Comments in response to Editorial Comments

Referee 1 raises the issue of the effects/influences of the 'carbonate ion effect, temperature and dissolution' of foraminiferal d18O and d13C and asks (Page 148, line 25-26.) '..is a progressive enrichment in 13C for increasing size.' Could this observation be due to changing sea water temperature of carbonate ion concentration during TIII? The authors response is very appropriate and I suggest that this finds its place in the revised msc.

We have included this as the final paragraph, prior to our conclusions.

Although, the authors discuss the carbonate ion concentration in the carbon section of the discussion, their data set would allow to play around and try to isolate some of the effects. I understand that this would be too much to discuss in this paper but would be delighted to see a follow up paper specifically on this issue!

We are quite happy to follow this up in a future paper

I would argue that, as a general rule, larger specimens have seen more favourable conditions than smaller ones. In this context, Ezard et al. (2015) state that: "Trends in body size and isotopic composition, particularly in dinoflagellate bearing taxa, suggest that much of the size-dependent isotopic variation observed in death assemblages (i.e., core tops and sediments) relates to factors influencing the maximum size obtained by adults rather than ontogeny." As suggested by referee 2, I suggest that the authors do consider this paper as well.

We agree, earlier work by G.-J. Brummer and F.J.C. Peeters (and unpublished work by the first author) have shown that a range in sizes occurs for different depth habitats and that this changes between the population seen when collected living and dead. We have stated, including in our comment to the reviewer, that we hold the opinion that larger than average specimens should be considered "giants" and smaller than average specimens as "dwarfs" instead of 'juvenile' and 'adult'. Our papers conclusion that smaller specimens record a more surface signal is related to favourable and unfavourable conditions. For instance "deeper" dwellers that can be found close to the surface (i.e. *G.inflata* and occasionally *G. truncatulinoides*) are likely to be outside of their favourable conditions, potentially more likely to be predated upon or have a reduced food supply (if for example they are detritivores instead of carnivores).

Comments in response to Referee 1

We thank you for the careful consideration of our manuscript. Please find outlined below our response to your reviewer comments and corrections of the manuscript, " Late Pleistocene Glacial-Interglacial related shell size isotope variability in planktonic foraminifera as a function of local hydrology.", submitted to Biogeosciences. We have split the referee comments into those that merit a longer discussion, from those that can be answered with a short comment (i.e. we agree to change the text).

Specific comments:

Page 136, line 21-23. 'Seasonal insolation patterns' – What is the sedimentation rate of the core of interest? I am assuming it is relatively low to moderate and I would not expect to records/data to be able to resolve 'seasonality'? I suppose the authors are attributing the overlap (or spread of d18O) for G. bulloides d18O to represent forams tests that have live/grown in different seasons.

The core has a sedimentation rate of between 1.7 and 3.1 cm per kyr during this core interval, based upon the age control points of Huybers (2007) as discussed in Feldmeijer et al.(2015). Whilst this

sedimentation is not varve like, if you consider that there is some degree of symmetry in the insolation pattern of a given period then whilst we may not record autumn with a given species (i.e. G. bulloides), as its main flux is in Spring, the information gathered on only a few seasons can give us information on the remainder. If for example you look at Figure 3 D you will see there are periods (indicated by arrows) when the annual insolation budget changes. Factoring in the offset that occurs annually between actual insolation change and changes in the ocean, you'd expect that the growing season of a cold species would be longer when the relatively high insolation has contracted.

Page 137, line 12. The d18O and d13C of foraminiferal calcite is also a function of carbonate content (e.g. Spero et al., 1997), temperature (e.g. Bemis et al., 2000) and dissolution (e.g. Lohmann, 1995, Rosenthal et al. 2000). These impacts on foraminiferal d18O and d13C should also be mentioned in the text.

A short sentence has been included: "The isotopic composition has been shown to be a function of the ambient carbonate ion concentration ([CO32-], e.g. Spero et al., 1997), temperature (e.g. Bemis et al., 2000) and post-mortems effects (e.g. Lohmann, 1995; Rosenthal et al., 2000)."

Page 137, line 24. Shell size – What about shell mass (e.g. shell weight)? How does shell mass affect isotopic values? I suppose shell mass may reflect a direct relationship of environmental stimuli in both growth/environmental conditions and/or post depositional conditions. Page 138, line 4. 'hence large sizes' – Is there any correlation of these studies with shell size and mass?

Shell mass is a byproduct of number of chambers, wall thickness and the porosity of the shell all of which can be influenced by growth and environmental conditions. Whilst, the mass was determined for these specimens we have chosen not to discuss this dataset because: (1) there is no relationship between isotope and shell weight for this dataset and (2) studies that focus on shell size vs. isotopic composition do not use it. Our shell mass for these species do however show that G. bulloides and G. inflata follow a similar pattern as the *p*CO2 curve from Vostok.

Page 139, line 9. T90-9p location. Please include 'water depth' for the core location. I am assuming APNAP core T90-9p was collected well above the modern calcite saturation horizon? Hence, what about post depositional effects of foraminiferal stable isotopic composition over time at this site? Can these post depositional effects on foraminiferal isotopes be excluded from the isotope results presented here?

Water depth of the core is 2934 m, the average modern CCD in the North Atlantic is considerably deeper. Post depositional effects are dealt with in Feldmeijer et al. (2015), bioturbation has been ruled out given the abundance counts, coiling direction of G. truncatulinoides and XRF records. Whilst, the core lies well above the modern CCD there was a glacial shift in the preservation potential in the North Atlantic. A visual inspection, plus the shell weight signal would indicate that dissolution is minimal.

Page 141, line 12. 'following ultrasonic cleaning in ethanol' – Ethanol? We typically use methanol for cleaning foram tests prior to analysis. I suppose each laboratory has a preference for a cleaning media during sonication just as long as there is no isotopic effect on the foraminiferal d18O and d13C during the cleaning process.

There was no active decision to use ethanol over methanol, we pick foraminifera with ethanol as it dries under microscope lights faster than water and therefore it is the 'closest thing to hand'. It is unlikely that using ethanol would lead to an alteration of the isotopic signature.

Page 148, line 6-26. What about the effects/influences of the 'carbonate ion effect, temperature and dissolution' of foraminiferal d18O and d13C?

The effect of temperature, dissolution and carbonate ion could influence our signal. Like d18Osw we can assume that within sample the SST and [CO32-] should remain the same (albeit with depth related changes) and are different between samples. Therefore We do discuss the carbonate ion concentration in the carbon section of the discussion.

Page 148, line 25-26. '..is a progressive enrichment in 13C for increasing size.' Could this observation be due to changing sea water temperature of carbonate ion concentration during TIII?

It could be both, Bemis et al., 2000 suggested that the d13 of DIC of the surface ocean during the glacial would have to increase by 0.3 to 0.4 per mil to account for changes in sea surface temperature and alkalinity. A similar figure was estimated by Broecker and Henderson (1998), at 0.35 per mil, although they considered that it should be as a response to an enhanced biological pump drawing down CO2. A conservative estimate, given the poorly constrained alkalinity inventory, of 60 umol kg-1 change in [CO32-] at the LGM would have decreased the d13C of G. bulloides by 0.72 per mil. Given that the pCO2 of MIS8 never reaches the lower boundary of 180 ppm it is likely that this value is lower for the period of study. If we use shell weight from this core section as a rough predictor then a change of only 25 umol kg-1 in [CO32-] would have occurred (but this is full of caveats). Page 159 outlines the differences between the temperature and carbonate ion effect, the problem is unravelling the dominant influence. Our data is further complicated by the fact that if we use the d18o to estimate the calcification depth then they do not fit the d13c profiles. Shackleton (1978) pointed out that trying to estimate the carbon isotope composition of the surface ocean is particularly tenuous given the gradient in carbon isotope values is steepest at the surface when couple with the limitations and uncertainties regarding the precise depth of calcification.

Page 154, line 1-25. 'Seasonality' – Are there any sediment trap foraminiferal studies in this region on foraminiferal flux, size, mass, isotopes (d18O and d13C). I suppose a comparison of what might be seen in sediment trap data may provide further insights into the 'mixed' isotope values that are seen in the figures?

We agree and are looking into such an effort, however in this instance the use of glacial-interglacial transition between MIS7 and MIS8 complicates matters. Numerous papers have commented on the fact that Heinrich events, glacial and interglacial periods should be considered separately in respect to overall conditions. Therefore we haven't gone into detail with sediment trap studies in the region. With respect to 'mixed' isotope values, we believe that if one is referring to the large spread in small specimens which could represent a shallower depth habitat, with a larger range in temperature (see Figure 11), this 'mixed' signal could just relate to normal conditions.

Page 157, line 16-19. The sentence 'Given the seasonal flux: : :.large scale transport.' It would be interesting to see if there any data (e.g. foram isotopes, flux weight info, size fractions) for the NABE48 sediment. The spread of this seasonal information could be averaged, computed to see if it fits the observations seen in the results presented here?

We agree, and such a study with modern coretop samples has been compiled as the change between glacial and interglacial may complicate these matters, however NABE 48 does not have size fraction or isotope data.

<u>Detailed comments:</u>

The following outlines our comments that involve small changes to the manuscript:

Consider changing the title from "Late Pleistocene Glacial-Interglacial related shell size isotope variability in planktonic foraminifera as a function of local hydrology" to "Late Pleistocene Glacial-Interglacial shell size isotope variability in planktonic foraminifera"

'Related' removed from title

Page 136, line 4; Consider changing 'foraminifer shells hamper' to 'foraminifer shells that hamper'

Changed

Page 136, line 12; What do the authors mean by 'dynamic size range'?

Altered to provide clarity

Page 136, line 13; Change 'G. inflata' to 'Globorotalia inflata' as this is the first time it is mentioned. Likewise, change 'G. truncatulinoides' (line 14) and G. bulloides (line 19).

Changed

Page 137, line 17. Added to this is the complication is the shell-size dependency of isotopic offsets from dissolved carbonates (e.g. Kahn, 1979, Curry & Mathews 1981, Kahn & Williams 1981, Oppo & Fairbanks 1989, Oppo et al., 1990, Elderfield et al., 2002, Hillaire-Marcel et al., 2004.)

Changed

Page 138, line 28. 'Subsequent investigations: : :..single depth in core or core top,: : :' Studies like King and Howard 2004, 2005 examined the offsets in 'planktonic foraminiferal isotope values' and then looked at the isotopic values in sediment trap and sediment core tops etc.

Our point here is to highlight that very few studies have tested the size isotope relationship over a glacial or interglacial period.

Page 139, line 4. Consider changing 'We here test' to 'Here we test..'

Changed

Page 139, line 5. Expand 'TIII' to 'Termination III' as this is the first time it is mentioned.

Expanded

It would also be an idea to let readers know the 'sedimentation rate' at this site? Is this site a low, moderate, high sedimentation rate site where past seasonality climate signals can be resolved?

We can make a point of adding this to the text, although readers can easily calculate this given that the samples were taken evenly spaced at 4cm intervals.

Page 140, line 6. Change '(Termination III)' to '(TIII)'

Changed

Page 140, line 16. '2.1 Calculation of average size and weight'. This following section does not provide any information on 'weight' calculations. The text provides information on 'foraminiferal abundances (e.g. numbers per gram)'.

Shell weight has been removed

Page 140, line 20. 'into small aliquots approximately' – Did the authors 'split into small aliquots where 200 forams were collected/picked' or do they mean '_200 particles collected – including forams (all species), particles etc'?

200 particles, given that most abundance counts are performed on two size fractions: 125-250 μm and >250 μm whereas here we count from four size fractions we felt that this was sufficient to provide an estimate of the abundance.

Page 140, line 22-23. 'numbers per gram' – the numbers per gram was calculated per Peeters et al. 1999. Did the authors consider calculating the shell normalised weight (mass) for each of the foram species during this step to obtain an average weight?

The shell normalized weight for each foram species has been determined but we decided not to publish it in this instance as it does not add to the manuscript.

Page 140, line 20-24. With the dried residual – did the authors consider further cleaning of the 200 foraminiferal species to remove any nanno fossil or carbonate particles contained within the foram tests prior to other analysis? E.g. for the stable isotopic measurements – the authors sonicated in ethanol to remove any foreign calcite/carbonate not from the foram tests for single foram isotope analysis.

Specimens were sonicated in ethanol. We did not do any further pre-treatment as we have shown that this has little impact on a number of proxies, see Feldmeijer, Metcalfe, Scussolini, Arthur, 2013. G^3

Page 141, line 2. 'Bulk measurements routinely consist of between 8-40 specimens'. Were the bulk measures ultrasonically cleaned in methanol/ethanol?

Here we are not referring to our own work but to the general isotope methodology applied to palaeoceanography.

Page 144, line 8. 'Faunal abundance counts and size' – the methodology section has the subtitle 'Calculation of average size and weight'. In this section I assumed 'weight' was actually faunal abundance. Please clarify this in the text.

Weight has been removed, faunal abundance was added

Page 144, line 9. I am assuming the percentage (%) values after each species is the abundance (in %)? From looking at the figures, there are large changes in the abundances for G. bulloides and G. inflata. I suppose these large difference or at least the time periods when these changes occur should be mentioned. Consider changing these first sentences to: "Over the time period of interest G. truncatulinoides abundance is generally <10% (Fig. 3.). Faunal abundance for G. inflata ranges between 10 to 40% with higher abundance corresponding with warmer interval MIS73 and the

lower abundances preceding cold interval MIS8. The abundance for G. bulloides ranges between _10 to 35%.....'.

Changed

Page 144, line 14. 'The calculated average size' – I am assuming 'the average size is a SFD'?

It is the average size based upon a SFD

Page 144, line 20. I am assuming the 'Foraminiferal stable isotope values (d18O and d13C)' are for single test measurements. Consider changing from 'The oxygen isotope: : :' to 'Single foraminiferal test oxygen isotope: : :.'.

Changed

Page 150, line 1-6. It would have been interesting to know the shell normalised mass (weight) of forams between the different size fractions.

Weight, whilst measured will be dealt with elsewhere as it does not link to the current understanding in this paper.

Page 154, line 7. Consider changing 'Given the overlap of the larger than >250um: : :' to 'Given the overlap of the >250um: : :'

Changed

Page 160, line 16. Consider changing 'This depletion' to 'The depletion for globorotalia species..'

Changed

Page 161, line 2. 'how this size-isotope relationship varies: : :..' Consider including 'shell mass' as well?

Unchanged

Page 174, Table 2. Consider changing caption to include information of size fractions. Eg. 'Smallest (212 – 250um) and largest (300-355um) size fraction : : :..

Changed

Page 176. Table 4. There is a typo in table 4. I think 'G. inflata' should be G. bulloides?

Changed

Page 178. Figure 1. Consider adding some information on the colour coding for relative temperatures? Eg. Is blue – cold, Orange – intermediate temp, Red – warm? Or at provide information on the temperature range for the colour codes.

Changed

Page 180. Figure 3. Consider having (A) – G. bulloides single d18O values in a separate figure. There is lots of information in Figure 3 as it is. Also, the title of the figure caption should also be changed. Consider ‘ Figure 3. Relative abundance and average size of G. bulloides (blue), G. inflata (red) and G. truncatulinoides (green): : :: : :.etc.

Changed caption however we felt it is better to keep (A) in the figure as it gives the position of isotope changes that can be used to compare the abundance and insolation patterns.

