about the rest of the variability? And this would be the case for every species. The larger their depth range, the larger the variability would become.

Author´s response: This might be counterintuitive to the reviewer, but the temperature variability becomes less with increasing depth. Still, we appreciate the comment, as based on this we now also realize that the foraminifera are apparently very stable in their calcification trajectory as this would otherwise have added considerably to the variability.

Referee: 19-26: which is which in this sentence?

Author´s response: We do not understand to what sentence of the manuscript this comment is referring.

Referee: 20. first part: this uses the final chamber Mg/Ca or the overall Mg/Ca? These data should also go into a table. You can leave all these numbers out of the discussion then and just refer to the table.

Author´s response: This data has been added to the table.

Referee: Model: how are the two constants determined?

Author´s response: The two constants were determined first using the Mg/Ca-based temperature of the F-1 chamber, to delimit the depth at which 95% of the calcite production was completed and subsequently matching $\delta^{18}O_{expected}$ to the measured $\delta^{18}O_{cc}$. This is now clarified in the revised manuscript.

Referee: 23-14: “extended version”. This is mentioned but not shown. The impact of secondary calcification is well-known and can take up the majority of the shell mass, not only in scitula but also in dutertrei and obliquiloculata.

Author´s response: We fully agree with the reviewer that the addition of secondary calcite potentially plays a major role in the overall carbonate addition. The model used here is, however, not able to separate the curve into two different parts, each with his own fractionation.

Whereas this would be very interesting, separate fractionation factors for both lamellar and crust calcite would be needed, which do not exist at the moment.

Referee: 24-9: remove the size trend part.

Author´s response: Line 9 on page 24 is not mentioning size trends.

Referee: 25-8: Why are all expected values higher than the measured ones?

Author´s response: This is discussed at page 17279 lines 28-30: there is a temperature dependent offset in $d^{13}C$.

Referee: 26-11: How does the $\delta^{13}C$ indicate that Mg/Ca is a good indicator?

Author´s response: The carbon isotopes are used as an independent check. The calculated $\delta^{13}C$ overall matches the measured $\delta^{13}C$, with offsets that can be explained with what is known from literature. Since the Mg/Ca was used to drive the model, this fit indicates that Mg/Ca agrees well with calcification temperature of the individual chambers.

Figures:
Referee: No new Mg/Ca data are shown

Author´s response: This has been addressed in the previous points (see above comments).

Referee: it would be interesting to see how the data vary with temperature (and salinity) during the time the sediment trap was employed. Do the analysed data follow natural changes?

Author´s response: This is exactly what the paper aims at: we contrasted temperatures from eddy versus non-eddy times. Previous studies (Fallet et al.) addressed seasonal trends as well.

Referee: Fig. 4b: why is this split up into different chambers? The exponential fit is not very convincing. The data may also be seen as constant values up to 20°C and a linear increase >20°C. Remove the 2 from the Mg/Ca axis that is not going to be a real value; this figure integrates all different species and different growth stages.

Author´s response: The fact that this correlates at all (which is a statistic fact and not something to believe or not) is quite remarkable. The correlation coefficient also indicates that close to 60 percent of the observed variability is not due to temperature alone. Part of the variability is related to comparing single chamber and whole shell data. Teasing out these effects is exactly what this manuscript aims at. These observations have now been added to the manuscript in the Figure caption of Fig. 4.

Referee: Fig. 5: there seems to be more discrepancy between Mg/Ca and d18O than between eddy vs non-eddy;

Author´s response: We could not agree more.

Referee: fig.6: remove typos from the caption; what are the non-grey boxes?

Author´s response: We have made changes according to the referee’s advice. The grey box indicates the zone of the close-up on the right (upper 200 m). This is explained in the figure caption.

Referee: Fig.7: there is no axis for the Mg/Ca values. The figure is way too small.

Author´s response: There is no Mg/Ca axis, since Mg/Ca-based temperatures are plotted. We have changed figure size and layout.

Short comment M. Weinkauf:

Review paper

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

by J. Steinhardt et al.

This is a very interesting paper. Upon skimming through it I just stumbled over one little curiosity. You state yourself several times (p. 17268, lines 11–12; Eq. (4); caption of Fig. 4) that the supposed relationship between δ^{18}O temperature and Mg/Ca should be positive exponential. Why then (according to your caption and from the looks of it) are you fitting a polynomial second degree to your data (Fig. 4, right panel)? An exponential function would be much more reasonable on a mechanistically basis (as you state yourself). Unless you have a particular reason to believe that the relationship should have a local minimum at around 8°C and then rise again, but then some of your other statements are incorrect and this would have to be discussed.

Best regards, Manuel Weinkauf

We have corrected figure 4 to an exponential fit ($f = a*\exp(b*x)$, $a=0.7\pm0.1$, $b=0.06\pm0.005$; $r^2=0.47$), although this slope is very similar to the previous polynomial slope that was fitted previously. The correlation coefficient also indicates that close to 60 percent of the observed variability is not due to temperature alone. Part of the variability is related to comparing single chamber and whole shell data. These observations have now been added to the manuscript in the Figure caption of Fig. 4.

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

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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 therefore 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 (e.g. Mg/Ca and $\delta^{18}O$), which is less for species calcifying below the thermocline. Obtained single-chamber Mg/Ca are combined with single specimen $\delta^{18}O$ and $\delta^{13}C$ of the surface water inhabitant *Globigerinoides ruber*, the thermocline-dwelling *Neogloboquadrina dutertrei* and *Pulleniatina obliquiloculata* and the deep dweller *Globorotalia scitula* from the Mozambique Channel. Species-specific Mg/Ca, $\delta^{13}C$ and $\delta^{18}O$ data combined with a depth-resolved mass balance model confirm distinctive migration and calcification patterns for each species as a function of hydrography. Whereas single specimen $\delta^{18}O$ not always reveal changes in depth habitat related to hydrography (e.g. temperature), measured Mg/Ca of the last chambers can only be explained by active migration in response to changes in temperature stratification. Foraminiferal geochemistry and modeled depth habitats shows that the single chamber Mg/Ca and single shell $\delta^{18}O$ are in agreement with each other and in line with the changes in hydrography induced by eddies.

1. Introduction

Most planktonic foraminifera inhabit the upper 200 meters 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 found reflect their ecology (e.g. feeding behavior), ontogeny and seasonal preferences. Stable oxygen isotope values ($\delta^{18}O$) and Mg/Ca ratios (Shackleton et al., 1974; Fairbanks et al., 1980; Ortiz 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., 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, 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 $\delta^{18}O$) of their shells 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 in vertical structure of the water column by using geochemical proxies, e.g. for temperature ($\delta^{18}O$ 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 $\delta^{13}C$ and $\delta^{18}O$ measurements made on several species of planktonic foraminifera across a range of tightly constrained size windows. From size controlled $\delta^{18}O$ 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 (e.g. McClanahan, 1988; Damassa et al., 2006; Hastenrath et al., 1993). 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 (i.e. temperature) more directly to their shell chemistry.

Single-chamber Mg/Ca compositions from specimens with contrasting calcification depths (the surface-dweller *Globigerinoides ruber* (d' Orbigny, 1839), the thermocline-dwelling 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 affected by eddy-induced changes, which is reflected by the geochemistry of *G. ruber* and *N. dutertrei* (Steinhardt et al., 2014), 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 shell $\delta^{18}O$-values we evaluate our results using a mass balance model for depth related carbonate addition of four species of planktonic foraminifera.

2. Oceanographic setting

In the oligotrophic Mozambique Channel (MC) (Fig. 1) sea surface temperatures (SST) vary seasonally and with eddy-induced transport (Fallet et al., 2011). The SSTs range from 25°C to over 30°C with an annual mean of 27.6°C, the seasonal change in temperatures is associated with the monsoon system. 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). Depth of the calcite compensation in the Western Indian Ocean is below 3000 meters and hence promotes preservation of foraminiferal calcite at the seafloor of the Mozambique Channel that has a depth of 2225 m at the trap location. 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 km.d^{-1}) before joining the Agulhas Current. An eddy passage is associated with vertical movement of isopycnals, which can occasionally exceed 40 m per day in the upper layer (Ullgren et al., 2012). The formation of meso-scale eddies in the Mozambique Channel is related to variability in the South Equatorial Current (SEC) transport (Backeberg and Reason, 2010) (Fig. 1). The main water masses contributing to 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 SEC (New et al., 2007). In the proximity of 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).

3. Material & Methods

3.1 Sediment trap and mooring array

Within the Long-term Ocean Climate Observations (LOCO) program, an array of eight moorings across the narrowest part of the Mozambique Channel, provides continuous measurements of current velocities, temperatures and salinities at fixed depths since November 2003 (Ullgren et al., 2012). Sediment traps of the type Technicap PPS 5 were deployed at 16.8°S and 40.8°E in the central MC (Fig. 1), equipped with an automated sampling carousel of 24 cups and a baffled collecting area of 1 m^2. The trap was positioned 250 m above the channel floor at 2250 m water depth. Between November 2003 and February 2009, a total of four sediment trap deployments took place, each programmed to a 17, 21 or 23 days sampling interval. Prior to deployments, sample cups were filled with an $HgCl_2$-poisoned and borax-buffered solution of seawater collected from the deployments depth (Lončarić et al., 2007). Sediment trap samples were wet-split, sieved and foraminiferal shells were cleaned according to the protocol of Barker et al. (2003), modified after Fallet et al. (2009) (Fallet et al., 2010; Steinhardt et al., 2014).

Using sediment trap material allows to link the chemistry of the shells to actual ambient *in situ* measurements from the moorings and from real-time satellite derived observations. Therefore we are able to link short time changes in hydrography (i.e. eddies) to the differences in shell chemistry. Calculated back trajectories, based on a high-resolution INALT01 model (Durgadoo, 2013), show that specimens ending up in the sediment trap all originate from the area under influence of the eddy-variability (Steinhardt et al., 2014). We selected the sediment trap intervals during which the complete sediment cup collection took place under either full eddy or full non-eddy conditions (for full description see Steinhardt et al., 2014; supplement). For the selected collecting intervals, temperature and salinity observations from the mooring (lmc5a) are compiled and daily means were used to calculate eddy and non-eddy temperature profiles.

3.2 Temperature and Salinity data

For this study, we used temperatures recorded at 110 m; 200 m and 400 m water depth by a CTD deployed on mooring lmc5A (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 68K to achieve meter-wise data resolution. Sea surface 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://poet.jpl.nasa.gov/). Surface salinity data is not available for the complete deployment period and instead, CTD-based 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 110 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 non-existent between 400 and 1525 m, we have chosen 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

We selected four species from the sediment trap samples according to differences in depth habitats as reported in previous studies. *Globigerinoides ruber* (white) is a shallow, surface mixed layer dwelling species, occupying the upper 50 m of the water column and is commonly used to reconstruct paleo-SST (Hemleben et al., 1989). To minimize a potential biases in δ^{18}O and Mg/Ca associated when combining different morphotypes (Steinke et al., 2005), we used only *G. ruber* sensu stricto that was by far the most abundant in these samples (Fallet et al., 2010).
The subsurface-dwellers *Neogloboquadrina dutertrei* and *Pulleniatina obliquiloculata* have been associated with a calcification depth of 0 - 100 meters and 60 - 150 meters 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). The

deep-dwelling species *Globorotalia scitula* was used as a representative for 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 µm size fraction. In a limited number of samples, abundances of this species were low in this size fraction, and geochemical analyses were therefore performed on specimens from a larger size fraction (315 - 400 µm). Analyses on *N. dutertrei*, *P. obliquiloculata* and *G. scitula* were generally done on the size range >315 µm, with additional measurements on the 250 - 315 µm size fraction depending on the specimen's abundance within a sample. All specimens show excellent preservation and do not show any signs of diagenesis (based on SEM microscopy). Recently, Fallet et al. (2012) showed that shell size normalized weights of three species of planktonic foraminifera from the same sediment trap location do not differ from those of the surface sediment samples below this trap. Absence of dissolution is also reported by Birch et al. (2013) describing planktonic foraminifera from surface sediments at ~ 3000 m water depth, in the northern part of the Mozambique Channel, as being glassy and preserved excellently.

3.4 Mg/Ca and Stable isotope analyses

The Mg/Ca ratios of single chambers used in this study were previously published (Steinhardt et al., 2014) and were determined by Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) at Utrecht University (Reichart et al., 2003) (for summary of the results see Tab. 1). Subsequently, specimens were analyzed for whole shell δ^{18}O and δ^{13}C after microscopic removal from the laser ablation stub with ethanol and inspection for possible contaminations. Measurements were performed at the Universitat Autònoma de Barcelona on a Thermo Finnigan MAT253 mass spectrometer coupled to a Kiel IV device for CO_2 sample gas preparation. External reproducibility (1σ) 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 sample gas and the CO_2 is separated from other possible contaminant gases on a poraplot Q GC column. Reproducibility (1σ) 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 $\delta^{18}O_{CC}$ are in good agreement (Tab. 2). Measurements with the GASBENCH-II have a somewhat wider standard deviation inherent to continuous flow mass spectrometry. In total, 391 single shell stable isotope values were obtained. Values deviating more than twice the standard deviation from the average of the total dataset were regarded as outliers (n=23) and removed from the dataset (Tab. S3).

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 $\delta^{18}O_{calc}$ following equation (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).

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

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 (see supplementary table, 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)

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

This linear relationship (3) is subsequently used to estimate $\delta^{18}O_{sw}$ 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 estimated $\delta^{18}O_{sw}$ 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 single chamber Mg/Ca analyses (Steinhardt et al., 2014), to calculate the $\delta^{18}O$-derived calcification temperature for all species, following the temperature equation of Kim and O'Neil (1997):

$$(3)\ T = 16.1 - 4.64*(\delta^{18}O_{CC} - (\delta^{18}O_{SW}-0.27)) + 0.09*(\delta^{18}O_{CC} - (\delta^{18}O_{SW}-0.27))^2$$

The temperature equation of Kim an O'Neil (1997) is the most general calibration, which allows comparing inter specific differences that are automatically accounted for when using species-specific calibrations.

4. Results

4.1 Oxygen isotopes

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 average $\delta^{18}O_{CC}$ and $\delta^{13}C_{CC}$ (Fig. 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* (Tab. 1, Fig. 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 shell-$\delta^{18}O$ signature, reflecting their different mean calcification depth. *G. ruber* (-2.57±0.04‰, SD: ±0.24‰), *N. dutertrei* and *P. obliquiloculata* record negative $\delta^{18}O_{CC}$ values between -1.53±0.03‰ (standard deviation (SD): ±0. 42‰) and -1.13± 0.04‰ (SD: ±0.24‰), more noticeable positive values are found for *G. scitula* with 1.47± 0.14‰ (SD: ±0.87‰) (Fig. 3). No significant trend between size fractions 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).

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

4.2 Carbon isotopes

Values for $\delta^{13}C$ range from -1.5‰ to 2.0‰. Most enriched $\delta^{13}C$ values are found in *N. dutertrei* ($\delta^{13}C$= 0.53±0.042‰, SD: ±0.44‰), whereas values for *P. obliquiloculata* are most depleted ($\delta^{13}C$= 0.04±0.04‰, SD: ±0.21‰). Individuals of *G. ruber* reflect a relatively large range in $\delta^{13}C_{cc}$ values (0.51±0.04‰, SD: ±0.47‰), whereas *G. scitula* (0.27±0.04‰, SD: ±0.22‰) displays a much more limited variability in $\delta^{13}C_{CC}$ (Tab. 1, Fig. 3). Species specific $\delta^{13}C$ - $\delta^{18}O$ relationships (Fig. 2) differ and only *G. scitula* showed a positive 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 $\delta^{13}C$ (0.27‰, SD: ±0.22‰) and relatively enriched $\delta^{18}O$ values (1.47‰, SD: ±0.87‰).

From the four investigated species, only *G. scitula (*N: 37) did not show a significant difference in $\delta^{13}C$ 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 $\delta^{13}C$ values during non-eddy conditions. During non-eddy condition however, *N. dutertrei* (N: 118; U= 939.5, p = 0.002) recorded more negative $\delta^{13}C$ values (Fig. 3).

4.3 Calcification temperatures

The calculated multi-specimen $\delta^{18}O$-based temperature from eq. (3) 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 22.5±3.7°C and 21.6±3.1ºC, 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 14.4±3.4°C (Fig. 5). Calcification temperatures based on $\delta^{18}O$ result in markedly different values, ranging from 29.4±1.3°C for *G. ruber* to 24.4±2°C for *N. dutertrei*, 22.5±1.1°C, for *P. obliquiloculata* and 10.4±3.9°C for *G. scitula* (Tab. 1). 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 non-eddy condition. Mean $\delta^{18}O$ from Eq. (3) for eddy intervals yield 22.8±0.9°C for *P. obliquiloculata* and 7.9±2.1°C for *G. scitula*. For non-eddy intervals calcification temperatures are 22.5±1.2°C for *P. obliquiloculata* and 11.8±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 et al., 2009, respectively), which is close to the satellite-derived annual mean SST of 27.6°C (Fallet et al., 2010). When applying the equation of Kim and O'Neil (1997) for conversion of $\delta^{18}O_{CC}$ into temperature SST is considerably higher (29.4±1.3°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 may be offset compared to the temperature-$\delta^{18}O_{CC}$ relationship of biogenic carbonates. Nevertheless this temperature estimate based on Kim and O'Neil (1997) is in good agreement with the average temperature of 28±1.1°C during the investigated intervals. The intertest variability of this species can be explained by the high temperature variability at the sea surface, as well as differences in symbiont activity. 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 (e.g. Deuser et al*.,* 1981*;* Lončarić 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 meters, mixed layer) conditions (e.g. Deuser, 1987; Anand et al., 2003; Field, 2004; Fallet et al., 2010). Birch at al. (2013) show that shell size of specimens of *G. ruber* is not correlated to $\delta^{18}Occ$, 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 in some areas relatively equally throughout the year (e.g. Deuser, 1987; Mohtadi et al., 2006; Tedesco et al., 2007), whereas in other areas, including the MC, they occur at highest densities during summer months (e.g. Tolderlund and Bé, 1971; Duplessy et al., 1981; Ganssen and Sarnthein, 1983; Deuser and Ross, 1989; Eguchi et al., 2003; Lončarić et al., 2006; Fallet et al., 2010). This seasonal preference results in SSTs that are slightly biased towards summer conditions when using fossil specimens of this species.