Anonymous Referee 2

We thank you for the careful consideration of our manuscript. Please find outlined below our response to your reviewer comments and corrections of the manuscript, " Late Pleistocene Glacial-Interglacial related shell size isotope variability in planktonic foraminifera as a function of local hydrology.", submitted to Biogeosciences.

Specific comments on the text and figures.

First a comment on terminology. The authors consistently use the terms ‘enriched’ and ‘depleted’ to describe both isotopic ratios and the amount of each isotope. This is at times very confusing. Can I please request that when referring to enrichment or depletion of a specific isotope that it is noted which one is being discussed. Further, isotope ratios themselves are not strictly speaking enriched/depleted they are, e.g., higher/lower. A little thing but separating the terms out this manner would help to simply matters considerably.

Isotope ratios are indeed strictly speaking higher or lower (as they are ratios), but when referring to a change in the relative abundance between one isotope and another isotope of a given element then the terms enriched and depleted can be used. Of course we will endeavor in the correction to mention which specific isotope it is that we are referring to.

P136 L13 - do you mean that size-isotope trends within each species are not constant through time and thus, comparison of isotopic data from same sized-individuals in different species are also not constant through time? Can you please be more explicit about which of these options you're referring to or if both.

Our results show that the offset between different size fractions is not constant, whether this means that using the same size fraction for all species makes the species not comparable is dependent on your use for the information. Most researchers pick different species with the intent to get a different signal (i.e. thermocline, deep water etc.), so being more explicit would serve no purpose.

P136 L20 – implying that these taxa calcify in a similar water depth throughout their life cycle – worth being explicit here as for the globorotalids?

Unfortunately this is not as simple, and thus the reason for vague or lack of explicit definition of whether different sized individuals calcified in different or similar water depths. Calcification during the winter mixing/start of the spring bloom gives the same isotopic equilibrium value for the upper 200 m (the defined water depth of this species) which means that distinguishing the water depth for this species is particularly difficult (see fig 11), therefore we felt it was prudent to leave it at similar isotope values.

P138 L13 – are planktic foraminifera really limited in their ability to track favorable conditions? If plankton can be anywhere (see Norris, 2000) then they can maintain populations wherever suitable conditions pop up.

The sentence does mention that when favourable conditions a population can be maintained, however the recent work of van Sebille et al. [2015; Nature Communications] highlights just how fast oceanic dispersal occurs. As an individual, a foraminifer does not have the ability to actively seek favorable conditions (it does not have a flagellum or biological mechanism in which active swimming can occur). Both Weyl's [1978; Science] oceanic carousel and Cifelli and Smith's (1970) statement that "Owing to the environments mobility, planktonic organisms are constant involuntary travelers that during their lifetimes, may find themselves in places they do not care to be" is what we are referring to here.

P140 L17-20– specify planktonic. Also a bit more detail needed here. Specify if dry residue weighed within each narrow sieve size fraction or total dry bulk weight? Why 200 particles? Abundance counts usually on >300 specimens to obtain representative numbers. Also please note if sample splitter used to obtain aliquots or if they are representative splits.

Each size fraction was split into an aliquot of roughly 200 particles and counted, normal abundance counts of 300 particles are performed on the 150-250um and >250um or just the >250um size fraction(s) which can underestimate small-larger and/or rare species. We have changed the text to highlight this.

P145 L12 onwards – mention in brackets with table that samples for which null hypothesis is rejected highlighted in grey

We agree that it would be better to indicate which samples had the null hypothesis rejected, however for G. inflata this is 20 out of 26 samples and G. truncatulinoides has 25 out of 26, which would make it impractical. Therefore we feel that is better to leave it as it is.

P145 L2 – also mention that these offsets are not constant through time and refer to insets here?

Whilst this does show that the offsets are not constant through time, it would be better in our opinion to wait to the section in which we discuss the t-test results to mention this.

P145 L19 – Is this not also implied by the largest offset from the 1:1 line in terms of the gradient compared to other taxa?

We agree it could, but the 1:1 only uses the smallest and largest size fractions, which could be called into question (by selecting only the "end-members"). Therefore, we felt that it is better to use all the available data.

P145 L23 – a little bit of text streamlining in this section, e.g., ditch "thus for this species" and "whereas all size fractions show a statistical difference and thus"

It is our opinion that re-iterating what we mean by the null hypothesis saves the reader having to search for it in the methods section, and therefore it is better to keep this section of text.

P151 L22 – not necessarily the zone of optimal conditions for bulloides may be much broader than in the modern ocean if bulloides prefers cooler and more eutrophic water masses. Feels like a lot of discussion in size change across the G-IG given no size change is apparent in the dataset to the naked eye at least. Does the Schmidt data show any significant changes across G-IG cycles in this taxa at a similar latitude? Removing unnecessary words and just giving the key information relevant to the story ultimately could significantly shorten this section that no decrease in size, implying optimal conditions at site and influenced but increased productivity in this region.

This discussion is pertinent to our results, we state on page 150 that "in the modern ocean *G. bulloides* has its largest size at 50°N, if one is to consider that a compression or elimination of certain transitional water masses occurs during glacial periods then this maximum size should be centered at or to the south of the location of the studied core, *i.e.* **a size decrease should be observable at our core location**.". Our results do not tie into what is known in the literature and therefore we felt that this mismatch should be discussed.

P159 – 160 – Lots of discussion of controls on d13C but not well linked back to original data. For instance no conclusion is reached on the main mechanisms controlling the datasets presented here and only for gametogenic calcite is it mentioned whether or not the hypothesis is consistent with the new data,

One of the major reasons we have not been explicit in the main mechanism is the lack of consistency, shell-size isotope relationships are not consistent through time which means that finding a mechanism that explains all of our data is difficult.

P160 L12 – it might be worth mentioning earlier in the text that the deeper dwellers particularly G. truncatulinoides may actually have a longer life span than 2-4 weeks like bulloides and ruber perhaps more like a year, which may help to explain calcification in different seasons.

It is true that it is considered to have a life cycle that extends to a year, but no paper has concretely proven this. Many papers, using sediment traps have seen a single flux event and considered that this is proof of a year long life cycle, however in order for a single foraminifera to calcify in different seasons it would have to somehow negate both sinking and the movement of oceanic currents staying static at a given spot

in the ocean. Therefore, whilst it could explain the data, we have refrained from pursing that line of reasoning.

P160 L26 – on what basis is 300-355 um best? Can you add a comment about why? Most consistent offsets?

We state that: "Our results would suggest that 300-355 µm would serve this purpose given the offsets between the species, however we would caution against using a 'one-size fits all' approach given the seasonal structure of the water column and seasonal succession of species at this core location".

P160 L23 "and that previously published" Also rephrase next sentence consider deleting "between studies" so reads "lack of a resolution in the existing literature as to the recommended size fraction : : :." –

Changed.

doesn't birch make a decision about the best size fraction based on correlation of foram d13C to d13C of DIC? 250-300 um?

With respect to Birch et al., they do make a decision, but other authors suggest other size fractions. So therefore the issue is not resolved. What we're attempting to say is that different authors from different ocean basins give different size fractions, but our results show that this can easily be misinterpreted (through no fault of the previous authors).

P160 – the authors use differences between size fractions – I wonder whether it would be better to discuss size-isotope trends to avoid confusion with differences between the same size but different species? It might be worth checking out the new paper in Paleoceanography by Ezard et al. 2015, which compiled and modeled the size-isotopic relationships for all modern taxa and includes a large discussion of potential biases on isotope-size trends.

We use differences between size fractions as this wording does not imply any link between the size fractions. Trend would suggest that there is a progression in isotopic values or connection between different sizes which we have not tested. This wordage ('trend') suggests that the different sizes are linked i.e. by age. Although we do admit it that 'trend' can also be used to show a general tendency.

Specifically you should consider the potential role of changes in preservation (particularly dissolution) on your datasets given the large associated changes in carbonate chemistry.

Unpublished work, using single specimen isotopes for G. bulloides and G. inflata along a depth transect close to the core location, but deeper then it between 2700 and 4500 m, put the d18O change (using the average) between shallow and deep core tops at 0.34 and -0.14 ‰. The d13C change (using the average) between shallow and deep is larger at 1.16 and -0.04 ‰. As these results are deeper we would suggest that the dissolution effect is minimal for the core location.

These authors also nicely highlight that in sediment cores, body size doesn't necessarily equate to foram 'age' something alluded to here and that it may instead relate to maximum adult size a function of growing conditions so consider tying this into the discussion.

In actuality we discuss this on page 149 lines 18-24, albeit rather shortly: "Consider that the transition from juvenile-neanic to adult stages occurs between 100 and 200 µm (Brummer et al., 1987), then all specimens above 200 µm are adult. The shape of the size frequency distribution of the pre-adult

population is exponential whereas in comparison the adult population has a distinct Gaussian shape (Brummer et al. 1986, 1987; Peeters et al., 1999), which suggests that adult specimens that are larger than the mean should be considered giants and on the contrary smaller specimens as dwarfs (Berger, 1971)".

Detailed comments:

Title – ditch the "related"

'Related' removed

P136-L5 – delete "the" so text reads "from equilibrium"

Changed

P136-L12 – please clarify what you mean by "dynamic" – this could refer to using difference sieve size fractions in different samples for example. I think you mean, ": : : utilizing measurements from multiple narrow sieve size fractions spanning a large range of total body sizes"

Replaced with your wording

P136 L15 – define small in um

212-250 um added to text

P136 L23 - ": : :may be used to reconstruct past..."

Changed

P137 L3 – "physical proxies determine"

Changed

P137 L5 – specify here d13C and d18O

Changed

P137 L10 - This sentence doesn't make too much sense at the moment needs reorganizing, e.g., "Vital effects are isotopic offsets from equilibrium values reflecting.."

Changed

P137 L13 – specify reduce effects on palaeonvironmental reconstructions?

Added

P138 L15 – need to add "that growth occurs"

Changed

P138 L17 – 25 – very long sentences consider breaking up for increased clarity.

Changed

P138 L26 – delete "sized"

Deleted

P139 L4 –The first sentence is a little unclear so some suggestions below to increase clarity. "Here we test", specify planktonic foraminiferal tests

Changed

and ": : :to large-scale environmental perturbation across a glacial-interglacial transition (TIII). We utilize data from Feld... and present new data that expands upon shell-size isotope relationships between species and through time"

Changed

P139 L8 – a little expansion on the methods please – e.g., Individual foraminifera were picked from narrow sieve size fractions from JGOFS: : :. Please specify your sieve size fractions.

Changed

P139 L12 – specify dextrally and sinistrally coiled?

Changed

P139 L15 – perhaps "multiple specimens" would be better?

Changed

P139 L15 – Specify multi-specimen analyses were repeated and delete "seen" as unnecessary. Add reference for this statement as has been demonstrated elsewhere and very specific in L18.

Changed

P139-L19 – Specify "In other words by combining multiple specimens for each analysis, : : :.." for clarity.

Changed

P140 L 1 – typo "recrystallization"

Changed

P140 L5-14 – necessary? Seems nicer to finish mentioning that single specimens give us a discrete snapshot of ocean conditions at time of calcification? Can you include some of this info at the beginning of the section when you say why MIS7-8?

We have altered the structure so that the MIS7 follows our introduction of T-III and then finish as you suggested when we mention that single specimens give a discrete snapshot of the ocean.

P140 L24 – "the absolute number of individuals by the split: : :" and "size frequency distribution (SFD) was approximated"

Changed

P141 L1 – careful here bulk measurements could be confused with bulk sediment analyses (i.e., total carbonate) so best to be specific that typically 8-40 : : :. , use same number of decimal places on weights here.

Changed

P141 L7 – ": : :on the analytical methodology: : :"

Changed

P141 L10 – replace "about" with "up to"

Changed

P141 L15 – A little more specificity here please particularly for test 2 – so test 1 = to test for any statistical differences between size fractions with each species in each sample and test 2 = to test whether any differences between body size and isotope values are constant within each species downcore? And/or to assess whether the differencebetween same size fractions in each species varied downcore? P141 L26 – I'd argue that this depends on what you're trying to determine!

Changed

P142 L30 – delete "are different"

Changed

P144 L9 – specify that figures in brackets are relative abundances ": : :have higher abundances during MIS7e and lower abundances: : :".

Changed

P144 L18 – "during which time the abundance of the species is low"

Changed

P145 L3 – specify d18O values

Unsure of what this comment refers to, as pg 145, L3 is an introductory sentence to figure 6

P146 – "with larger insolation differences : : :"

Changed

P146 – Not really necessary to give all this detail about d13C values is it? Sometimes a little too wordy which reduces clarity. I'd suggest just go straight for the key points (1) D13C is typically lower in G. trunc and G. inflate small than large specimens but not clear distinction between small fractions continuously throughout record. May be larger = higher d13C. (2) bulloides more difficult to discern differences. Even better can you not integrate the descriptive observations of your graphs with the stats to cut the text and make this snappier?

Changed

P146 L23 – "deviate" typo

Changed

P147 – L10 – in reference to what are they statistically significant = new paragraph here so you need to be explicit.

Changed

P148 –L15-20 – references needed here. Also carbonate ion effect (Spero et al 1997) impacts values

References added

P148 L22 "significant variation of size with d18O values.."

Not changed

P148 L23 – should better employ Figure 10 here to mention that overall patterns are consistent with previous studies.

We'd prefer to leave it til later in the text to employ this figure.

P148 L26 "with increasing: : :"

Changed

P148 L26 – I'm not convinced that the discussion of these curves in the context of Berger, 1978 really adds much as effectively repeats findings from sentences above.

It relates our work to one of the original workers of the subject and therefore we consider it relevant to discuss it here.

P149 L7 – these physical parameters are presumably a function of depth habitat though with smaller individuals calcifying at shallower depths and thus the same as (iii)?

Not really, (i) can refer to not only depth habitat (i.e. the same as (iii)) but also to spatial variation in physical parameters. Whereas (iii) is specifically depth habitat.

P149 – need to be specific that it's isotopic disequilibrium that you're referring to

Unsure as to what you are referring to here, page 149 is discussing the isotopic composition of foraminifer.

P149 L7 – doesn't really explain why these factors might create the 'normal' trend.

We provide a short summary of Berger's (1978) ideas for what may cause a 'normal' trend, with links to papers that highlight such scenarios, but for a detailed explanation any reader should read the original paper for a more refined explanation.

P150 – the change in size during the interglacial is only really visible in truncatulinoides so be explicit in this opening sentence. I'd actually restructure this sentence to be clear that you're talking only about bulloides right up front at the beginning otherwise this is potentially confusing. Don't need the bit about concurrent in size or magnitude as already said see a minor change in abundance/size? So key point is that there is no isotopic variation between size fractions.

Unchanged, it is clear that we are referring to G. bulloides in this sentence

P151 L12 – be explicit that your talking about your site

Changed

P151 L15 -replace "occur' with "extend"?

Changed

P151 L19 - delete "occurring" as unnecessary

Changed

P151 L23 – sentence overly long

Unchanged

P151 L3 typos "development" and "with a .."