Based on an average $\delta^{18}O_{CC}$-derived temperature of 24.3±2°C (Tab. 2), following the equation of Kim and O'Neil (1997), calcification depths of *N. dutertrei* are in the range of 20 - 130 m (Fig. 6) with an average of 58 m. For eddy conditions, the average calcification depth is approximately 80 m, for non-eddy condition it is approximately 37 m. Average Mg/Ca-based temperature of 22.5±4°C is in relatively good agreement with the average $\delta^{18}O_{CC}$-derived temperature (Tab. 2). The difference between Mg/Ca- and $\delta^{18}O$-based temperatures are smaller than the 1.2°C uncertainty associate with the Mg/Ca calibration (Anand et al., 2003). Previous studies using *N. dutertrei* from Indian Ocean core top samples and Mozambique Channel sediment traps have reported similar depth ranges between 40 - 150 m (Kiefer et al., 2006) and similar average depths of 80 m (Fallet et al., 2011), respectively. Both of these studies used pooled specimen for their stable 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 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 shell walls of *N. dutertrei* from the Timor Sea suggested temperatures between 12 and 23°C, implying migration through 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 shell calcite has been viewed in terms of discrete calcification events (Elderfield et al., 1996; Erez et al., 2003). Plankton tow studies (Fairbanks et al., 1980) showed oxygen isotope equilibrium calcification for *N. dutertrei* and *P. obliquiloculata*.

The $\delta^{18}O_{CC}$-based calcification depths for *P. obliquiloculata* reported here (48-125 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 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), indicating 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).

The average $\delta^{18}O_{CC}$ for *G. scitula* yields a calcification temperature of 10.4±3.9°C, suggesting that this species calcifies between 290 and 1100 m (Fig. 6) with an average of approximately 500 m. This overlaps with the depth rage indicated by the Mg/Ca temperatures of 14.4±3.4°C derived from the last few chambers added, suggesting that these shells formed at a depth between about 250 and 350 meter for non-eddy and eddy conditions respectively. The $\delta^{18}O_{cc}$ based estimates, however, do not consider possible vital effects that were previously suggested for this species (e.g. Kahn and Williams, 1981). If taken into account, this would lower the temperature and depth habitat estimates by some 4°C and 500 m, respectively.

Birch et al. (2013) support previous findings of a distinct positive correlation between $\delta^{18}O$ 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 inter-specimen variability in $\delta^{18}O_{CC}$ for *G. scitula*, than in the other species.

5.2 Habitat depth versus calcification depth

Planktonic foraminifera collected by sediment traps might record $\delta^{18}O_{cc}$ signals comprising 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; Lončarić 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 preferences of planktonic foraminifera. Contrasting eddy and non-eddy conditions, a short-term feature, allow us to disentangle seasonal and other short-term local hydrography changes and their effect on foraminiferal calcification depth.

While Mg/Ca-based temperatures of *G. ruber* and *N. dutertrei* record eddy induced changes in upper water column stratification (Steinhardt et al., 2014), $\delta^{18}O$-based temperatures are relatively similar for both species (Fig. 6). Using the paleo-temperature equation (equation (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 at shallower depth, between 20 and 77 m (average calcification depth 60 m) during non-eddy condition. Largest changes in calcification depth in this study are inferred from *G. scitula*. From a calcification range between 500 to 1100 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).

Conversely, $\delta^{18}O$-based temperatures are significantly different for *P. obliquiloculata* and *G. scitula*, while the Mg/Ca-based temperature of the last formed chambers of *P. obliquiloculata* indicate similar calcification temperature (Tab. 1). 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 depths 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 compared to observed satellite SST likely results from the spatial resolution employed here. 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 shell 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 standard deviation of $\delta^{18}O$ results in a temperature variability of ±0.87ºC. Such a variability could explain between 12 and 38% of the variability in $\delta^{18}O$-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 hours (Bé, 1979). Considering that our sample duration ranges between 17 and 21 days, $\delta^{18}O$ variability is likely to be affected by other parameters (e.g. temperature). Therefore, the observed variability in $\delta^{18}O$-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 under different conditions or water depth.

5.3 Reconciling $\delta^{18}O$ and Mg/Ca-derived calcification depths

Mg/Ca-derived temperatures indicate that calcification depths of *N. dutertrei* range 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 (Steinhardt et al., 2014). Thus, the shoaling in average calcification depth from 98 m during eddy conditions to 81 m during non-eddy conditions, indicated by the whole shell $\delta^{18}O_{cc}$ is less as than 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 (Steinhardt et al., 2014). The Mg/Ca-derived shift is hence larger 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 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 approximately 200 and 460 m (average 330 m) during eddy conditions to shallower depths between approximately 120 and 420 m (average 270 m) during non-eddy conditions (Steinhardt et al., 2014). Although the $\delta^{18}O_{cc}$ suggests calcification somewhat deeper than the Mg/Ca data, both Mg/Ca and $\delta^{18}O$-derived calcification depth indicate a shoaling for this species during non-eddy conditions. Furthermore, the average $\delta^{18}O$-derived calcification temperature of 10.4±3.9°C is in good agreement with previously published results for this species (Fallet et al. 2011; Birch et al. 2013). We refrain from correcting for a vital effect, as this would lower $\delta^{18}O$-derived calcification temperature to values unrealistically lower than the Mg/Ca-derived calcification temperatures for the last chambers. The observed remaining offset between single-specimen $\delta^{18}O$ and single chamber Mg/Ca in *G. scitula* suggest that either 1) there is a vital effect resulting in more enriched (i.e. positive) $\delta^{18}O$ values than when this species would precipitate its shell in isotopic equilibrium with seawater, 2) a more shallow calcification depth during formation of the final chamber, 3) that crust carbonate adds significantly to the total shell mass, or, 4) the Mg/Ca calibration for *G. hirsuta* (Anand et al., 2003) might be different from that of *G. scitula*. Following the vital effect correction of Williams and Kahn (1981), calcification temperature is 6.4°C±3.9°C, which is equivalent to an average calcification depth for *G. scitula* between 600 and deeper than 1100 m. This is in agreement with a suggested depth habitat within the upper 1000 m for this species (Schiebel et al., 1995; Ortiz et al., 1996; Itou et al., 2001). In our opinion the last two explanations are most likely, however, irrespective of the underlying mechanism it is clear that the majority of the test carbonate precipitated at a depth greater or comparable to that of the ontogenetic carbonate of the final chambers.

The range of uncertainties 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 conditions. 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, 2006; 2009), 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. 4), relating the shell mass 'M' to depth (z) using two constants (α and β) determining the shape of this relationship:

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

Since shell size of planktonic foraminifera is thought to increase with water depth (Hemleben and Bijma, 1994; Peeters and Brummer, 2002) shell mass must also increase 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 equation (5), the expected stable isotope composition of a specimen for a discrete water depth interval can be calculated as follows:

(5) $\delta^{18}O_{model} = \sum_{i}^{n} \frac{(M_i - M_{i-1}) + \delta^{18}Oeq,i}{M_i}$

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 depth of the last chambers, indicating the base of the calcite production zone. The Mg/Ca-based temperature of the F-1 chamber was used to delimit 95% of the calcite production. In equation (5), $\delta^{18}O_{eq,i}$ denotes the interval averaged $\delta^{18}O$ 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 equation 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 position of the base of the productive zone. In contrast to Wilke's (Wilke et al., 2006; 2009) 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 $\delta^{18}O_{sw}$ from expected equilibrium ('the vital effect'), is assumed to be constant over the temperature range in which the species calcifies. We have adapted $\delta^{18}O_{sw}$ in meter steps as calculated from *in situ* salinity measurements, which where interpolated for the upper 2000 meters. 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.