Changed

P152 L12 - delete "for example occurring" as unnecessary

Changed

P152 L11 – be specific "species abundance counts in plankton tows" also isotopic analysis of foraminifera tests not sedimentary material – this implies bulk carbonate currently which is not what you mean

Changed

P152 L21 – be explicit that differences in the depth of the DCM relates to seasonality and water column structure

Changed

P152 L24 – Ok so seasonality controls the DCM by impacting stratification but did the Ottens paper say anything about whether the deeper habitat in april also corresponded to an increase in the deep of the DCM? If so, please say so.

Unfortunately this is not outlined in her original text.

P152 - ditch associated with subpolar to tropical water masses in above sentence because same info given in following sentence.

Changed

P153 L3 "in the South" typo

Changed

P153 L13 – too many "its" be specific and give species name in sentence somewhere

Changed

P154 L7 – again please be specific. "Given the isotopic overlap: : :" redundant to say larger than and use > - pick one

Changed

P158 L6 – Suggest switching/adding reference to Birch et al. (2013) or Friedrich et al (2012) instead here as these papers look at all of the same species in your study in contrast to Franco-Fragaus et al. 2011 which just looks at truncatulinoides and ruber. Also more explicitly link back to previous sentence, e.g., A positive size-d13C relationship have been explained by...."

Changed

P158 L8 - Need to be more specific because strictly speaking 13C of plankton didn't invoke photosymbiosis previous studies invoked photosymbionts etc. to explain the trend so please rephrase.

Changed

P158 L11 – sentence overly long. Split into two for clarity.

Changed

P158 L120-123 – do you mean that forams calcifying in surface waters have a higher d13C values than those calcifying at depth? a shallower depth habitat relative to what? specify "foraminiferal d13C" here

Changed – the depth habitat inferred from using the 13C and comparing it to the DIC d13C profile is different from the depth habitat inferred from 18O

P158 L123 – This sentence is another example of where it is important to be more specific as to exactly what you're referring to – enrichment of 12C in deeper dwellers? I think you need to clearly distinguish between size-isotope trends and inter-specific offsets between similar sized fractions so that the two (and most importantly the mechanisms are not confused)– separate paragraphs? Perhaps talk about the absolute offsets between taxa, i.e., some species live deeper than others with lower d13C values and then lead onto the size-specific isotope relationships?

Our results however are not in line with the d13C profile, figure 9D highlights the complexity of the d13C. The example given that some species live deeper than others with lower d13C values is incorrect as G. bulloides (a shallow dweller) clearly has the lowest d13C values (Fig. 9D)

P159 L1 – "increases"

Changed

P159 L15 – now using test rather than shell – be consistent

Changed

P159 L18 – "raising their d13C values"

Changed

P159 29-P160L6 – sentences provide essentially the same info consider combining.

Changed

P160 L3 – clarity "whilst we find no systematic differences between the d18O of G. bulloides: : :.."

Changed

Figure 1 – Nice clear map. Just need to specify in caption that main ocean currents indicated by arrows and that these are surface? currents. Without a key for temperature need to write that red is warmest and blue coolest temperatures.

Changed

Figure 2 – specify top, middle and bottom ROWS in caption

Changed

Figure 3 – specify in caption that "Size in planktonic foraminifera across MIS7-8". In caption use lowercase a-d but in figure capitalized – style? No need to mention oxygen isotopes explicitly on y-axis of a if also use d18O. Is this the relative abundance of each taxa from whole sample or relative to each other. I assume the former but please specify in caption. Please note what vertical dashed lines and HI5 etc.. are. To avoid confusion with how average size was calculated can you please explicitly mention average size within the text of section 2.1 – is average size = sfd?

Changed

Figure 4 – Y-axis "Single specimen" and add space between number and units on figure for sizes. Any reason why axis given to 2 dp? Might be neater to stick to 0 dp? Are Heinrich events HI4 etc. in which case please note in caption explicitly for non-specialist..

Changed

Figure 5 - Mean insolation not marked on figure – remove note in caption?

Changed

Figure 6 – Specify in caption header that isotopic differences are for each species. ": : :in d18O (top panel) and d13C (bottom panel). Careful phrasing - Equations of linear regressions not shown by coloured lines – regressions are shown and equations in table 4.

Changed

Figure 9 – Just use d13C not necessary to include description in full here. Perhapsadd the coloured species outlines behind a-c rather than grey for increased continuity.

Changed

Figure 10 - Just use d13C/d18O not necessary to include description on figure axes.
"..an average size-isotope curve was : : :"

Changed

Late Pleistocene Glacial-Interglacial ~~related~~ shell size isotope variability in planktonic foraminifera as a function of local ~~hydrology~~ hydrography

B. Metcalfe[1], W. Feldmeijer[1], M. de Vringer-Picon[1], G.-J.A. Brummer[1,2], F.J.C. Peeters[1] and G. M. Ganssen[1]

[1] {Earth and Climate Cluster, Faculty of Earth and Life Sciences, VU University Amsterdam, De Boelelaan 1085, 1081 HV, The Netherlands}

[2] {Department of Geology and Chemical Oceanography, NIOZ Royal Netherlands Institute for Sea Research, Landsdiep 4, 1797 SZ t' Horntje, Texel, The Netherlands}

Correspondence to: B. Metcalfe (b.metcalfe@vu.nl)

Abstract

So called 'vital effects', a collective noun for a suite of physiological and metabolic induced variability, in oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope ratios of planktonic foraminifer that shells hamper precise quantitative reconstruction of past ocean parameters. Correction for potential isotopic offsets from ~~the~~ equilibrium or the expected value is paramount, as too is the ability to define a comparable life-stage for each species that allows for direct comparison. Past research has focused upon finding a specific size range for individual species in lieu of other identifiable features, that allow ocean parameters from a particular constant (*i.e.* a specific depth or season) to be reconstructed. Single shell isotope analysis of fossil shells from a mid-latitude North Atlantic Ocean piston-core covering Termination III (200 kyr to 250 kyr) highlight the advantage of using a dynamic size range ~~in studies of palaeoclimate~~, i.e. utilizing measurements from multiple narrow sieve size fractions spanning a large range of total body sizes, in studies of palaeoclimate. Using this methodology, we show that isotopic offsets between specimens in successive size fractions of *G. loborotalia inflata* and *G. loborotalia truncatulinoides* are not constant over time, contrary to previous findings. For $\delta^{18}O$ in smaller sized globorotalids (212-

250 µm) it is suggested that the offset from other size fractions may reflect a shallower habitat in an early ontogenetic stage. A reduction in the difference between small and large specimens of *G. inflata* between insolation minima and maxima is interpreted to relate to a prolonged period of reduced water column stratification. For the shallow dwelling species *Globigerina. bulloides* no size isotope difference between size fractions is observed, and the variability in the oxygen isotopic values are shown to correlate well with the seasonal insolation patterns. As such, patterns in oxygen isotope variability of fossil populations may be used successfully forto reconstruction of past seasonality changes.

1 Introduction

1.1 Size of planktonic foraminifera

A series of biogeochemical and physical proxies exist to determine the mechanisms of short-term and long-term climate change from archives such as deep sea sediments. Notably amongst these is the oxygen and carbon isotopeic composition of planktonic foraminifera because of the continuous export flux of shells to the ocean floor and their near-global occurrence. The inherent weakness within these proxy archives is that these are neither the original nor the unaltered reflection of the primary signal. Therefore, quantifying the limitations and potential artefacts are imperative for drawing robust conclusions. Deviation from equilibrium values, Vital effects are an isotopic offsets from equilibrium values reflecting caused by biological fractionation commonly referred to as the 'vital effect' likely reflects, i.e., changes in metabolic processes and growth rates during shell formation. The isotopic composition has been shown to be a function of the ambient carbonate ion concentration ($[CO_3^{2-}]$, e.g. Spero et al., 1997), temperature (e.g. Bemis et al., 2000) and post-mortems effects (e.g. Lohmann, 1995; Rosenthal et al., 2000). Previous studies have shown that, in order to minimise or reduce the potential influence of metabolic effects and therefore spurious palaeoenvironmental reconstructions, specimens should be constrained to a similar size and shape (Berger et al., 1978; Billups and Spero, 1995; Bouvier-Soumagnac and Duplessy, 1985; Curry and Matthews, 1981; Elderfield et al., 2002; Friedrich et al., 2012; Kroon and Darling, 1995; Ravelo and Fairbanks,

Formatted: Subscript

Formatted: Superscript

1992; Ravelo and Fairbanks, 1995; Shackleton and Vincent, 1978; Weiner, 1975; Williams et al., 1981). Shell size dependence of isotopic offsets from dissolved carbonates (e.g. Kahn, 1979; Curry & Mathews 1981, Kahn & Williams 1981, Oppo & Fairbanks 1989, Oppo et al., 1990, Elderfield et al., 2002, Hillaire-Marcel et al., 2004) also serves to further complicate matters. However, the factors that govern/regulate the biomineralisation process in planktonic foraminifera are currently not implicitly understood with many studies making no distinction between biocalcification and inorganic precipitation. Weinkauf et al. (2013) considered that there is some implied trade-off, with respect to resource allocation between production of biomass and biomineralisation, this would fit with the implicit assumption of the optimum growth hypothesis of de Villiers (2004) which is consistent with size reflecting optimum ecological conditions (Schmidt et al., 2004). Shell size, in itself, reflects an easily measured parameter with a direct relation between both inherited (genetic) and environmental stimuli (e.g. temperature, availability of food). In practical terms, throughout its life an organism will invariably increase in size until some discrete threshold limit is reached due to either mechanical (i.e. test construction), physiological (i.e. maturation; reproduction) or physical constraints (i.e. abiotic/biotic factors) (Schmidt et al., 2004; 2006; 2008). Schmidt et al. (2006) considered that optimum conditions for planktonic organisms could either lead to rapid reproduction and therefore small body size, or fast growth rates and hence larger sizes. Hecht et al. (1976) demonstrated the latter using North Atlantic core top material, *i.e.* that species of planktonic foraminifera obtain their maximum size in waters that are considered (close to-) optimal for that species, decreasing in size away from this point. Although what is considered optimal for pelagic organisms can be complicated by the fact that optimal conditions can occur both geographically and vertically (water depth) (Telford and Kucera, 2013). Despite this, as environmental conditions change through time organisms can either adapt to new conditions (*i.e* plasticity: ecophenotypes) or 'track' their preferred habitat leading to a change in body size, the severity of which is dependent upon the location (Malmgren and Kennett, 1976). Whilst foraminifera are limited in their ability to track their preferred habitat , being free-floating members of the plankton, it is likely when transported into favourable environmental conditions that growth occurs (van Sebille et al., 2015). The effect of this plasticity of size, and potential growth rate variations, upon stable isotopes is less clear.

Emilani~~'s~~ (1954) was the first to ~~investigation~~ investigate ~~on~~ the isotopic composition of foraminifera of two different sizes (250-500 μm and 500-1000 μm~~),~~). A ~~in combination with a~~ subsequent study extending this line of enquiry (Emiliani, 1971)~~,~~ postulated that this size-isotope relationship could be influenced by a change in depth habitat after finding a difference between samples from glacials and interglacials. Certainly if depth habitats are ultimately constrained by food supply and therefore by the penetrative depth of light, then during glacials, when productivity was high, a reduced transmission of light may have occurred (Volten et al., 1998) thus foraminifera would have undergone an "upward migration" of depth habitats (Berger et al., 1978). Whilst a depth-habitat ranking based upon large ~~sized~~ specimens would not differ from the general attribution of depth to individual species, this is not the case for smaller sized groups which in general have a warmer and thus shallower signal (Kahn, 1978). Subsequent investigations have contented themselves with using a single depth in core, or core top, to determine the size-isotope relationship at a given geographic location despite these earlier postulations on the contrary.

1.2 Aims and objectives

H~~We h~~ere we test the sensitivity of planktonic foraminiferal shell size to a large-scale environmental ~~perturbances~~ perturbation across~~seen at~~ a glacial-interglacial transition, by focusing upon Termination III (TIII). The transition from Marine Isotope Stage (MIS) 8 to 7 at around 232 kyr b.p. (T III), studied here is generally characterized by a reduced amplitude in oxygen isotope values compared with other glacial terminations, as the preceding cold stage (MIS 8) is muted, with only a reported shift of ~1.1 ‰ in benthic foraminiferal $\delta^{18}O$. MIS 7 is composed of three warm (MIS 7 substages MIS 7a, MIS 7c and MIS 7e) and two cold phases (MIS 7 substages MIS 7b and MIS 7d) (Roucoux et al., 2006) with the termination characterised by relatively high eccentricity and hence by a heightened difference in the maximum seasonal insolation as defined by the difference between the maximum and minimum insolation during the year (Berger et al., 2006). We utilize data from ~~based upon prior research~~ ~~(~~Feldmeijer et al.~~,~~ ~~(submitted~~2015)~~,~~ and present new data that expands ~~further elucidate~~ upon ~~the~~ shell-~~-~~size isotope relationships between species and through time (Birch et al., 2013; Friedrich et al., 2012) ~~via~~ through the use of single shell stable isotope analysis (Ganssen et al., 2011 and references

therein). Individual foraminifera were picked from narrow size size fractions (212-250; 250-300; 300-355 and 355-400 µm) ~~Specimens are~~ from a section of JGOFS APNAP core T90-9p (45°17.5'N 27°41.3'W; core length = 1028 cm, Figure 1), recovered from the eastern flank of the Mid-Atlantic Ridge (water depth 2934 m), in the North Atlantic Ocean (Lototskaya and Ganssen, 1999; Lototskaya et al., 1998; Feldmeijer et al., ~~submitted~~2015). Sedimentation rate in the core interval selected is between 1.7 and 3.1 cm per kyr, dissolution is considered to be minimal (Feldmeijer et al., 2015). Data on small (212-250 µm) and large (355-400 µm) specimens of both dextrally and sinistrally coiled *Globorotalia truncatulinoides* have been reported elsewhere (Feldmeijer et al., ~~submitted~~2015). Planktonic foraminifera collected from sediments form the basis of palaeoceanographic reconstructions, usually through $\delta^{18}O$ and $\delta^{13}C$ on ~~a group of~~multiple specimens. If ~~such an~~multi-specimen ~~analysis~~ analyses were repeated several times, then the variability ~~seen~~ would be expected to be smaller compared with the variability one would obtain if specimens were measured individually. This variability is expected to decrease with the reciprocal value of the square root of the number of specimens within a single analysis. In other words by combining multiple specimens for each analysis~~, using this method,~~ the variability is reduced for the sake of eliminating noise that may otherwise unduly influence time series analysis. The isotopic information within single specimens is however lost. Given the dynamic nature of the ocean, individuals collected together in a single sedimentary sample may have calcified in different seasons (or years), at different depths, or even in different water masses. Intra and inter specific variability in isotopes have been used to explain either upper ocean processes such as (1) calcification depth changes (Emiliani, 1954); (2) variations in metabolism through ontogeny (Killingley et al., 1981; Vergnaud-Grazzini, 1976; Rink et al., 1998) and/or bottom water processes: (3) bioturbation and benthic organism interaction (Bard, 2001; Bard et al., 1987; Löwemark et al., 2008; Wit et al., 2013) and (4) dissolution/~~recrystalisation~~ recrystallization (Bonneau et al., 1980). Given that the life cycle of upper ocean dwelling species is probably completed within a few weeks (Bé et al., 1977; Berger, 1969a), and that a single chamber is formed over a few hours single shell analysis allows us to glimpse at short-term conditions in the ocean (Killingley et al., 1981). ~~The transition from Marine Isotope Stage (MIS) 8 to 7 at around 232 kyr b.p. (Termination III), studied here is generally characterized by a reduced amplitude in oxygen isotope values compared with other glacial terminations, as the~~

~~preceding cold stage (MIS 8) is muted, with only a reported shift of ~1.1 ‰ in benthic foraminiferal $\delta^{18}O$. MIS 7 is composed of three warm (MIS 7 substages MIS 7a, MIS 7c and MIS 7e) and two cold phases (MIS 7 substages MIS 7b and MIS 7d) (Roucoux et al., 2006) with the termination characterised by relatively high eccentricity and hence by a heightened difference in the maximum seasonal insolation as defined by the difference between the maximum and minimum insolation during the year (Berger et al., 2006).~~

2 Methodology

2.1 Calculation of average size and faunal abundance~~and weight~~

Abundance counts of planktonic foraminifera were performed at four cm resolution on sediment that was first weighed so that the proportion of~~to calculate~~ <63 µm could be computed, then ~~wet sieved~~washed over a sieve with a 63 µm mesh~~,~~ and dried overnight in an oven at 50°C~~,~~. Once dry it was passed over a nest of sieves ~~of~~ with mesh sizes of: 125 µm~~,~~; 212 µm~~,~~; 250 µm~~,~~; 300 µm~~,~~; 355 µm and 400 µm ~~mesh size and~~. ~~the resultant~~ Each size fraction was weighed ~~dry residues were weighed~~. ~~The dried residues were~~ and split using an OTTO microsplitter ~~–~~into small aliquots approximately containing two hundred particles and the number of *Globigerina bulloides*, *Globorotalia inflata* and *Globorotalia truncatulinoides* (Figure 2) ~~were~~ counted for each size fraction. Counts were subsequently converted into numbers per gram by multiplying the absolute number of individuals by the split and the size frequency distribution (SFD) was approximated, following the methodology of Peeters et al. (1999).