Calcification depths inferred from the cumulative $\delta^{18}O$ model (Fig. 7) match previously published calcification depths and associated temperatures for each of the 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 consistent with the general model of migration to greater depth during growth. In case of the deep dwelling *G. scitula,* however*,* $\delta^{18}O$-based calcification depth is below that of the final chambers as derived from Mg/Ca-temperatures. Without applying a temperature correction for $\delta^{18}O$-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 would suggest that the majority of the previously formed calcite was precipitated deeper in the water column. 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 calcification conditions (Steinhardt et al., 2014). This calcification response is also reflected in more enriched $\delta^{13}C$ 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 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 with depth seem to be species-specific. We modified the model by including Mg/Ca-based temperatures (following the species specific equations of Anand et al., 2003) of the F-1 chamber to constrain the 95% calcification level. 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 calcite added as a result of wall thickening due to gametogenic calcite or the precipitation of crust (secondary calcite, Bé, 1980; Duplessy et al., 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 (about 1‰) between $\delta^{18}O_{model}$ and $\delta^{18}O_{CC}$. This suggests that relatively more 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 $\delta^{13}C$ values found in planktonic foraminifera is primarily a function of the carbon isotope composition of the dissolved inorganic carbon (DIC) in seawater (e.g. Urey, 1947; Epstein et al., 1953; McCorkle et al., 1990), which changes with water depth (e.g. Fairbanks et al., 1980, Curry and Crowley, 1987). Therefore, we can use the cumulative mass balance model output of the mass added per meter to 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 each species of foraminifera ($\delta^{13}C_{expect}$). Since there is no relation between size and stable carbon isotopes in our specimens, the employed size fractions contained only mature (adult) specimens (Brummer et al., 1986, 1987). Comparing water column $\delta^{13}C_{DIC}$ data (Supplement, Fig. A1) 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, the $\delta^{13}C$ of *Globorotalia scitula* increases with depth. Low temperatures and reduced food availability have been suggested to result in relatively low metabolic rates in deep dwelling species, so that their $\delta^{13}C$ likely approaches $\delta^{13}C_{DIC}$ values (Birch et al., 2013). This suggests the involvement of biological controls on the $\delta^{13}C$ of the different genera (*Globigerinoides, Neogloboquadrina, Pulleniatina 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. ruber* is formed in surface waters (Fig. 7). Equal $\delta^{13}C_{expect}$ values for eddy and non-eddy 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) are 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-poor and chlorophyll-depleted water in the center, which implies that also δ^{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* during eddy conditions (deeper calcification) is also reflected by more depleted δ^{13}Ccc values. Remineralization of organic matter at greater depth cause enrichment of δ^{13}C$_{DIC}$, resulting in the incorporation of lighter carbon isotopes into the shell 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 δ^{13}C$_{DIC}$. This is in agreement with previous findings (Mulitza et al., 1999), showing that the carbon isotopic composition of *N. dutertrei* exhibits a constant and temperature-independent off-set from δ^{13}C$_{DIC}$ of ~0.5‰ over a wide temperature range. This difference is in line with the offset in our dataset between δ^{13}C$_{expect}$ and δ^{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 δ^{13}C$_{DIC}$ with water depth (see supplementary information, Fig. A1 and A2). The more depleted δ^{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 δ^{13}C$_{cc}$ for *G. scitula* during eddy versus 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 δ^{13}C$_{CC}$ differences 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 δ^{13}C$_{expect}$ and δ^{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, δ^{13}C values indicate a significant difference between eddy and non-eddy 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 individual $\delta^{13}C$ 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 (supplementary, Fig. A1 and A2). 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 $\delta^{13}C_{DIC}$ 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 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. Conclusion

Documenting changes in upper ocean stratification is essential for understanding past climatic conditions from sediment cores and is commonly estimated by determining the difference in $\delta^{18}O$ 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 MC.

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 results 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 $\delta^{18}O$. Furthermore, the results of the $\delta^{18}O$ cumulative mass balance model agree with previous findings that thermocline dwelling *N. dutertrei* and deep dwelling *G. scitula* are suitable recorders of eddy induced hydrographic changes (Steinhardt et al., 2014). The combination of various proxies (e.g. Mg/Ca, $\delta^{18}O$ and $\delta^{13}C$) can thus provide a useful set of geochemical proxies to reconstruct the thermal and nutrient structure of the upper part of the water column.

All species analyzed have unique offsets from ambient seawater $\delta^{13}C$. However, comparison of species specific isotopic trajectories with water column $\delta^{13}C$ reveals that ambient $\delta^{13}C_{DIC}$ may be recorded by the species used in this study. The $\delta^{13}C$ 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.

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Figures:

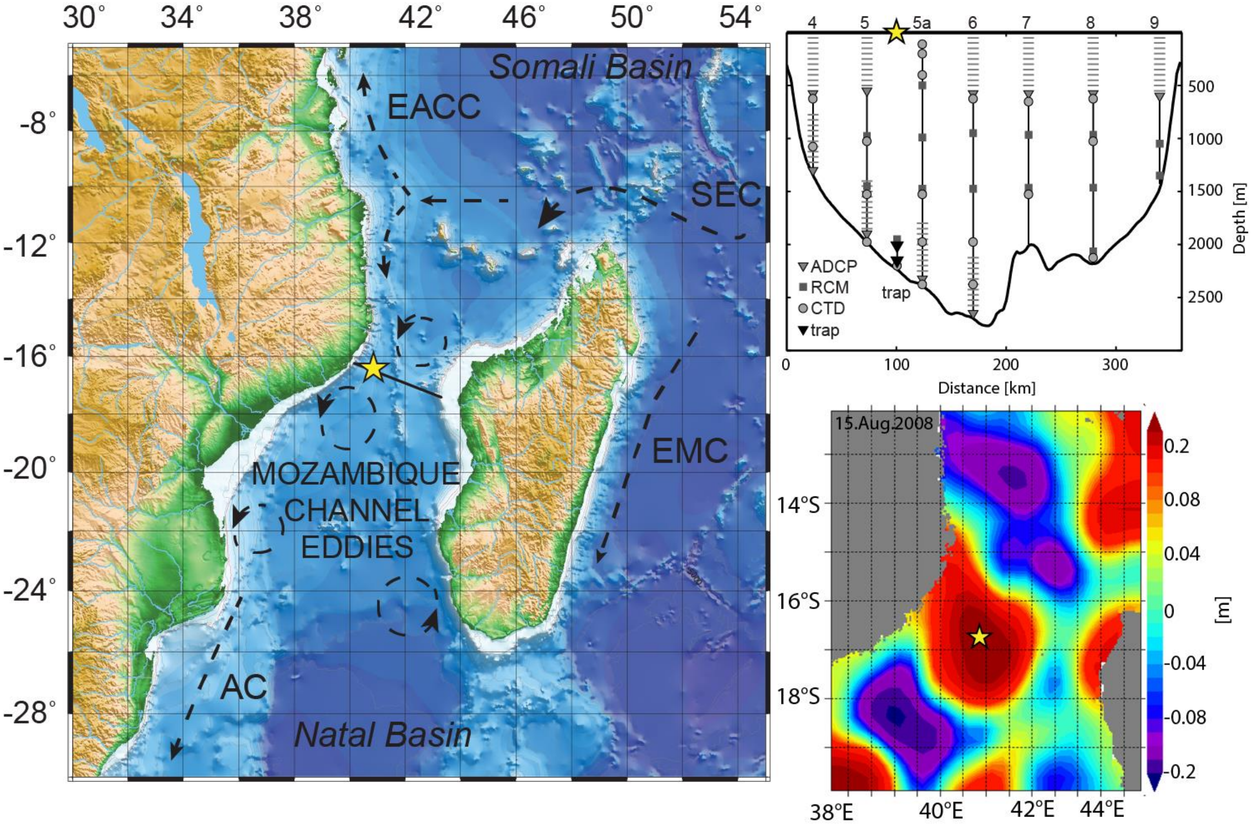


Fig. 1

species	Mg/Ca [mmol/mol]	Mg/Ca SD [mmol/mol]	Mg/Ca-based temperatures [°C]	$\delta^{18}O$ [‰]	$\delta^{18}O$ SD [‰]	$\delta^{18}O$-based temperatures [°C]	$\delta^{13}C$±SE [‰]	$\delta^{13}C$ SD [‰]
G. ruber	5.3±0.09	±1.2	28.1±2.8	-2.57±0.04	±0.35	29.4±1.3	0.51±0.03	±0.47
N. dutertrei	2.6±0.06	±1.0	22.5±3.7	-1.53±0.03	±0.48	24.3±2.0	0.53±0.04	±0.44
P. obliquiloculata	2.3±0.1	±0.6	21.6±3.1	-1.13±0.04	±0.24	22.3±1.1	0.04±0.04	±0.21
G. scitula	1.5±0.07	±0.4	14.4±3.4	1.47±0.14	±0.87	14.4±3.9*	0.27±0.04	±0.22