2.2 Stable isotope geochemistry ($\delta^{18}O$)

~~Bulk m~~Measurements using multiple specimens routinely consist of between 8–40 ~~specimens~~ individuals which depending on the species represent ~0.30-1.50 mg of calcium carbonate per sample (Waelbroeck et al., 2005a). Sample preparation in combination with improved mass spectrometry techniques now allows for measurement of single shells down to a few micrograms (Ganssen et al., 2011), or even analysis to the level of individual chambers (Kozdon et al., 2009; Vetter et al., 2013) depending on the analytical methodology followed. This constitutes an improvement by a factor of 10-1000 compared to the early pioneering studies of

Emiliani (1955) and Shackleton (1965). Specimens of *G. bulloides*, *G. inflata* and *G. truncatulinoides* were analysed singularly with ~~about~~ up to 20 individuals picked from each of four successive size fractions (212-250 µm; 250-300 µm; 300-355 µm and 355-400 µm) following ultrasonic cleaning in ethanol. Analysis was conducted on a Thermo Finnigan Delta^{+} mass spectrometer equipped with a ~~GASBENCH~~ GasBench II preparation device. In order to analyse individual specimens, ranging in weight between 5-50 µg, samples are placed in He-filled 3 ml exetainer vial with a set of glass beads (~2 mm). The beads act both as a heat buffer and as a preventative measure against loss upon on contact with the acid, a problem that is generally overcome when measuring in groups. Each sample is digested in concentrated phosphoric acid (H_3PO_4) at 45 °C. Isotope values are reported as $\delta^{18}O$ and $\delta^{13}C$ versus Vienna Peedee Belemnite (V-PDB) calculated using the standard delta notation (δ) and reported in per mil (‰). The reproducibility of routinely analysed laboratory calcium carbonate standards is better than 0.12 ‰ (1σ) for both $\delta^{18}O$ and $\delta^{13}C$, given the heterogeneity of carbonate standards at this critical low concentration of material analysed (Ishimura et al., 2008). This represents ~5 % of the measured range and therefore is considered negligible.

2.3 Statistical Analysis

Single specimen analysis allows for a more stringent battery of statistical tests to be carried out than "traditional", grouped, analysis. We follow methodological procedures described in Ganssen *et al.* (2011), in which the individual datasets (multiple analyses of single specimens from one size fraction) are checked for potential outliers in order to both produce a robust estimate of the range and the mean. Lower and upper bound were calculated using the first quartile (Q_1), third quartile (Q_3) and the interquartile range (IQR). This does however remove the extremes in $\delta^{18}O_c$ – and potential minima and maxima in temperature – yet in order to compare size fractions using a student t-distribution based confidence interval the calculated mean must be robust. Whilst no dataset fits the normal distribution, distributions that approximate the normal distribution are considered to be unimodal with the measures of central tendency (mean, median and mode) equal and located at the centre of the curve. Only a few depths in core showed significant evidence to reject normality, based upon a Shapiro-Wilk test, however for convenience and for a visual comparison we assumed that they were normal when generating a t-

based confidence intervals on the mean. For all figures we present the means with the attached 95% confidence level, given our experimental design in an attempting to discern whether the size fractions and thus for simplicity their means are statistically similar or different this confidence level was chosen to not mislead the reader as they encompass a larger uncertainty.

Two t-tests were performed, the first to test for any statistical difference between all four size fractions with each species in each sample~~within sample differences~~ ~~between all four size fractions~~ and the second to test ~~assess~~ whether the differences between size fraction~~s~~ isotope values are constant within each species~~ are different~~ downcore, these were performed as follows: (1) In order to examine whether there is a significant relationship between size and stable isotopes, a one sample t-test was performed on the differences, smallest size fraction value minus the largest, between the means of the size fractions of both $\delta^{18}O$ (Table 1) and $\delta^{13}C$ (Table 3). This statistical choice is the result of speed and efficiency as it would require six paired t-tests per sample multiplied by 26 samples, increasing the likelihood of an error associated with a false positive. The null hypothesis of the performed test is that the difference in $\delta^{18}O$ and $\delta^{13}C$ between two size fractions is zero (H_0: $\mu_1 - \mu_2 = 0$), thus all means are equal (H_0: $\mu_1 = \mu_2 = \mu_3 = \mu_4$), and the resultant hypothesis is that at least one of the means is different from the others ~~are different~~ (H_1: $\mu_1 \neq \mu_2 \neq \mu_3 \neq \mu_4$). Analysis was performed at both the 90% and 95% confidence level (α values of 0.10 and 0.05; critical t-values of 2.015 and 2.571 respectively). For (2) testing whether the relationship remains constant through time over a large climatic perturbation a two tailed t-test for dependent samples was performed between size fractions for the entire core (n = 6). The H_0 is that the differences between size fractions is zero, thus all means are equal and that this is consistent down core. The critical values of the t distribution for n = 26 samples of the 90% and 95% confidence level (α values of 0.10 and 0.05) are 1.708 and 2.060 respectively. No ice volume correction prior to statistical analysis was performed as it was deemed that the difference between two size fractions within the same sample should negate this effect.

The downcore means of the smallest (212-250 μm) and largest (355-400 μm) specimens of all species were plotted against each other for both $\delta^{18}O$ and $\delta^{13}C$ respectively as per Sarkar et al. (1990) (Table 2). The resultant slope was tested against a 1:1 relationship or iso-δ line using a two-tailed t-test, the slope of such a line is considered to be unity as y would be equal to x (H_0:

slope = 1; H_1: slope ≠ 1). Deviations from the iso-δ line would indicate a change in the relative depletion or enrichment between the two size fractions at either the warm or cold temperature end for $\delta^{18}O$. To calculate the estimated standard error of the regression the vertical difference between the observed and fitted values, using a linear regression, was calculated using an ordinary least squares (OLS), which minimizes the resultant sum of the squared residuals (SSR). The magnitude of the SSR is influenced by the number of data points, a larger number of datapoints results in a larger SSR, to account for this it was divided by the degrees of freedom (n-2). The resultant expression was square rooted. The test value at α 0.05 for two tailed is 2.064 for n = 26.

Interdependence, or the degree of linear relationship, between $\delta^{18}O$ and $\delta^{13}C$ was tested for using covariance upon the outlier corrected values of oxygen and carbon for each size fraction and for all size fractions combined (Table 4 and 5) using the PAST software package (Hammer et al., 2001). Independence, where $\delta^{18}O$ and $\delta^{13}C$ vary without a connection, is implied when covariance has a value of 0, or the relationship between the two parameters is nonlinear. The degree to which values larger than 0 are independent necessitates transformation into a dimensionless quantity independent of scaling relationships. Therefore we interpret the data using the correlation coefficient, in which the covariance is divided by the product of the standard deviation of both oxygen and carbon. Such transformation gives a limit of ±1, in which values that approach ±1 represent a higher degree of linear co-dependence.

3 Results

3.1 Faunal abundance counts and Size

Over the time period of interest G. truncatulinoides abundance is generally <10% (Fig. 3.). Faunal abundance for G. inflata ranges between 10 to 40% with higher abundance corresponding with warmer intervals in MIS7~~3~~ and the lower abundances preceding the cold interval in MIS8. The abundance for G. bulloides ranges between _10 to 35%.

~~*Globorotalia truncatulinoides* (<10%) and *G. inflata* (~10-40%) have higher abundance corresponding with the warmer interval of MIS7e and lower abundance during the preceding cold interval (MIS8) (Figure 3). The abundance of *G. bulloides* (~10-35%) appears~~ appearing to

Formatted: Font: Not Italic

Formatted: Font: Not Italic

Formatted: Font: Not Italic

Formatted: Font: Not Italic

Formatted: Font: Not Italic

follow the expansion and contraction of insolation, with periods of reduced seasonality, *i.e.* milder (lower insolation) summer and winter months, showing higher relative abundances (Figure 3). Calculated average size for this interval falls between 250-300 μm for both *G. bulloides* and *G. inflata* with only minor variation (~30 μm) (Figure 3c). The size of *G. truncatulinoides* is more erratic varying between 250 μm and 355 μm, especially between 227-252 kya ~~in~~ during which time the abundance of this species is low.

3.2 Oxygen stable isotope values ($\delta^{18}O$)

Single foraminiferal shell ~~The~~ oxygen isotope values of *G. bulloides* (n =1921) and *G. truncatulinoides* (n = 1933) show the characteristic pattern consistent with a transition between a glacial, with values enriched in $\delta^{18}O$, and interglacial, with depleted $\delta^{18}O$ values. Visually there is an overlap between the oxygen isotope values of all size fractions of *G. bulloides* whereas this is only present in the larger size fractions of both *G. inflata* (n = 1855) and *G. truncatulinoides* (Figure 4 and 5). For the latter two species the smaller size fraction (212-250 μm) appears to be relatively more depleted in $\delta^{18}O$ than the larger size fractions (250-400 μm). Plotting the mean, per sample, smallest (212-250 μm) and largest (355-400 μm) size fraction $\delta^{18}O$ against each other (Figure 6), shows that the slopes of *G. bulloides*, *G. inflata* and *G. truncatulinoides* are statistically significant from 0 (t-test values for correlation coefficient: 6.5776, 3.5421 and 6.8653 respectively with a two tailed test value of 2.064 at α 0.05, H_0: p = 0). However there is insufficient evidence to suggest that the value of the slope is statistically different from a 1:1 iso-δ line (t-test values for difference: -1.305, -1.288 and -1.669 respectively). At the minimum value the offset between smallest and largest size fractions is 0.4535, 1.5919 and 1.8467, however given that the slopes are 0.8033, 0.5687 and 0.8929 this value decreases with more enriched $\delta^{18}O$ values, i.e. at colder values (Figure 6).

For *G. bulloides* only 4 out of 26 samples show sufficient evidence to reject the null hypothesis thus for this species the size fractions have predominately the same mean values, whereas all size fractions show a statistical difference and thus the difference between size fractions is not constant (Table 1). For *G. inflata* 20 out of 26 samples show sufficient evidence to reject the null hypothesis thus for this species the size fractions have predominately different mean values, whereas apart from the difference between 250-300 μm and 300-355 μm all size

fractions show a statistical difference and thus the difference between size fractions through time is not constant (Table 1). Whilst visually there appears to be a difference (Figure 5b), when viewed simply as the size-isotope relationship for a single sample then the statistical significance to either accept the alternative hypothesis (Figure 5b - i and iv) or reject the null hypothesis (Figure 5b- ii and iii) becomes apparent (See supplementary figures 1-6). For *G. truncatulinoides* 25 out of 26 samples show sufficient evidence to reject the null hypothesis, thus for this species the size fractions have predominately different mean $\delta^{18}O$ values, whereas all size fractions show a statistical difference and thus the difference between size fractions is not constant (Table 1). Curiously the means of small specimens of *G. inflata* and *G. truncatulinoides* are more depleted and show differences from those of coeval small specimens of *G. bulloides*, this is not present in the other, larger, size fractions.

Comparison of the spread, using the standard deviation per size fraction (Supplementary figure 7-8), in *G. bulloides* against the insolation difference between July and December reveals a negative correlation, with ~~higher values of~~larger insolation differences associated with a lower standard deviation. The relationship is stronger (r = 0.5748) however when the insolation difference between the months associated with the end of the deep Winter mixing and Summer stratification (March and June) in the modern ocean are used. It would appear that when the $\Delta\delta^{18}O$ between small and large *G. inflata* ($\Delta\delta^{18}O_{s\text{-}l}$) is reduced, so that the smallest specimens of *G. inflata* have similar values as larger specimens (>250 µm), insolation is halfway between a minimum and maximum, apart from at 234-239 kyr during the onset of the termination. During these transient events the $\delta^{18}O$ of *G. inflata* shows a relationship with the $\delta^{18}O$ of the largest size fraction (355-400 µm) of *G. bulloides* (r^2 = 0.4935; n = 8). Given that these events occur in relationship to the insolation the first derivative of the seasonal difference at 45°N was taken as the magnitude and direction of change in seasonality and compared with $\Delta\delta^{18}O_{s\text{-}l}$ for *G. inflata*. This reveals that there is a linear relationship that positively correlates during MIS8 (r = 0.6538) and negatively correlates during Interglacial MIS7 (r = 0.6882).

3.3 Carbon stable isotope values ($\delta^{13}C$)

In contrast with $\delta^{18}O$, the $\delta^{13}C$ of the means of the smallest sized specimens have a larger range than that of the largest sized specimens. Carbon isotope values are generally lower in the

smaller size fractions of *G. inflata* and *G. truncatulinoides*, although this pattern is not consistent throughout the record, than the largest size fraction~~In contrast with $\delta^{18}O$, the $\delta^{13}C$ of the means of the smallest sized specimens have a larger range than that of the largest sized specimens, none of the linear regressions are statistically significant, and likewise show a statistical offset from the δ iso-line~~ (Table 2, Figure 6). ~~However, whilst t~~There is however an overlap between the mean $\delta^{13}C$ values of the smallest sized specimens ~~overlap between~~ of different species~~.~~. ~~there is a distinct ranking between the largest size fractions with *G. bulloides* having a relatively offset from *G. inflata* and *G. truncatulinoides*.~~ G. bulloides has a less discernible trend,

~~range between -2.00 ‰ and +1.50 ‰ (Figure's 7 8). The species range, between their maximum and minimum points for all samples, from the depleted values of -2.00 ‰ and 0.00 ‰ for *G. bulloides*, a range of -1.50 and +1.20 ‰ for *G. inflata* and enriched values of -1.00 to +1.50 ‰ for *G. truncatulinoides*. T~~there are only two samples, out of 26, where the smallest size fraction of *G. bulloides* appears to deviate~~s~~ from the others, i.e. at 244 and 246 kyr (Figure 8). In comparison only the samples at 246 and 252 kyr show similar isotope values between all size fractions~~, while for the rest 212-250 µm is depleted. Between 225-236 kyr – the transition from MIS8 to MIS7 – the largest specimens of *G. inflata*, analysed here (355-400 µm), become more enriched in ^{13}C than the other size fractions. For *G. truncatulinoides* in the intervals 208, 230, 240 and 244-252 kyr, the values for the two size fractions 212-250 µm to 250-300 µm overlap. In contrast at 205, 207, 216, and 218 kyr the usually overlapping 300-355 µm to 355-400 µm size fractions deviate, with the larger size fraction becoming more enriched~~ (Figure 8).