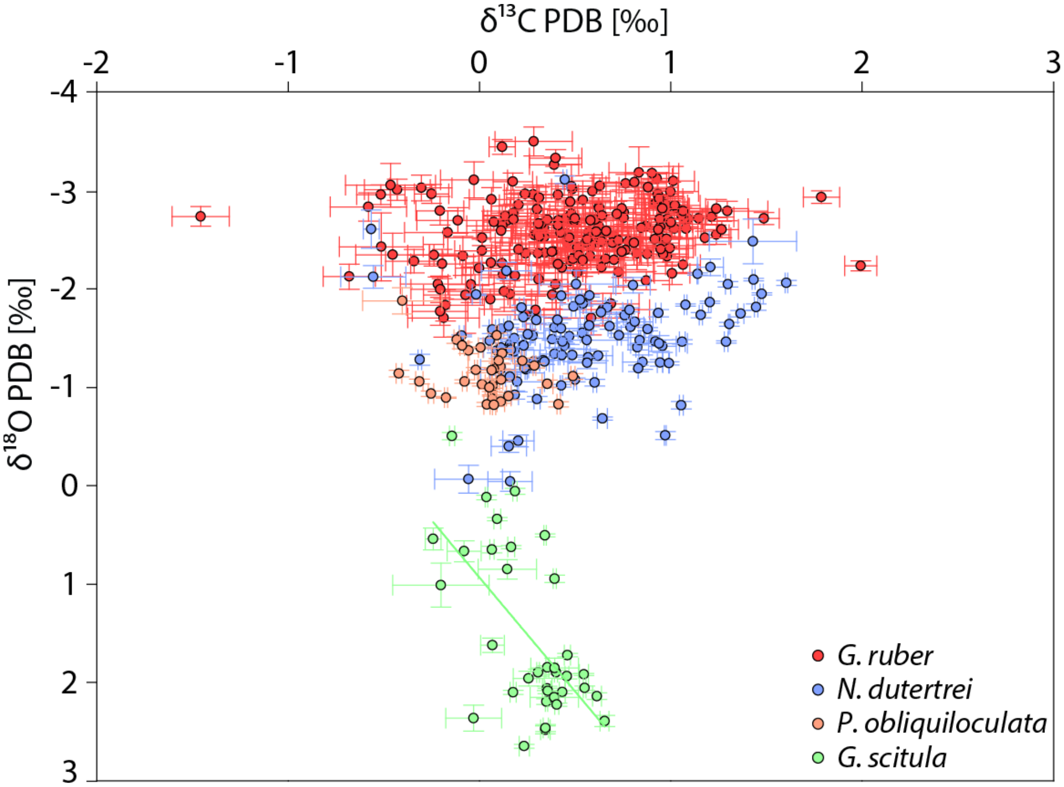
** vital effect corrected [Kahn an Williams, 1981]*

data from Steinhardt et al. 2014

Tab. 1

species	$\delta^{13}C$ [‰]		$\delta^{13}C$ SD [‰]		$\delta^{18}O$ [‰]		$\delta^{18}O$ SD [‰]	
	VU	BCN	VU	BCN	VU	BCN	VU	BCN
G. rub	-	0.51±0.03	-	±0.47	-	-2.57±0.04	-	0.35
N. dut	0.41±0.12	0.54±0.01	0.41	0.45	-1.37±0.09	-1.58±0.03	0.59	0.46
P. obli	-0.07±0.13	0.05±0.01	0.29	0.20	-1.46±0.09	-1.10±0.02	0.37	0.21
G. scit	0.13±0.14	0.3±0.02	0.24	0.21	1.55±0.11	1.45±0.04	0.69	0.92

Tab. 2



δ13C PDB [‰]
-2
-1
0
1
2
3
δ18O PDB [‰]
-4
-3
-2
-1
0
1
2
3
G. ruber
N. dutertrei
P. obliquiloculata
G. scitula

Fig. 2

Species	**δ^{18}O±SE [‰]**		**δ^{18}O SD [‰]**		**T [°C], (Kim&O'Neil, 1997)**		**δ^{13}C±SE [‰]**		**δ^{13}C SD [‰]**	
	Eddy	Non-Eddy	Eddy	Non-Eddy	Eddy	Non-Eddy	Eddy	Non-Eddy	Eddy	Non-Eddy
G. ruber	-2.56±0.03	-2.57±0.04	0.31	0.39	29.8	29.2	0.59±0.04	0.39±0.06	0.40	0.53
N. dutertrei	-1.53±0.08	-1.53±00.5	0.58	0.39	24.6	24.0	0.39±0.06	0.64±0.04	0.44	0.41
P. obliquiloculata	-1.25±0.06	-1.09±0.05	0.19	0.25	23.3	21.9	0.18±0.06	-0.02±0.04	0.18	0.19
G. scitula	1.99±0.1	1.18±0.2	0.48	0.92	8.2	11.5	0.31±0.05	0.25±0.06	0.18	0.26

Tab. 3

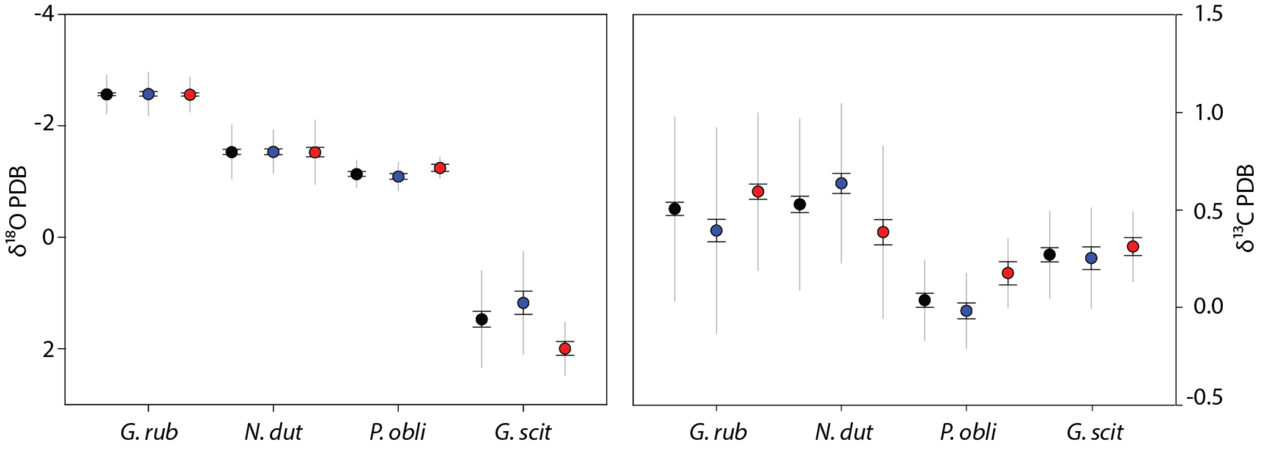


Figure 3

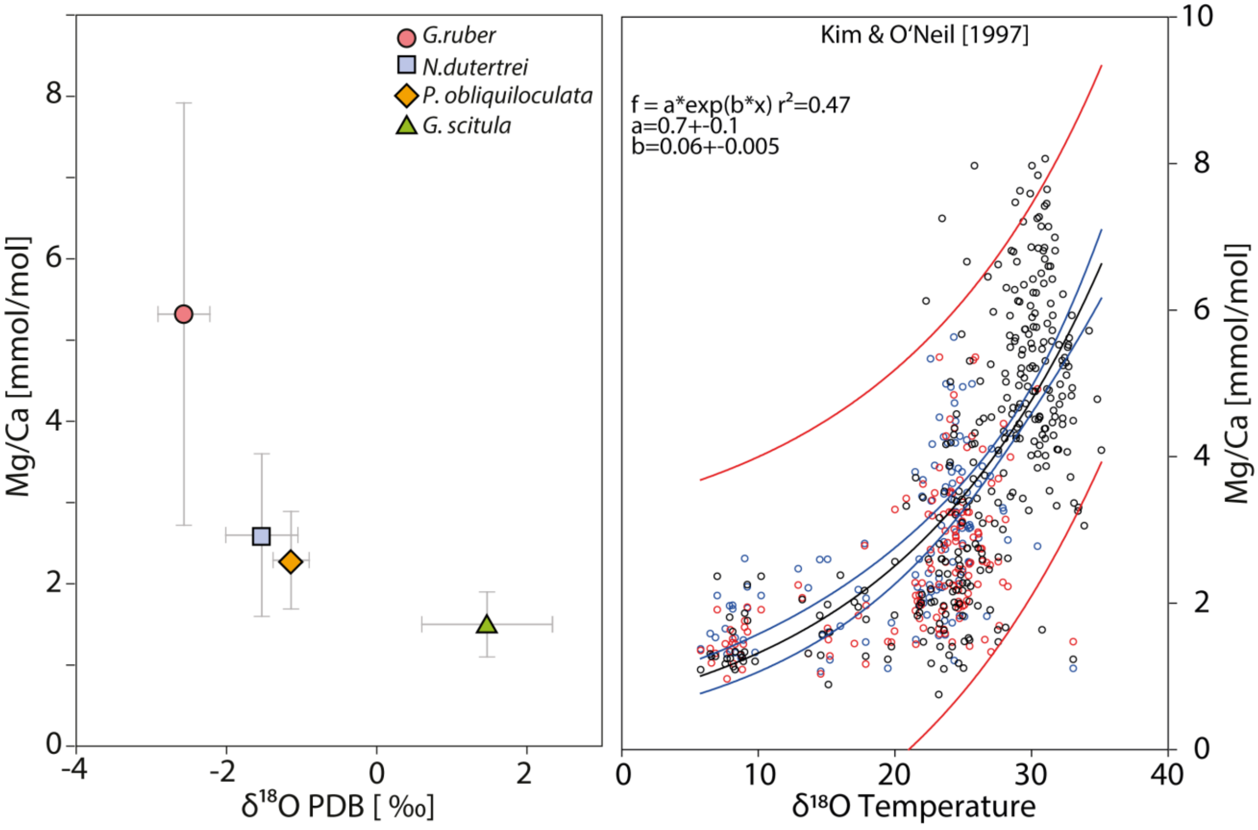


Figure 4

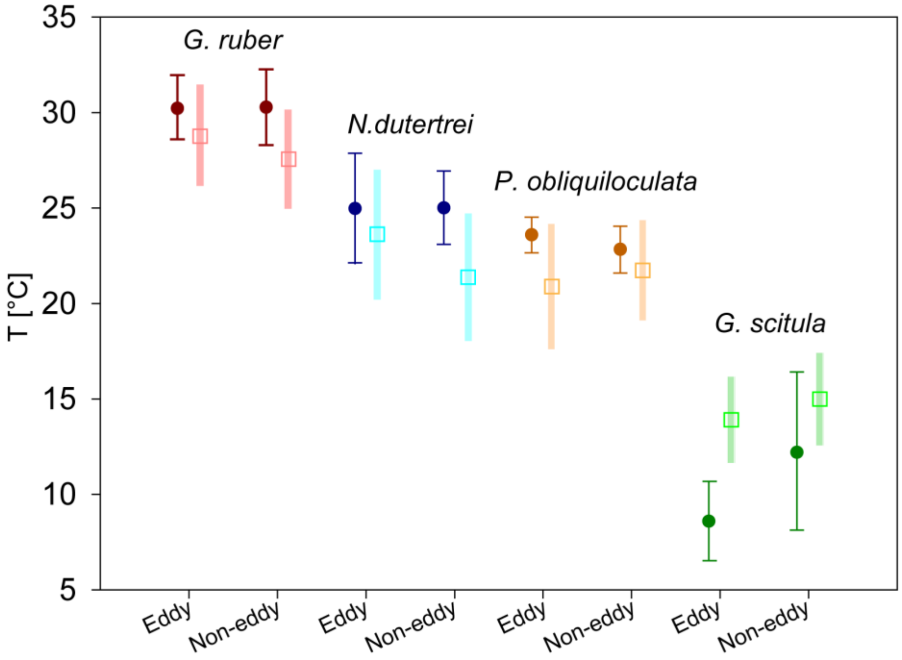


Figure 5

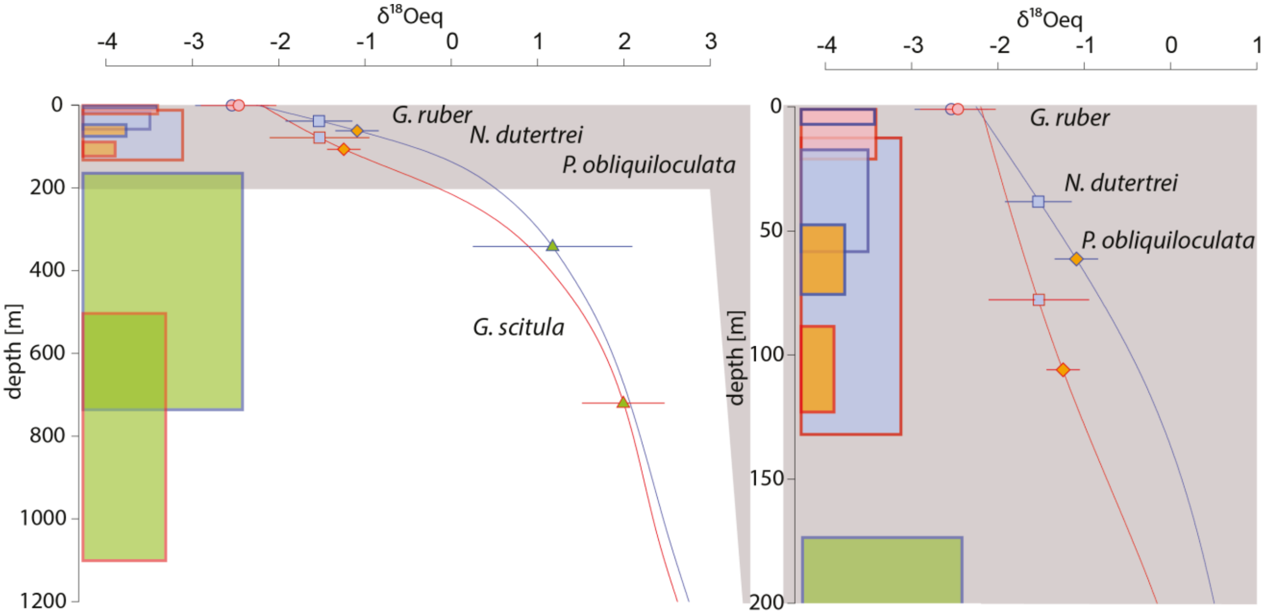
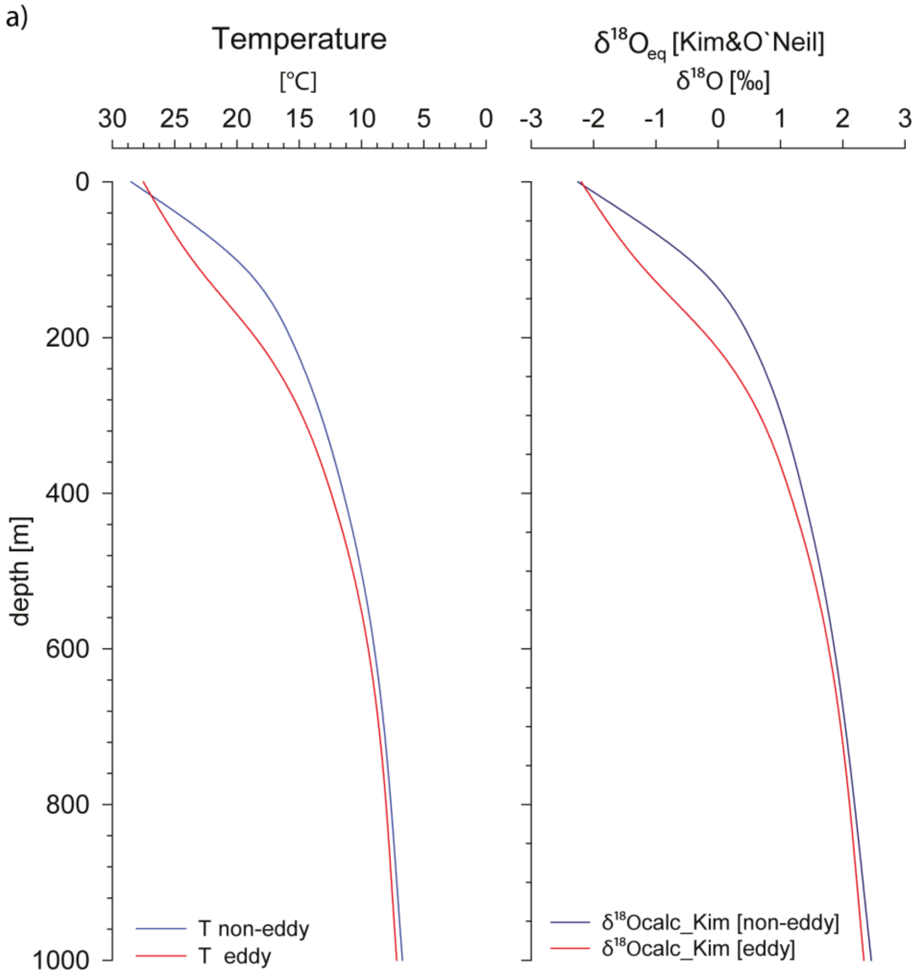
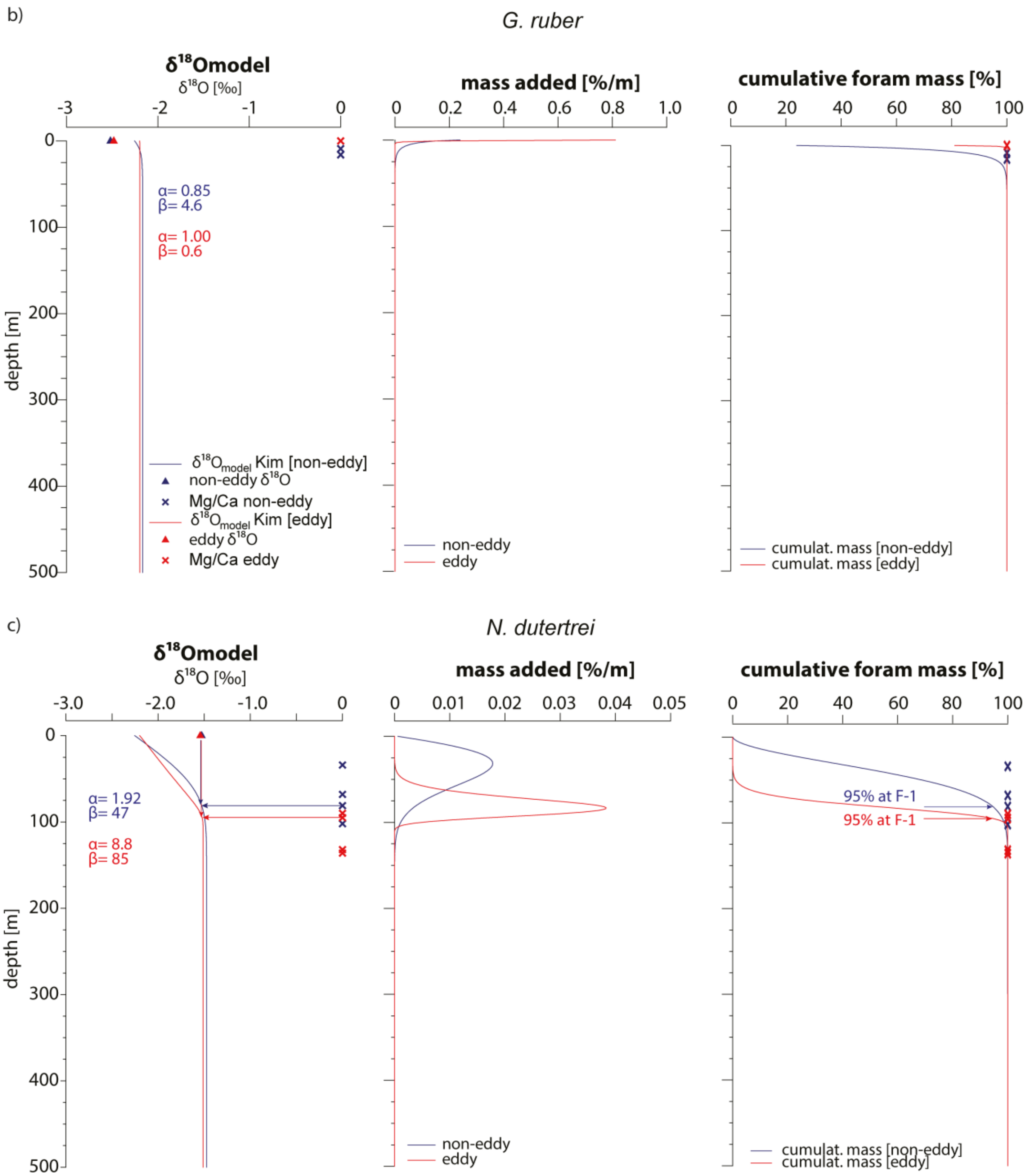