~~In contrast with $\delta^{18}O$, the $\delta^{13}C$ of the means of the smallest sized specimens have a larger range than that of the largest sized specimens, none of the linear regressions are statistically significant, and likewise show a statistical offset from the δ iso-line (Table 2, Figure 6). However, whilst the mean $\delta^{13}C$ of the smallest sized specimens overlap between species, there is a distinct ranking between the largest size fractions with *G. bulloides* having a relatively offset from *G. inflata* and *G. truncatulinoides*.~~

Statistically the within sample, size fraction differences, show that~~Statistically,~~ 19 of the *G. bulloides* samples (6 are 90% and 13 are 95% at the confidence level), 24 of the *G. inflata* (3 are 90% and 21 are 95% at the confidence level) and 26 of the *G. truncatulinoides* (26 are 95% at

Formatted: Font: Italic

Formatted: Font: Italic

the confidence level) are significantly different at, and above, the 90% confidence level (Table 3). Small (212-250 μm) specimens of surface dwelling *G. bulloides* and intermediate *G. inflata* have a larger range in mean $\delta^{13}C$ than larger specimens (Figure 6 and 8). Curiously the relationship between size and $\delta^{13}C$ is strikingly different from the relationship for $\delta^{18}O$; the large offset in oxygen between 212-250 μm and 250-300 μm for *G. truncatulinoides* is not visible in the carbon isotope record. The results of the t-test for dependent samples shows that all are statistically significantly different at the 95% confidence level suggesting that the offset between size fractions is not constant (Table 3).

3.4 Covariance

Interdependence between $\delta^{18}O$ and $\delta^{13}C$ (Table 4 and 5) is visualised in a crossplot (Figure 9). On average both *G. bulloides* and *G. inflata* show a decreasing correlation coefficient with size between 212 and 355 μm. Both however show a reversal of this trend towards the largest size fraction (355-400 μm; Table 4 and 5). The average correlation coefficient shows no variation consistent with changes between the Glacial and Interglacial, although *G. bulloides* shows marginally lower values during H14, H15 and TIII, and all species have their lowest correlation coefficient at 250 kya. *G. bulloides* has considerably more depleted values in $\delta^{13}C$ than the other species of planktonic foraminifera whilst smaller specimens of *G. inflata* overlap the area covered by all sizes of *G. bulloides*. Peculiarly, small sized specimens of *G. truncatulinoides* have on occasion more depleted values of $\delta^{18}O$ than the other species, for a similar size.

4 Discussion

4.1 Size-isotope relationship

In this paper we applied multiple individual specimen analysis (ISA) to the problem of the size-isotope relationship to more than one sample to assess: whether (1) there is a significant correlation between size and stable isotopes, and if so, (2) whether the relationship remains constant through time over a large climatic perturbation, i.e. Glacial Termination-III. Previous studies testing the relationship between shell size and the isotopic signal have shown systematic

differences between both oxygen and carbon isotopes (Berger et al., 1978; Billups and Spero, 1995; Kroon and Darling, 1995) (Figure 10). This represents a logical partitioning between the isotopes of the two elements carbon and oxygen: Carbon isotopes predominately represent biotic processes such as productivity as a function of metabolic rates and nutrient concentrations, as well as being influenced by the photo-auto/heterotrophic symbionts that some species of foraminifera host. They can also represent the abiotic *i.e.* ventilation of oceanic water masses and or carbonate ion concentrations (Spero et al., 1997). Oxygen isotope values are primarily influenced by abiotic factors such as glacioeustatic/ice volume, local hydrographic evaporation/precipitation, and temperature. At a cursory glance our results show that larger specimens of both *G. inflata* and *G. truncatulinoides* are enriched in both ^{18}O and ^{13}C compared to smaller specimens, although this relationship is only constant for *G. truncatulinoides*. Whilst specimens of *G. bulloides* show no significant variation with size for ^{18}O, with small and large specimens showing a near identical isotope trend across Termination III, there is a progressive enrichment in ^{13}C ~~for~~ with increasing size. Berger et al. (1978) considered that the size-isotope relationship can be broadly grouped into three categories: 1) "normal" in which progressively larger sizes are more enriched, 2) "reversed" in which larger sizes are more depleted and 3) "mixed" in which no clear trend can be deduced, for both $\delta^{18}O$ and $\delta^{13}C$. The results presented here show that *G. bulloides* and *G. inflata* vary between "normal" and "mixed", whilst only *G. truncatulinoides* shows a consistent "normal" trend (see Supplementary figures 1-6).

With respect to the "normal" trend Berger (1979) considered four possible explanations for an enrichment in oxygen isotope composition with increasing size: (i) size is related to physical parameters, *i.e.* temperature (Schmidt et al., 2006) and thus larger specimens relate to optimum conditions (Bé and Lott, 1964; Bé et al., 1966; Berger, 1971); (ii) the degree of isotopic disequilibrium in calcification changes with growth (Vergnaud-Grazzini, 1976) and/or physical parameters (*i.e.* temperature); (iii) growth related depth change - with smaller individuals being found in greater concentrations closer to the surface - the implication being that small shells are prematurely (i.e. pre-reproduction) terminated individuals (Emiliani, 1954; 1971); (iv) adults that sink but do not reproduce continue to calcify giving a more enriched $\delta^{18}O$ signal (Figure 11). "Mixed" trends however pose a problem in explaining oxygen isotopes solely related to growth related depth change. Consider that the transition from juvenile-neanic to adult stages occurs

between 100 and 200 μm (Brummer et al., 1987), then all specimens above 200 μm are adult. The shape of the size frequency distribution of the pre-adult population is exponential whereas in comparison the adult population has a distinct Gaussian shape (Brummer et al. 1986, 1987; Peeters et al., 1999), which suggests that adult specimens that are larger than the mean should be considered giants and on the contrary smaller specimens as dwarfs (Berger, 1971). It has been shown that tropical species increase in size with warmer waters, whereas polar species are larger in colder waters (Stone, 1956; Kennett, 1968; Be et al., 1973; Hecht 1974; Hecht et al., 1976; Schmidt et al., 2006), favourable conditions between seasons may explain a "mixed" signal. The oxygen isotope data presented in this paper will be discussed with respect to these possibilities in the following sections.

4.2 Size of planktonic foraminifera

Whilst the faunal transition from the glacial MIS8 to interglacial MIS7 shows the characteristic pattern associated with a warming climate and despite a moderate increase in size occurring during the glacial period (234 – 252 kyr; Figure 3) the changes in abundance are not concurrent in size or magnitude, with any variation in the isotopic composition in *G. bulloides* between size fractions. Likewise no pattern can be discerned in either *G. inflata* or *G. truncatulinoides* which whilst displaying a (predominately) statistically significant isotopic offset between the difference size fractions and/or change in average size through time are not correlatable. If one considers that the modern size of foraminifera is related to a number of factors, including: temperature and productivity, then the modern size of foraminifera is related to the modern oceanographic regime. At present this regime is composed of a cyclonic and anti-cyclonic gyre system, controlling and maintaining the continued existence of the associated water masses. During glacials the North Atlantic is surrounded by continental ice sheets which are inferred to ~~occur~~ extend down to the 40°N in the west and 50°N to the east (McIntyre et al., 1976) as such no analogue to the mixing of water masses synonymous with the modern Gulf Stream-North Atlantic Drift water via cyclonic and anticyclonic eddies (McIntyre et al., 1976) occurs, as polar water masses extended as far south as 45°N. In the modern ocean *G. bulloides* has its largest size ~~occurring~~ at 50°N, if one is to consider that a compression or elimination of certain transitional water masses occurs during glacial periods then this maximum size should be

centered at or to the south of the location of the studied core, *i.e.* a size decrease should be observable at our core location. However, the control on size is not as clearly known for non-symbiotic species as it is for symbiont bearing species, whilst temperature may play an important role the dynamics of the upper water column such as the strength of winter mixing or the Spring transition from a well-mixed to stratified water column has been linked to certain seasonal successions between species (Wolftreich, 1994; Ganssen and Kroon, 2000; Salmon et al., 2014). In the modern North Atlantic, late Winter deep mixing supplies the surface layer with on average approximately 8 µmol/l of nitrate and 6 µmol/l of silicate, the rise in insolation triggers the development of the thermocline that in combination with a rapidly shoaling nutricline into the euphotic zone generates the spring bloom of phytoplankton (Broerse et al., 2000). For the modern ocean a proxy for stratification, introduced by Lototskaya and Ganssen (1998) using the same core presented here, was deduced ~~for~~ from a north-south transect of box-core tops in the North Atlantic (Ganssen and Kroon, 2000). Based upon the investigation of the modern latitudinal variability in planktonic foraminiferal stable isotopes they observed that *G. bulloides* dwells at a shallower depth then *G. inflata*. Hence, the difference ($\Delta\delta^{18}O$) between these surface and subsurface dwellers can be converted into an approximate temperature difference by taking into account that a change of approximately -0.22‰ occurs per °C increase. When this difference equals (or approaches) zero, such as ~~for example occurring~~ in the modern ocean at approximately 58°N, the water column was mixed down to the permanent thermocline, while higher values indicate a stratified water column (Ganssen and Kroon, 2000). Through the estimation of the strength of stratification, the intensity of the spring bloom can be deduced. Feldmeijer et al. (submitted) estimate that during the glacial the ocean is well mixed, becoming stratified at the termination, before transitioning toward a well mixed water column during the climate minima of MIS7d. Faunal and geochemical data between MIS9 and MIS7 suggests that a sharp temperature gradient existed between the North Atlantic ocean (55°N) and the Nordic Seas (68°-76°N) (Ruddiman and McIntyre, 1976; Ruddiman et al., 1986; Bauch, 1997), as a result of a relatively minor ingress of warm Atlantic surface water into the Nordic Sea. The deviation from an expected size decrease for both *G. bulloides* and *G. inflata*, due to a reduction in temperature at the glacial, may have been counter balanced by a more productive water column.

4.3 Depth habitat

Planktonic foraminifera, as pelagic organisms, can be considered to have optimal conditions that are both geographic and vertical. The fact that the expected size decrease in relation to the geographic movement of the oceanic fronts appears to not occur could also have some relation to changes in depth habitat. The depth habitat of planktonic foraminifera has long been considered to relate to temperature (Emiliani, 1954), although later related to the specific thermal structure *i.e.* stratification of the water column (McKenna and Prell, 2004), development of the thermocline, the depth and development of the chlorophyll maximum zone, food availability, *i.e.* phytoplankton and the depth of light penetration (Caron et al., 1981; Hemleben et al., 1989). Different ecological niches are associated with differences in the depth habitat. Spinose species for example are commonly associated with both a shallower depth habitat and symbionts that act as important food source in oligotrophic conditions. Depth habitat reconstructions, calculated via species abundance counts ~~of~~in plankton tows and/or the isotopic ~~composition of sedimentary material~~analysis of foraminifera tests from the sediment, have placed the species analysed as distinct ecological niches associated with '*shallow*', '*intermediate*' and '*deep*' depths, for *G. bulloides*, *G. inflata* and *G. truncatulinoides* respectively.

Hemleben and Spindler (1983) reported that the preferred depth habitat of *G. bulloides* is between the surface mixed layer and 200 m. Both Bé (1977) and Deuser and Ross (1989), however, suggested a shallower depth habitat of 50-100 m and 25-50 m, respectively. The species depth habitat appears strongly controlled by the distribution of particulate food. The Deep Chlorophyll Maximum (DCM) is often associated with high(er) abundance of this species and since the DCM may be found at different depths seasonally or due to water column structure, although predominately at the base of the surface mixed layer, one can expect this species to follow the food rich levels in the water column. Seasonal variability in the depth habitat may account for this discrepancy between authors. Based upon plankton tow sampling Ottens (1992b) ascribed a greater depth (0-100 m) in April than in August (0-50 m). Whereas, the non-spinose *G. inflata* is considered to be an intermediate to deeper dwelling species, typically associated with the base of the seasonal thermocline (Cléroux et al., 2008; Cléroux et al., 2007; Ganssen and Kroon, 2000; Groeneveld and Chiessi, 2011; Lončarić et al., 2006) associated with subpolar to

subtropical water masses which in the South Atlantic have been quantified to be between 13-19°C (Bé, 1969; Farmer et al., 2011; Ganssen and Sarnthein, 1983; Thiede, 1971; Thiede, 1975). ~~In the South Atlantic, for instance, *G. inflata* reaches its highest relative abundance in the transitional waters of the subtropical and subantarctic regions at water temperatures between 13-19°C.~~ However, it has been shown to dominate the lower temperature (2-6°C) subantarctic region in the South Pacific (Bé, 1969). Calcification, however, occurs from the mixed layer down to water depths of 500-800 m (Hemleben and Spindler, 1983; Wilke et al., 2006). Narrower depth intervals have been proposed for both the North Atlantic, at 0-150 m (Ottens, 1992b) and 300-400 m (Elderfield and Ganssen, 2000), and the South Atlantic at 50-300 m (Mortyn and Charles, 2003). The non-spinose species *G. truncatulinoides* has a dimorphic coiling provincialism (dextral and sinistral) although it is considered to inhabit a deep depth, approximately down to ~800 m or even deeper (Hemleben et al., 1985; Lohmann, 1992; Lohmann and Schweitzer, 1990) where they are considered to secrete a secondary 'gametogenetic' crust (Bé and Ericson, 1963; Hemleben et al., 1985). Given the considerable depths ~~it~~ that *G. truncatulinoides* inhabits it likely feeds on detritus settling from the photic zone. Its morphology, more explicitly the height of the conical shell, has changed temporally and spatially (Lohmann, 1992 and references therein) with different populations having different isotopic compositions (Williams et al., 1988). Fairbanks et al. (1980) found, using plankton tows, that this species ~~is~~ has enriched values of $\delta^{18}O$ ~~isotopically~~, compared to equilibrium values, when found above the thermocline, in equilibrium on the thermocline and depleted values of $\delta^{18}O$ below it. This deviation is likely caused by offsets between primary and secondary crusts (McKenna and Prell, 2004; Mulitza et al., 1997; Vergnaud Grazzini, 1976), although this may be a seasonal-encrusting artefact (Spear et al., 2011). Our results show that species with a larger modern depth habitat, such as globorotalids, have for the most part a statistically significant offset between smaller sized and larger sized specimens in the sedimentary record. With increasing water depth, oxygen isotope equilibrium values become successively more enriched (Figure 11), considering that size and depth are linked then our results parallel the work of Williams et al. (1981) and the later work of Lončarić et al. (2006) in suggesting that the $\delta^{18}O$ of smaller sized (predominately globorotalid) foraminifera record upper ocean/surface conditions. During the descent through the water column foraminifera add new

calcite, their shell's geochemical composition is therefore an integrated history of the hydrology at different water depths (Hemleben and Bijma, 1994; Wilke et al., 2006) (Figure 11).