Figure 6


a)
Temperature
[°C]
30
25
20
15
10
5
0
δ18Oeq [Kim&O`Neil]
δ18O [‰]
-3
-2
-1
0
1
2
3
depth [m]
0
200
400
600
800
1000
T non-eddy
T eddy
δ18Ocalc_Kim [non-eddy]
δ18Ocalc_Kim [eddy]


b)
G. ruber
δ18Omodel
δ18O [‰]
-3
-2
-1
0
depth [m]
0
100
200
300
400
500
α= 0.85
β= 4.6
α= 1.00
β= 0.6
δ18Omodel Kim [non-eddy]
non-eddy δ18O
Mg/Ca non-eddy
δ18Omodel Kim [eddy]
eddy δ18O
Mg/Ca eddy
mass added [%/m]
0
0.2
0.4
0.6
0.8
1.0
non-eddy
eddy
cumulative foram mass [%]
0
20
40
60
80
100
cumulat. mass [non-eddy]
cumulat. mass [eddy]
c)
N. dutertrei
δ18Omodel
δ18O [‰]
-3.0
-2.0
-1.0
0
depth [m]
0
100
200
300
400
500
α= 1.92
β= 47
α= 8.8
β= 85
mass added [%/m]
0
0.01
0.02
0.03
0.04
0.05
non-eddy
eddy
cumulative foram mass [%]
0
20
40
60
80
100
95% at F-1
95% at F-1
cumulat. mass [non-eddy]
cumulat. mass [eddy]

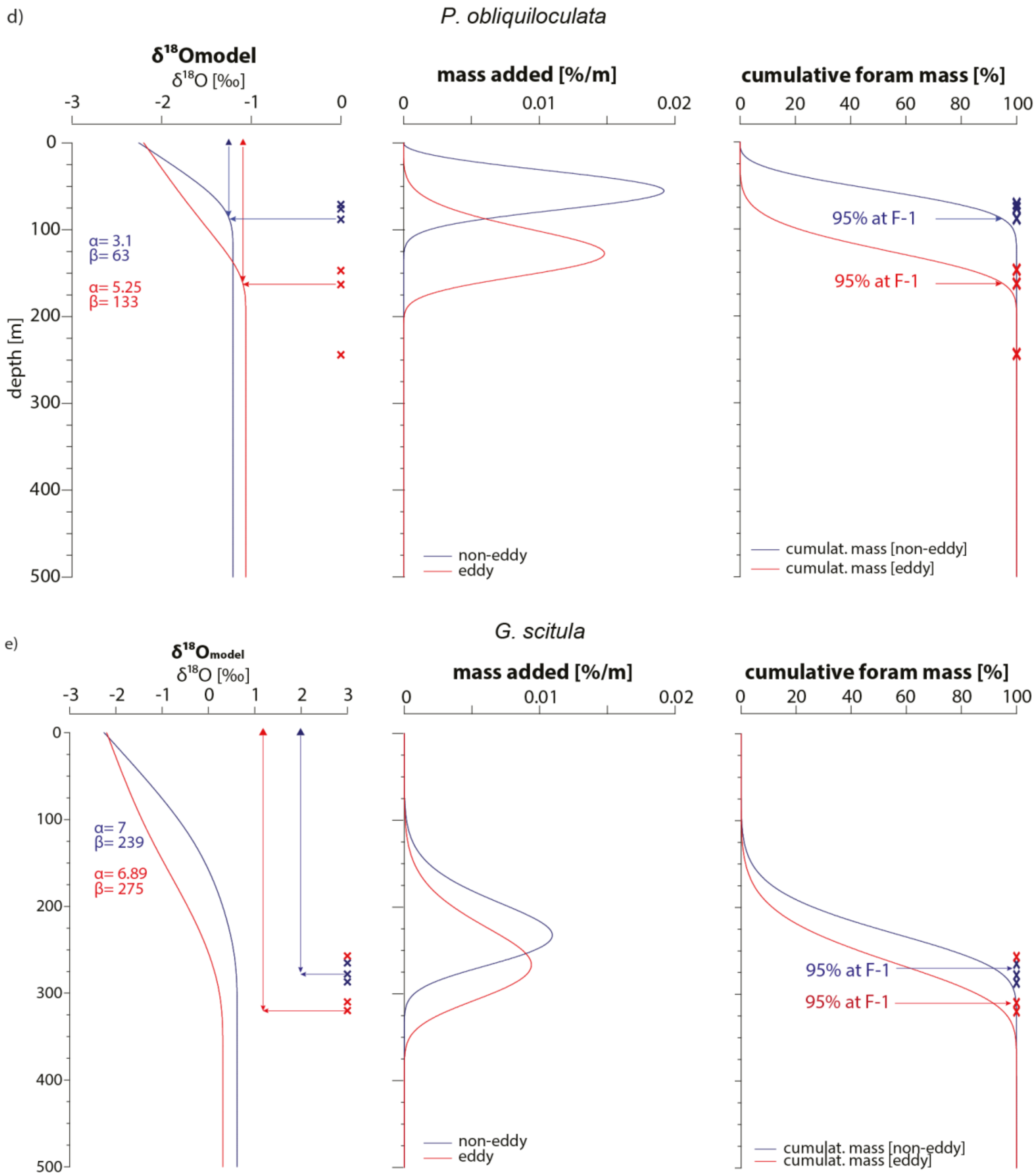

d)
P. obliquiloculata
δ18Omodel
δ18O [‰]
-3
-2
-1
0
0
100
200
300
400
500
depth [m]
α= 3.1
β= 63
α= 5.25
β= 133
mass added [%/m]
0
0.01
0.02
non-eddy
eddy
cumulative foram mass [%]
0
20
40
60
80
100
95% at F-1
95% at F-1
cumulat. mass [non-eddy]
cumulat. mass [eddy]
e)
G. scitula
δ18Omodel
δ18O [‰]
-3
-2
-1
0
1
2
3
α= 7
β= 239
α= 6.89
β= 275
mass added [%/m]
non-eddy
eddy
cumulative foram mass [%]
95% at F-1
95% at F-1
cumulat. mass [non-eddy]
cumulat. mass [eddy]