4.4 Seasonality

The isotopic composition of larger specimens represents continuous calcification through the water column to deeper waters with lower temperatures, thus giving ~~isotopically~~ enriched values in $\delta^{18}O$. Given the isotopic overlap of the ~~larger than~~ >250 µm in all species it is possible that no size-depth stratification occurs after a given growth stage. Although given that the seasonal temperature variation with depth is small (<1°C for 200 m, <0.6°C for 500 m) different sizes may represent growth in different seasons with varying ecological constraints. However, the "mixed" signal, for instance at 214.5 kyr for *G. bulloides* where both small and large specimens have the same $\delta^{18}O$ would suggest a seasonal effect. The modern seasonal temperature range at the core site is 10-12°C, assuming that a change of 1‰ corresponds to a 4°C then the amplitude of the seasonal temperature signal alone is approximately 2.5-3.0‰. This is further complicated by potential changes attributable to evaporation and precipitation and the occasional-intermittent presence of freshwater pulses, as the core site is situated within the ice rafted debris belt (Hodell and Curtis, 2008). If we consider that the isotope values of 250-355 µm occurs during favourable conditions, the two end members (212-250 and 355-400 µm) could occur during unfavourable conditions during the height of summer when the water column is strongly stratified. Curiously, the average correlation coefficient between $\delta^{18}O$ and $\delta^{13}C$ shows a reversal in its decrease with size trend in this larger size fraction (355-400 µm) which may support this seasonal explanation, although it may also be a change in vital effect or metabolic dominance of the isotopic signal.

Intriguingly there are a number of instances where the smallest specimens of *G. inflata* have similar values as larger specimens (>250 µm) these events occurring halfway between insolation minima and maxima, apart from at 234-239 kyr during the onset of the termination. Were it to be a shoaling of the depth habitat then larger specimens would be expected to show similar values to smaller specimens and not the other way around. The fact that these values show a relationship with $\delta^{18}O_{355\text{-}400\mu m}$ *G. bulloides* ($r = 0.7025$; $n = 8$) suggests a modification of the structure of the upper ocean. The biological vertical structure of the water column is dependent upon the amount of incidental light, notwithstanding surface ocean processes such as surface layer mixing (Figure

11d-f). In the modern ocean the average wind velocity increases between November and February which mixes the ocean down to depths of 150-300m (Broerse et al., 2000). The penetrative depth of sunlight, and thus the surface available to direct heating, is greater in the ocean (~100m) than on land (~1-2m) accordingly temperature change in the ocean is distributed over a larger area than on land which has a lower capacity to either conduct or store heat. Variation in the ocean-land heat contrast directly affects the influence of wind strength in the region and thus the strength of wind driven turbulence that the mixes the upper ocean. The fact that these events occur halfway between a minima and maxima in insolation may suggest that the wind regime over this region of the North Atlantic is particular sensitive to the reduction in extremes. Likewise, the shift in both the relative abundance (Figure 3) and the oxygen isotopic standard deviation (Supplementary Figure 7) of *G. bulloides* corresponds to a change in the insolation difference between the vernal Equinox and the summer Solstice (e.g. between March and June) ($r = 0.5748$; $n = 26$). This means that, when the difference between the two seasons is greatest the growing season is reduced, thus the surface species has a 'reduced' range of values. It is postulated that during periods of reduced seasonality the stratification that exists in the summer months was not as strong as it is today.

4.5 $\Delta\delta^{18}O$ between species

Oxygen isotopes between similar sizes of different species show differences between small specimens (212-250 μm) of the deep-dwelling *G. truncatulinoides*, and the surface dwelling *G. bulloides*, of up to 1.3 ‰ $\Delta\delta^{18}O$ (corresponding to ~5 °C) during some periods, although on average this offset is smaller at ~0.5 ‰ or 2 °C (Figure 12). This pattern can be accomplished by: (1) differences in $\delta^{18}O$ fractionation factors between species confirmed by numerous authors (Curry and Matthews 1981; Duplessy et al., 1981; Fairbanks et al., 1980; Shackleton, 1974; Shackleton et al.,1973; Vergnaud-Grazzini, 1976; Williams et al., 1979); (2) calcification in a water mass with a different ambient $\delta^{18}O_{eq}$, *i.e.* convection and sinking of isotopically depleted water (Macdonald et al., 1995) during sea ice formation (Rohling and Bigg, 1998; Strain and Tan, 1993); (3) expatriation of more southerly grown specimens via a proto-gulf stream deflected by a southerly Polar Front (Cifelli and Smith, 1970; Lototskaya and Ganssen, 1999; Phleger et al., 1953; Weyl, 1978); or (4) calcification in distinct seasons. Explanation (ii) that calcification

occurs in a water mass with a different $\delta^{18}O_{sw}$ is plausible. For instance during sea ice formation surrounding water masses become isotopically depleted as the $\delta^{18}O$ of sea ice is 2.57 ±0.10 ‰ enriched relative to the isotopic composition of sea water (Macdonald et al., 1995). The formation of which increases surface ocean salinity enough to lead to convection and sinking of this depleted water mass (Rohling and Bigg, 1998; Strain and Tan, 1993). This depleted water mass is replaced by surface waters (to some degree) unaffected by the freezing process (Rohling and Bigg, 1998) meaning that species that calcify during sea ice formation will have ~~a more~~ depleted $\delta^{18}O$ values ~~signal~~. Similarly the core site is situated within the ice rafted debris belt (Hodell and Curtis, 2008; Park, 1998) indicating that this area would have been affected by meltwater during certain periods of the year. However, both of these hypotheses cannot satisfactorily explain the continuation of this phenomena in shallower 'interglacial' depths of the core.

Explanation (3) finds support from observations of Phleger et al. (1953) that low latitude faunas are circulated northwards in the western portion of the Atlantic basin, whereas high latitudes faunas are displaced southwards in the eastern basin, as dictated by the clockwise direction of the currents within the North Atlantic gyre (Figure 1). The large difference between the fine fractions of *G. bulloides* and *G. truncatulinoides* (up to 1.3‰) cannot account for differences in calcification depth alone as it would indicate a deeper calcification for *G. bulloides*. Instead calcification at a more southerly and warmer location is plausible. During glacial conditions the biogeographic distribution of this species contracts to lower latitudes as the boundary of the Polar Front moves southwards down to the latitude of the Iberian margin. Expatriates carried by the proto-Gulfstream would have been deflected along the polar front (Lototskaya and Ganssen, 1999; Weyl, 1978) into this core-location as deduced by the IRD belt (Berger and Jansen, 1995; Ruddiman and McIntyre, 1981). Cifelli and Smith (1970) through releasing drift bodies from eastern North America indicated that surface currents could redistribute organisms when they collected these same drift bodies in the Azores. It is possible that the specimens with more depleted ~~in~~ $\delta^{18}O$ values~~specimens~~ represent the endemic population, and the more enriched specimens are expatriates (Lototskaya and Ganssen, 1998). Were these expatriates to emigrate into unfavourable conditions they may not have grown

additional chambers in equilibrium with the ambient conditions and thus an observable offset would occur.

Both (2) and (3) can be discounted given that the phenomenon occurs irrespective of oceanic mode (i.e. glacial-interglacial). Given the seasonal flux (Tolderlund and Bé, 1971) this isotopic difference could relate to deep-sea sediments being composed of specimens from species that potentially calcify during different seasons (Williams et al., 1979), therefore requiring no problematic large scale transport. Tolderlund and Bé (1971) based upon four years of seasonally collected plankton tows at weather station Delta (44°00'N, 41°00'W) considered that *G. bulloides* had a continuous flux throughout the period of November to August, while both *G. inflata* and *G. truncatulinoides* show two flux maxima, one between December and March and between December and January respectively. This relates to temperatures during this time window of between 10-23°C for *G. bulloides*, 10-23°C for *G. inflata* and 8–22°C *G. truncatulinoides*. Whilst these temperature distributions suggest that *G. truncatulinoides* occurs in colder waters the optimum temperatures of these species are 10-12°C, 10-17°C and 15-18°C, respectively, consistent with the idea of calcification in warmer temperatures (Tolderlund and Bé, 1971). *Globigerina bulloides* has highest fluxes during the spring bloom prior to stratification of the water column were *G. truncatulinoides* to calcify later in the year, at the base of the thermocline, then it would explain the deviation in isotopic composition between the two species.

4.6 Carbon isotopes

In comparison with oxygen isotopes there is generally an enrichment in ^{13}C with size, synonymous with previous studies (Franco-Fraguas et al., 2011; Fridrich et al., 2012; Birch et al., 2013), as per the "normal" trend (Berger et al., 1978). Changes in the $\delta^{13}C$ values of planktonic foraminifera have invoked ~~photosymbiosis~~ photosymbionts through changes in the microenvironment (Spero and DeNiro, 1987), metabolic fractionation *i.e.* respiration (Berger et al., 1978), diet (DeNiro and Epstein, 1978) and metabolic and/or symbiotic influences on the ambient and internal carbon pool (*i.e.* carbonate ion concentration). It is ~~self-evident~~self-evident that the same depth related size-$\delta^{18}O$ trends are not applicable to carbon isotopes~~,~~. In contrast to the $\delta^{18}O$ equilibrium values~~given~~ the vertical structure of the $\delta^{13}C$ of dissolved inorganic carbon ($DIC \equiv \sum CO_2$)~~DIC,~~ ~~which as~~ is a consequence of the surface photosynthesis and the oxidation of

organic matter at depth. Tthe isotopic composition of DIC ~~dissolved inorganic carbon (DIC ≡ $\sum CO_2$)~~ therefore varies vertically resulting in depleted $\delta^{13}C$ ~~isotopic~~ values at depth as opposed to ~~an~~ the enrichment seen in $\delta^{18}O$. As photosynthesis preferentially favours uptake of ^{12}C, organic matter produced through this pathway has typical $\delta^{13}C$ values of between -20 to -25 ‰, as a result the DIC at the surface, in the photic zone, is enriched in $\delta^{13}C$ by approximately ~2 ‰. As the isotopically depleted organic matter sinks it is oxidised lowering the ambient $\delta^{13}C$ value to approximately ~0 ‰. The calcification depth surmised from using only $\delta^{13}C$, when compared with the modern $\delta^{13}C_{DIC}$ vertical profile ~~(Feldmeijer et al., submitted)~~, would indicate a shallower depth habitat then that indicated by $\delta^{18}O$ (see Feldmeijer et al., 2015).

Our results however show that the relative enrichment in $\delta^{13}C$ between species is consistent with the depth habitat per se, *i.e.* deeper dwellers ~~have a larger~~are more enriched~~ment~~ than shallower dwellers (Figure 9d). This discrepancy could relate to either a (i) temperature related fractionation, (ii) diet and/or (iii) the addition of a secondary crust. Species specific temperature dependent fractionation is likely caused by the influence of temperature on the physiological rates of the organism, for instance a number of authors have demonstrated that over small temperature ranges the metabolic rate ~~increased~~ increases exponentially (Bijma et al., 1990; Ortiz et al., 1996). The change in $\delta^{13}C$ per degree Celcius for *G. bulloides* has been estimated experimentally as -0.11 ‰ $°C^{-1}$, whereas for the symbiotic species *Orbulina universa* it is 2-3 times less in the opposite direction 0 to +0.05 ‰ $°C^{-1}$ (Bemis et al., 2000). It is noteworthy to point out that for the non-symbiotic species *G. bulloides* this temperature effect will diminish the effect of higher glacial [CO_3^{2-}] (Bemis et al., 2000). Spero et al. (1997) through culturing experiments in which *G. bulloides* was grown at constant DIC showed that there is a strong dependence, -0.012 ‰/(µmol kg^{-1}) on $\delta^{13}C$, with [CO_3^{2-}]. This strong dependence, a consequence of both kinetic and metabolic fractionation factors (Bijma et al., 1999), is species specific (Peeters et al., 2002; Wilke et al., 2006). In the natural environment the [CO_3^{2-}] varies regionally as the solubility of CO_2 is temperature dependent and vertically as organic matter is remineralised and the subsequent CO_2 is released and hydrolysed. A 0.5 *p*H decrease at the shallow oxygen minimum zone for instance would account for a 1 ‰ enrichment in $\delta^{13}C$ for those species that inhabit it (Birch et al., 2013). This sinking organic matter may also contribute to changes in the $\delta^{13}C$ of ~~test~~ shell calcite through changes in food source, feeding efficiency and diet. DeNiro and

Epstein (1978) highlighted the fact that consumers are slightly enriched in $\delta^{13}C$ from the composition of their food with each trophic level raising their $\delta^{13}C$ values a process termed cumulative fractionation by McConnaughey and McRoy (1979a; 1979b). Carnivorous foraminifera are likely to have more enriched values in $\delta^{13}C$ than herbivorous foraminifera. Likewise Hemleben and Bijma (1994) suggested that dietary change between juveniles grazing on phytoplankton or feeding on detritus and the carnivorous diet of later neanic and/or adult stages should coincide with an increase in $\delta^{13}C$. Growth rate, final size, $\delta^{13}C$ and rate of chamber addition have all been shown to correlate positively with increased feeding rate (Bé et al., 1981; Bijma et al., 1992; Hemleben et al., 1987; Ortiz et al., 1996), *i.e.* a doubling in feeding rate resulted in a decrease in $\delta^{13}C$ by 1 ‰ for specimens of the symbiont bearing *Globigerinella siphonifera* (Hemleben and Bijma, 1994). Younger (or smaller) foraminifera are inferred to have higher respiration rates (high metabolic rate thus increased kinetic fractionation) which during calcification leads to a greater amount of metabolic CO_2 depleted in ^{13}C incorporated into ~~the test~~shell calcite (Bemis et al., 2000; Berger et al., 1978; Ravelo and Fairbanks, 1995).As metabolic rates slow with growth ~~down during ontogeny~~ the ~~test~~ shell becomes more isotopically enriched as the incorporation of light carbon decreases (Bemis et al., 2000; Berger et al., 1978; Birch et al., 2013; Fairbanks et al., 1982; Oppo and Fairbanks., 1989; Spero and Lea, 1996; Vincent and Berger, 1981). ~~Younger (or smaller) foraminifera are inferred to have higher respiration rates (high metabolic rate thus increased kinetic fractionation) which during calcification leads to a greater amount of metabolic CO_2 depleted in ^{13}C incorporated into the test calcite (Bemis et al., 2000; Berger et al., 1978; Ravelo and Fairbanks, 1995).~~ The addition of a secondary crust, or gametogenetic calcite, at depth potentially via absorption and remineralisation of earlier chambers and spines during preparations for reproduction may lead to an isotopic offset (Hemleben et al., 1989; Schiebel and Hemleben, 1995). When restricted to primary calcite Lohmann (1995) discerned there was no size-$\delta^{13}C$ trend however, as noted by Birch et al. (2013) this mechanism would result in depleted values not the enriched values observed.

The transition between a glacial and interglacial further exacerbates interpretation of carbon isotope trends. Bemis et al. (2000) suggested that the $\delta^{13}C$ of DIC of the surface ocean during the glacial would have to increase by 0.3 to 0.4 per mil to account for changes in sea surface temperature and alkalinity. A similar figure was estimated by Broecker and Henderson

Formatted: English (U.K.)

Formatted: English (U.K.), Superscript

Formatted: English (U.K.)

(1998), at 0.35 per mil, although they considered that it should be in response to an enhanced biological pump drawing down CO_2. A conservative estimate, given the poorly constrained alkalinity inventory, of 60 µmol kg^{-1}, change in $[CO_3^{2-}]$ at the LGM would have decreased the $\delta^{13}C$ of *G. bulloides*, by 0.72 per mil. Given that the pCO_2 of MIS8 never reaches the lower boundary of 180 ppm it is likely that this value is lower for the period of study. Irrespective of whether CO_2 or temperature changed first unravelling the dominant influence on shell $\delta^{13}C$ is problematic. If for instance a species altered its season of calcification so that during glacial periods it calcified in warmer months and during interglacials in colder months then this temperature influence could be negated. Regardless, this problem is further complicated by the fact that, as shown by our data, the use of $\delta^{18}O$ to estimate calcification depth leads to the specimens not fitting the $\delta^{13}C$ profiles. Shackleton (1978) pointed out that trying to estimate the carbon isotope composition of the surface ocean is particularly tenuous, given the gradient in carbon isotope values is steepest at the surface when coupled with the limitations and uncertainties regarding the precise depth of calcification.

5 Conclusion

Oxygen isotopic analysis of specimens from different size fractions reveal that for globorotalids smaller shells are isotopically depleted compared to larger shells, whilst we find ~~did~~ not~~ find a~~ systematic differences between the $\delta^{18}O$ of *G. bulloides* in different size fractions. ~~This~~ The depletion for globorotalid species is inferred to be an effect of different depths inhabited during ontogeny, with smaller specimens calcifying in the warmer shallower surface waters prior to migrating to depth. A large offset between small and larger specimens of *G. truncatulinoides* can be explained by calcification during a warmer season at a shallower water depth. Carbon isotopes show a greater degree of variability, which is inferred to relate to changes in metabolism. Differences between size fractions appear not constant temporally or even spatially as shown by the difference between the data presented here and that previously published. This is likely the reason for the lack of a resolution in the existing literature ~~between studies pertaining to decide on a preferred /~~ as to the recommended size fraction for isotopic analysis. Our results would suggest that 300-355 µm would serve this purpose given the offsets between the species, however we would caution against using a 'one-size fits all' approach given the seasonal structure of the

Formatted: English (U.K.), Subscript
Formatted: English (U.K.)
Formatted: English (U.K.), Superscript
Formatted: English (U.K.)
Formatted: English (U.K.), Subscript
Formatted: English (U.K.), Superscript
Formatted: English (U.K.)
Formatted: Font: Italic, English (U.K.)
Formatted: English (U.K.)
Formatted: Font: Italic, English (U.K.)
Formatted: English (U.K.)
Formatted: English (U.K.), Subscript
Formatted: English (U.K.)
Formatted: English (U.K.), Subscript
Formatted: English (U.K.)
Formatted: English (U.K.)
Formatted: English (U.K.)
Formatted: English (U.K.)
Formatted: English (U.K.), Superscript
Formatted: English (U.K.)
Formatted: English (U.K.)
Formatted: English (U.K.)
Formatted: English (U.K.)
Formatted: English (U.K.)

water column and seasonal succession of species at this core location. Further studies are needed to understand how this size-isotope relationship varies in regions with reduced seasonality, more/less stable and unstable water column dynamics and during transient events, for example associated with sapropel layers.

Acknowledgements

This paper is a contribution to the European 7th Framework Project, EPOCA (European Project for Ocean Acidification; FP7/211384), the Darwin Center for Biogeosciences Project 3040 'Sensing Seasonality' and the NWO funded project "Digging for density" (NWO/822.01.0.19). Financial assistance was also provided to the lead author by the VU University Amsterdam. Piston core T90-9p was taken during a joint JGOFS - APNAP expedition aboard the R/V Tyro funded by the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO).

References

Balmaseda, M. A., Mogensen, K., and Weaver, A. T.: Evaluation of the ECMWF ocean reanalysis system ORAS4, Quarterly Journal of the Royal Meteorological Society, 139, 1132-1161, 2013.

Bard, E.: Paleoceanographic implications of the difference in deep-sea sediment mixing between large and fine particles, Paleoceanography, 16, 235-239, 2001.

Bard, E., Arnold, M., Duprat, J., Moyes, J., and Duplessy, J.-C.: Reconstruction of the last deglaciation: deconvolved records of $\delta^{18}O$ profiles, micropaleontological variations and accelerator mass spectrometric ^{14}C dating, Climate Dynamics, 1, 1987.

Bauch, H. A.: Paleoceanography of the North Atlantic Ocean (68–76 N) during the past 450 ky deduced from planktic foraminiferal assemblages and stable isotopes, Contributions to the Micropaleontology and Paleoceanography of the Northern North Atlantic, 5, 83-100, 1997.

Bé, A. W. H.: An ecological, zoogeographic, and taxonomic review of recent Planktonic Foraminifera. In: Oceanic Micropalaeontology, Ramsay, A. T. S. (Ed.), Academic Press, London, 1977.

Bé, A. W. H.: Planktonic Foraminifera. In: Distribution of Selected Groups of Marine Invertebrates in Waters South of 35°S latitude, Antarctic Map Folio Series, American Geographical Society, 1969.

Bé, A. W. H., Caron, D. A., and Anderson, O. R.: Effects of feeding frequency on life processes of the planktonic foraminifer *Globigerinoides sacculifer* in laboratory culture, Journal of the Marine Biological Association of the UK, 61, 257-277, 1981.

Bé, A. W. H. and Ericson, D. B.: Aspects of calcification in planktonic foraminifera (Sarcodina)*, Annals of the New York Academy of Sciences, 109, 65-81, 1963.

Bé, A. W. H., Harrison, S. M., and Lott, L.: *Orbulina universa* d'Orbigny in the Indian Ocean. , Micropaleontology 19, 150-192 1973.

Bé, A. W. H., Hemleben, C., Anderson, O. R., Spindler, M., Hacunda, J., and Tuntivate-Choy, S.: Laboratory and field observations of living planktonic foraminifera, Micropaleontology, 23, 155-179, 1977.

Bé, A. W. H. and Lott, L.: Shell growth and structure of planktonic foraminifera, Science, 145, 823-824, 1964.

Bé, A. W. H., McIntyre, A., and Breger, D. L.: Shell Microstructure of a Planktonic Foraminifer, *Globorotalia menardii* (d'Orbigny), Eclogae geologicae Helvetiae, 59, 885-896, 1966.

Bé, A. W. H. and Tolderlund, D. S.: Distribution and ecology of living planktonic foraminifera in surface waters of the Atlantic and Indian Oceans. In: Micropaleontology of Oceans, Funnell, B. M. and Riedel, W. R. (Eds.), Cambridge University Press, London, 1971.

Bemis, B. E., Spero, H. J., Lea, D. W., and Bijma, J.: Temperature influence on the carbon isotopic composition of *Globigerina bulloides* and *Orbulina universa* (planktonic foraminifera), Marine Micropaleontology, 38, 213-228, 2000.

Berger, A., Loutre, M. F., and Mélice, J. L.: Equatorial insolation: from precession harmonics to eccentricity frequencies, Climate of the Past, 2, 131-136, 2006.

Berger, W. H.: Ecologic patterns of living planktonic Foraminifera, Deep Sea Research and Oceanographic Abstracts, 16, 1-24, 1969.

Berger, W. H.: Preservation of foraminifera, Houston1979, 105-155.

Berger, W. H.: Sedimentation of planktonic foraminifera, Marine Geology, 11, 325-358, 1971.

Berger, W. H., Diesterhaass, L., and Killingley, J. S.: Upwelling off northwest africa-holocene decrease as seen in carbon isotopes and sedimentological indicators, Oceanologica Acta, 1, 3-7, 1978a.

Berger, W. H. and Jansen, E.: Younger Dryas episode: ice collapse and super fjord heat pump. In: The Younger Dryas, Troelstra, S. R., Van Hinte, J. E., and Ganssen, G. M. (Eds.), Koninklijke Nederlandse Akademie van Wetenschappen verhandelingen, Afd. Natuurkunde, 1, Koninklijke Nederlandse Akademie van Wetenschappen, Amsterdam, 1995.

Berger, W. H., Killingley, J. S., and Vincent, E.: Stable isotopes in deep-sea carbonates: Box Core ERDC-92, west equatorial Pacific, Oceanological Acta, 1, 203-216, 1978b.

Bijma, J., Faber, W. W., and Hemleben, C.: Temperature and salinity limits for growth and survival of some planktonic foraminifers in laboratory cultures, Journal of Foraminiferal Research, 20, 95-116, 1990.

Bijma, J., Hemleben, C., Oberhaensli, H., and Spindler, M.: The effects of increased water fertility on tropical spinose planktonic foraminifers in laboratory cultures, Journal of Foraminiferal Research, 22, 242-256, 1992.

Bijma, J., Spero, H. J., and Lea, D. W.: Reassessing foraminiferal stable isotope geochemistry: Impacts of the oceanic carbonate system (Experimental results). In: Use of Proxies in Paleoceanography: Examples from the South Atlantic Fischer, G. and Wefer, G. (Eds.), Springer-Verlag, Berlin Heidelberg, 1999.

Billups, K. and Spero, H. J.: Relationship between shell size, thickness and stable isotopes in individual planktonic foraminifera from two equatorial Atlantic cores, Journal of Foraminiferal Research, 25, 24-37, 1995.

Birch, H., Coxall, H. K., Pearson, P. N., Kroon, D., and O'Regan, M.: Planktonic foraminifera stable isotopes and water column structure: Disentangling ecological signals, Marine Micropaleontology, doi: http://dx.doi.org/10.1016/j.marmicro.2013.02.002, 2013. 2013.

Bonneau, M.-C., Vergnaud-Grazzini, C., and Berger, W. H.: Stable isotope fractionation and differential dissolution in recent planktonic foraminifera from Pacific box-cores, Oceanological Acta, 3, 377-382, 1980.

Bouvier-Soumagnac, Y. and Duplessy, Y.: Carbon and oxygen isotopic composition of planktonic foraminifera from laboratory culture, plankton tows and recent sediment: implications for the reconstruction of paleoclimatic conditions and of the global carbon cycle, Journal of Foraminiferal Research, 15, 302-320, 1985.

Broerse, A. T. C., Ziveri, P., Van Hinte, J. E., and Honjo, S.: Coccolithophore export production, species composition, and coccolith-$CaCO_3$ fluxes in the NE Atlantic (34°N 21°W and 48°N 21°W), Deep-Sea Research II, 47, 1877-1906, 2000.

Brummer, G.-J. A., Hemleben, C., and Spindler, M.: Ontogeny of extant spinose planktonic foraminifera (Globigerinidae): A concept exemplified by *Globigerinoides sacculifer* (Brady) and *G. Ruber*(d'Orbigny), Marine Micropaleontology, 12, 357-381, 1987.

Brummer, G.-J. A., Hemleben, C., and Spindler, M.: Planktonic foraminiferal ontogeny and new perspectives for micropalaeontology, Nature Publishing Group, 1986. 1986.

Caron, D. A., Be, A. W. H., and O.R., A.: Effects of variations in light intensity on life processes of the planktonic foraminifera *Globigerinoides sacculifer* in laboratory culture, Journal of the Marine Biological Association of the UK, 62, 435-451, 1981.

Cifelli, R. and Smith, R. K.: Distribution of Planktonic Foraminifera in the Vicinity of the North Atlantic Current, Smithsonian Contributions to Paleobiology, 4, 51p, 1970.

Cléroux, C., Cortijo, E., Anand, P., Labeyrie, L., Bassinot, F., Caillon, N., and Duplessy, J.-C.: Mg/Ca and Sr/Ca ratios in planktonic foraminifera: Proxies for upper water column temperature reconstruction, Paleoceanography, 23, PA3214, 2008.

Cléroux, C., Cortijo, E., Duplessy, J.-C., and Zahn, R.: Deep-dwelling foraminifera as thermocline temperature recorders, Geochemistry, Geophysics, Geosystems, 8, Q04N11, 2007.

Curry, W. B. and Matthews, R.: Equilibrium ^{18}O fractionation in small size fraction planktonic foraminifera:evidence from recent Indian Ocean sediments, Marine Micropaleontology, 6, 327-337, 1981.

de Villiers, S.: Optimum growth conditions as opposed to calcite saturation as a control on the calcification rate and shell-weight of marine foraminifera, Marine Biology, 144, 45-49, 2004.

DeNiro, M. J. and Epstein, S.: Influence of diet on the distribution of carbon isotopes in animals, Geochimica et cosmochimica acta, 42, 495-506, 1978.

Deuser, W. G. and Ross, E. H.: Seasonally abundant planktonic foraminifera of the Sargasso Sea: Succession, deep-water fluxes, isotopic compositions, and paleoceanographic implications, Journal of Foraminiferal Research, 19, 268-293, 1989.

Duplessy, J. C., Bé, A. W. H., and Blanc, P. L.: Oxygen and carbon isotopic composition and biogeographic distribution of planktonic foraminifera in the Indian Ocean, Palaeogeography, Palaeoclimatology, Palaeoecology, 33, 9-46, 1981.

Elderfield, H. and Ganssen, G. M.: Past temperature and $\delta^{18}O$ of surface ocean waters inferred from foraminiferal Mg/Ca ratios, Nature, 405, 442-445, 2000.

Elderfield, H., Vautravers, M., and Cooper, M.: The relationship between shell size and Mg/Ca, Sr/Ca, ^{18}O, and ^{13}C of species of planktonic foraminifera, Geochemistry Geophysics Geosystems, 3, 2002.

Emiliani, C.: Depth habitats of some species of pelagic foraminifera as indicated by oxygen isotope ratios, American Journal of Science, 252, 149-158, 1954.

Emiliani, C.: Isotopic paleotemperatures and shell morphology of *Globigerinoides rubra* in the type section of the Pliocene-Pleistocene boundary, Micropaleontology, 17, 233-237, 1971.

Emiliani, C.: Pleistocene Temperatures, The Journal of Geology, 63, 538-578, 1955.

Fairbanks, R. G., Sverdlove, M., Free, R., Wiebe, P. H., and Bé, A. W. H.: Vertical distribution and isotopic fractionation of living planktonic foraminifera from the Panama Basin, Nature, 298, 841-844, 1982.

Fairbanks, R. G., Wiebe, P. H., and Be, A. W. H.: Vertical distribution and Isotopic Composition of Living Planktonic Foraminifera in the Western North Atlantic, Science, 207, 61-63, 1980.

Farmer, E. J., Chapman, M. R., and Andrews, J. E.: Holocene temperature evolution of the subpolar North Atlantic recorded in the Mg/Ca ratios of surface and thermocline dwelling planktonic foraminifers, Global and Planetary Change, 79, 234-243, 2011.