Figure 7

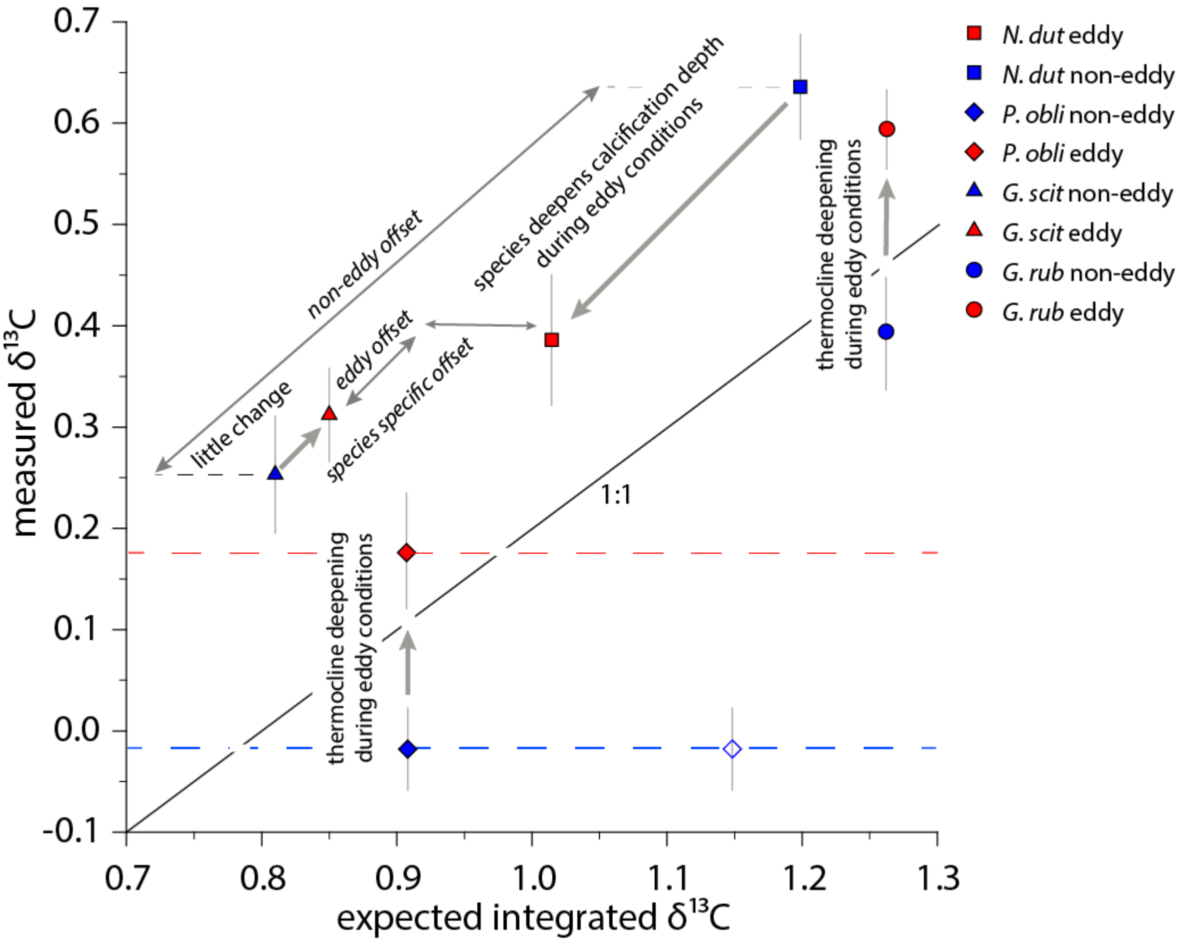


Figure 8

Figure captions:

Figure 1: Hydrography of southwestern Indian Ocean and location of the sediment trap (star) within the mooring array (right top). On the right bottom a map of sea level anomaly shows the passing of an anti-cyclonic eddy over the trap location (star). AVISO sea level anomaly map was produced using the AVISO live access server (http://las.aviso.altimetry.fr/las/getUI.do). EACC: East African Coastal Current, SEC: South Equatorial Current, AC: Agulhas Current.

Table 1: Average Mg/Ca ratios (Steinhardt et al., 2014), δ^{18}O and δ^{13}C with standard errors (SE) and corresponding standard deviations (SD). Mg/Ca-based temperature are based on species specific temperature equations. The equation developed by Fallet et al. (2010) was applied for *G. ruber*. The equations developed by Anand et al. (2003) were applied to *N. dutertrei*, *P. obliciloculata*. For *G. scitula* Anand's equation for *G. hirsuta* was applied following the example of Fallet et al. (2011). Calculate δ^{18}O-based temperatures are based on the equation of Kim and O'Neil (1997).

Table 2: Average measurements of δ^{18}O and δ^{13}C with standard errors (SE) and corresponding standard deviations (SD) 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 (BCN) and the Thermo Finnigan Delta Plus mass spectrometer equipped with a Gas Bench II preparation device at the VU University Amsterdam (VU). Measurements of *N. dutertrei*, *P. obliquiloculata* and *G. scitula* are comparable and species-specific values are in good agreement

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

Figure 3: Eddy (red circles), non-eddy (blue circles) comparison of δ^{13}C PDB and δ^{18}O PDB for the analyzed species. Grey lines indicate standard deviation (SD), black capped lines are indicative of standard error (SE).

Table 3: Results for δ^{18}O and δ^{13}C with standard errors (SE) and corresponding standard deviations (SD) under eddy and non-eddy conditions for *G. ruber*, *N. dutertrei*, *P. obliquiloculata* and *G. scitula*.

Figure 4: Scatter plot of Mg/Ca versus δ^{18}Occ (left panel). Right panel: single chamber Mg/Ca exponential relationship with δ^{18}O-derived Temperatures calculated using Kim & O'Neil (1997). Regression: f = a*exp(b*x), with a=-0.7, b=0.06, r^2=0.47 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* (red circles) and F-2 for *N. dutertrei, P. obliquiloculata* and *G. scitula* (blue circles). Mg/Ca data from Steinhardt et al. (2014). Note that the correlation coefficient also indicates that approximately 60% of the observed variability is not due to temperature alone.

Figure 5: Inter-species δ^{18}O- and Mg/Ca-derived temperature for eddy and non-eddy intervals. Circles: δ^{18}O-based temperatures using the equation of Kim and O'Neil (1997), Squares represent Mg/Ca-based temperatures using the species specific equations of Anand et al. (2003) for *N. dutertrei*, *P. obliquiloculata* and *G. scitula*. For *G. ruber*, the equation of Fallet et al. (2011) was used. 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 of species are generally shallower during non-eddy conditions. 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 $\delta^{18}O_{eq}$, using the equation of Kim and O'Neil (1997). We used $\delta^{18}O_{SW}$ from the species calcification depth. Grey box indicates 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 500m (a). 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 for *G. ruber* (b), *N. dutertrei* (c), *P. obliquiloculata* (c) and *G. scitula* (d)

Figure 8: Inter-species differences between expected $\delta^{13}C$ values, based on the cumulative mass balance model, and measured $\delta^{13}C$ values of *G. ruber*, *N. dutertrei, P. obliquiloculata* and *G. scitula*. Dashed line indicates the 1:1 line of measured and expected $\delta^{13}C$. 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 $\delta^{13}C_{exect}$, this is indicated by the dotted lines. Open diamond indicates $\delta^{13}C_{exect}$ for *P. obliquiloculata* non-eddy conditions.