Feldmeijer, W., Metcalfe, B., Brummer, G.-J. A., and Ganssen, G. M.: Reconstructing the depth of the permanent theromcline through the morphology and geochemistry of the deep dwelling foraminifer *Globorotalia truncatulinoides*, Paleoceanography, Submitted. Submitted.

Franco-Fraguas, P., Costa, K. B., and Toledo, F. A. L.: Relationship between isotopic composition ($\Delta^{18}O$ and $\Delta^{13}C$) and plaktonic foraminifera test size in core tops from the Brazilian Continental Margin, Brazilian Journal of Oceanography, 59, 327-338, 2011.

Friedrich, O., Schiebel, R., Wilson, P. A., Weldeab, S., Beer, C. J., Cooper, M. J., and Fiebig, J.: Influence of test size, water depth, and ecology on Mg/Ca, Sr/Ca, $\delta^{18}O$ and $\delta^{13}C$ in nine modern species of planktic foraminifers, Earth and Planetary Science Letters, 319-320, 133-145, 2012.

Ganssen, G. M. and Kroon, D.: The isotopic signature of planktonic foraminifera from NE Atlantic surface sediments: implications for the reconstruction of past oceanic conditions, Journal of the Geological Society, 157, 693-699, 2000.

Ganssen, G. M., Peeters, F. J. C., Metcalfe, B., Anand, P., Jung, S. J. A., Kroon, D., and Brummer, G.-J. A.: Quantifying sea surface temperature ranges of the Arabian Sea for the past 20,000 years, Climate of the Past, 7, 1337-2686, 2011.

Ganssen, G. M. and Sarnthein, M.: Stable-isotope composition of foraminifers: the surface and bottom water record of coastal upwelling. In: Coastal Upwelling Its Sediment Record, Springer, 1983.

Groeneveld, J. and Chiessi, C. M.: Mg/Ca of *Globorotalia inflata* as a recorder of permanent thermocline temperatures in the South Atlantic, Paleoceanography, 26, PA2203, 2011.

Hammer, Ø., Harper, D. A. T., and Ryan, P. D.: PAST: Paleontological Statistics software package for education and data analysis, Palaeontologica Electronica, 4, 9, 2001.

Hecht, A. D.: The oxygen isotopic record of foraminifera in deep-sea sediment, Foraminifera., Academic Press, London, 1974. 1-43, 1974.

Hecht, A. D., Be, A. W. H., and Lott, L.: Ecologic and paleoclimatic implications of morphologic variation of *Orbulina universa* in the Indian Ocean, Science, 194, 422-424, 1976.

Hemleben, C. and Bijma, J.: Foraminiferal population dynamics and stable carbon isotopes. In: Carbon Cycling in the Glacial Ocean: Constraints on the Ocean's Role in Global Change, Springer, 1994.

Hemleben, C. and Spindler, M.: Recent advances in research on living planktonic foraminifera. In: Reconstruction of marine Paleoenvironments, Meulenkamp, J. E. (Ed.), Utrecht Micropaleontological Bulletins, 1983.

Hemleben, C., Spindler, M., and Anderson, O. R.: Modern Planktonic Foraminifera, Springer-Verlag, New York, 1989.

Hemleben, C., Spindler, M., Breitinger, I., and Deuser, W. G.: Field and laboratory studies on the ontogeny and ecology of some globorotaliid species from the Sargasso Sea off Bermuda, The Journal of Foraminiferal Research, 15, 254-272, 1985.

Hemleben, C., Spindler, M., Breitinger, I., and Ott, R.: Morphological and physiological responses of *Globigerinoides sacculifer*(Brady) under varying laboratory conditions, Marine Micropaleontology, 12, 305-324, 1987.

Hodell, D. A. and Curtis, J. H.: Oxygen and carbon isotopes of detrital carbonate in North Atlantic Heinrich Events, Marine Geology, 256, 30-35, 2008.

Ishimura, T., Tsunogai, U., and Nakagawa, F.: Grain-scale heterogeneities in the stable carbon and oxygen isotopic compositions of the international standard calcite materials (NBS 19, NBS

18, IAEA-CO-1, and IAEA-CO-8), Rapid Communications in Mass Spectrometry, 22, 1925-1932, 2008.

Kahn, M. I.: Non-equilibrium oxygen and carbon isotopic fractionation in tests of living planktonic-foraminifera, Oceanologica Acta, 2, 195-208, 1979.

Kennett, J. P.: Latitudinal variation in *Globigerina pachyderma* (Ehrenberg) in surface sediments of the southwest Pacific Ocean, Micropaleontology, 1968. 305-318, 1968.

Killingley, J. S., Johnson, R. F., and Berger, W. H.: Oxygen and carbon isotopes of individual shells of planktonic foraminifera from Ontong-Java plateau, equatorial pacific, Palaeogeography, Palaeoclimatology, Palaeoecology, 33, 193-204, 1981.

Kozdon, R., Ushikubo, T., Kita, N. T., Spicuzza, M., and Valley, J. W.: Intratest oxygen isotope variability in the planktonic foraminifer *N. pachyderma*: Real vs. apparent vital effects by ion microprobe, Chemical Geology, 258, 327-337, 2009.

Kroon, D. and Darling, K.: Size and upwelling control of the stable isotope composition of *Neogloboquadrina dutertrei* (D'Orbigny), *Globigerinoides ruber* (D'Orbigny) and *Globigerina bulloides* D'Orbigny: Examples from the Panama Basin and Arabian Sea, Journal of Foraminiferal Research, 25, 39-52, 1995.

Kucera, M., Rosell-Melé, A., Schneider, R., Waelbroeck, C., and Weinelt, M.: Multiproxy approach for the reconstruction of the glacial ocean surface (MARGO), Quaternary Science Reviews, 24, 813-819, 2005.

Lohmann, G. P.: Increasing seasonal upwelling in the subtropical South Atlantic over the past 700,000 yrs: Evidence from deep-living planktonic foraminifera, Marine Micropaleontology, 19, 1-12, 1992.

Lohmann, G. P.: A Model for Variation in the Chemistry of Planktonic Foraminifera Due to Secondary Calcification and Selective Dissolution, Paleoceanography, 10, 445-457, 1995.

Lohmann, G. P. and Schweitzer, P. N.: *Globorotalia truncatulinoides*' Growth and chemistry as probes of the past thermocline: 1. Shell size, Paleoceanography, 5, 55-75, 1990.

Lončarić, N., Peeters, F. J. C., Kroon, D., and Brummer, G.-J. A.: Oxygen isotope ecology of recent planktic foraminifera at the central Walvis Ridge (SE Atlantic), Paleoceanography, 21, PA3009, 2006.

Lototskaya, A. and Ganssen, G. M.: The structure of Termination II (penultimate deglaciation and Eemian) in the North Atlantic, Quaternary Science Reviews, 18, 1641-1654, 1999.

Lototskaya, A., Ziveri, P., Ganssen, G. M., and van Hinte, J. E.: Calcareous nannofloral response to Termination II at 45°N, 25°W (northeast Atlantic), Marine Micropaleontology, 34, 47-70, 1998.

Löwemark, L., Konstantinou, K. I., and Steinke, S.: Bias in foraminiferal multispecies reconstructions of paleohydrographic conditions caused by foraminiferal abundance variations and bioturbational mixing: A model approach, Marine Geology, 256, 101-106, 2008.

Macdonald, R. W., Paton, D. W., Carmack, E. C., and Omstedt, A.: The freshwater budget and under-ice spreading of Mackenzie River water in the Canadian Beaufort Sea based on salinity and $^{18}O/^{16}O$ measurements in water and ice, Journal of Geophysical Research: Oceans (1978–2012), 100, 895-919, 1995.

Malmgren, B. and Kennett, J. P.: Biometric analysis of phenotypic variation in Recent *Globigerina bulloides* d'Orbigny in the southern Indian Ocean, Marine Micropaleontology, 1, 3-25, 1976.

McConnaughey, T. and McRoy, C. P.: ^{13}C label identifies eelgrass (Zostera marina) carbon in an Alaskan estuarine food web, Marine Biology, 53, 263-269, 1979a.

McConnaughey, T. and McRoy, C. P.: Food-web structure and the fractionation of carbon isotopes in the Bering Sea, Marine Biology, 53, 257-262, 1979b.

McIntyre, A., Kipp, N. G., Bé, A. W. H., Crowley, T., Kellogg, T., Gardner, J. V., Prell, W. L., and Ruddiman, W. F.: Glacial North Atlantic 18,000 years ago: A CLIMAP reconstruction, Geological Society of America Memoirs, 145, 43-76, 1976.

McKenna, V. S. and Prell, W. L.: Calibration of the Mg/Ca of *Globorotalia truncatulinoides* (R) for the reconstruction of marine temperature gradients, Paleoceanography, 19, PA2006, 2004.

Mortyn, P. G. and Charles, C. D.: Planktonic foraminiferal depth habitat and ^{18}O calibrations: Plankton tow results from the Atlantic Sector of the Southern Ocean, Paleoceanography, 18, 1037, 2003.

Mulitza, S., Dürkoop, A., Hale, W., Wefer, G., and Stefan Niebler, H.: Planktonic foraminifera as recorders of past surface-water stratification, Geology, 25, 335-338, 1997.

Oppo, D. W. and Fairbanks, R. G.: Carbon isotope composition of tropical surface water during the past 22,000 years, Paleoceanography, 4, 333-351, 1989.

Ortiz, J. D., Mix, A. C., Rugh, W., Watkins, J. M., and Collier, R. W.: Deep-dwelling planktonic foraminifera of the northeastern Pacific Ocean reveal environmental control of oxygen and carbon isotopic disequilibria, Geochimica et Cosmochimica Acta, 60, 4509-4523, 1996.

Ottens, J.: Planktic foraminifera as indicators of ocean environments in the Northeast Atlantic, PhD Academisch Proefschrift, Department of Sedimentary Geology, VU University Amsterdam, Amsterdam, 189 pp., 1992.

Park, M.-H.: Abrupt climatic changes induced by ice-rafting events in the eastern North Atlantic during the late Quarternary: stable isotope and X-ray mineralogical analyses, Geosciences Journal, 2, 59-67, 1998.

Peeters, F. J. C., Brummer, G.-J. A., and Ganssen, G. M.: The effect of upwelling on the distribution and stable isotope composition of *Globigerina bulloides* and *Globigerinoides ruber* planktic foraminifera) in modern surface waters of the NW Arabian Sea, Global and Planetary Change, 34, 269-291, 2002.

Peeters, F. J. C., Ivanova, E., Conan, S., and Brummer, G.-J. A.: A size analysis of planktic foraminifera from the Arabian Sea, Marine Micropaleontology, 1999a. 1999a.

Peeters, F. J. C., Ivanova, E., Conan, S. M. H., Brummer, G.-J. A., Ganssen, G. M., Troelstra, S., and van Hinte, J.: A size analysis of planktic foraminifera from the Arabian Sea, Marine Micropaleontology, 36, 31-63, 1999b.

Phleger, F. B., Parker, F. L., and Peirson, J. F.: North Atlantic Foraminifera, Elanders Boktryckeri Aktiebolag, 1953.

Ravelo, A. C. and Fairbanks, R. G.: Carbon isotopic fractionation in multiple species of planktonic foraminifera from core-tops in the tropical Atlantic, Journal of Foraminiferal Research, 25, 53-74, 1995.

Ravelo, A. C. and Fairbanks, R. G.: Oxygen isotopic composition of multiple species of planktonic foraminifera: recorders of the modern photic zone temperature gradient, Paleoceanography, 7, 815-831, 1992.

Rink, S., Kühl, M., Bijma, J., and Spero, H. J.: Microsensor studies of photosynthesis and respiration in the symbiotic foraminifer *Orbulina universa*, Marine Biology, 131, 583-595, 1998.

Rohling, E. J. and Bigg, G. R.: Paleosalinity and $\delta^{18}O$: a critical assessment, Journal of Geophysical Research: Oceans (1978–2012), 103, 1307-1318, 1998.

Roucoux, K. H., Tzedakis, P. C., De Abreu, L., and Shackleton, N. J.: Climate and vegetation changes 180,000 to 345,000 years ago recorded in a deep-sea core off Portugal, Earth and Planetary Science Letters, 249, 307-325, 2006.

Ruddiman, W. F. and McIntyre, A.: The North Atlantic Ocean during the last deglaciation, Palaeogeography, Palaeoclimatology, Palaeoecology, 35, 145-214, 1981.

Ruddiman, W. F. and McIntyre, A.: Northeast Atlantic paleoclimatic changes over the past 600,000 years, Geological Society of America Memoirs, 145, 111-146, 1976.

Ruddiman, W. F., Raymo, M., and McIntyre, A.: Matuyama 41,000-year cycles: North Atlantic Ocean and northern hemisphere ice sheets, Earth and Planetary Science Letters, 80, 117-129, 1986.

Salmon, K. H., Anand, P., Sexton, P. F., and Conte, M.: Upper ocean mixing controls the seasonality of planktonic foraminifer fluxes and associated strength of the carbonate pump in the oligotrophic North Atlantic, Biogeosciences Discussions, 11, 12223-12254, 2014.

Schiebel, R. and Hemleben, C.: Modern planktic foraminifera, Paläontologische Zeitschrift, 79, 135-148, 2005.

Schmidt, D. N., Elliott, T., and Kasemann, S. A.: The influences of growth rates on planktic foraminifers as proxies for palaeostudies a review, Geological Society, London, Special Publications, 303, 73-85, 2008.

Schmidt, D. N., Lazarus, D., Young, J. R., and Kucera, M.: Biogeography and evolution of body size in marine plankton, Earth-Science Reviews, 78, 239-266, 2006.

Schmidt, D. N., Thierstein, H. R., Bollmann, J., and Schiebel, R.: Abiotic Forcing of Plankton Evolution in the Cenozoic, Science, 303, 207-210, 2004.

Shackleton, N. J.: Attainment of isotopic equilibrium between ocean water and the benthonic foraminiferal genus *Uvigerina*: isotopic changes in the ocean during the last glacial, Cent. Nat. Rech. Sci. Colloq. Int., 219, 203-209, 1974.

Shackleton, N. J.: The high-precision isotopic analysis of oxygen and carbon in carbon dioxide, Journal of Scientific Instruments, 42, 689-692, 1965.

Shackleton, N. J. and Opdyke, N. D.: Oxygen isotope and palaeomagnetic stratigraphy of Equatorial Pacific core V28-238: Oxygen isotope temperatures and ice volumes on a 105 year and 106 year scale, Quaternary Research, 3, 39-55, 1973.

Shackleton, N. J. and Vincent, E.: Oxygen and carbon isotope studies in recent foraminifera from the southwest Indian Ocean, Marine Micropaleontology, 3, 1-13, 1978.

Spear, J. W., Poore, R. Z., and Quinn, T. M.: *Globorotalia truncatulinoides* (dextral) Mg/Ca as a proxy for Gulf of Mexico winter mixed-layer temperature: Evidence from a sediment trap in the northern Gulf of Mexico, Marine Micropaleontology, 80, 53-61, 2011.

Spero, H. J., Bijma, J., Lea, D. W., and Bemis, B. E.: Effect of seawater carbonate concentration on foraminiferal carbon and oxygen isotopes, Nature, 390, 497-500, 1997.

Spero, H. J. and DeNiro, M. J.: The influence of symbiont photosynthesis on the $\delta^{18}O$ and $\delta^{13}C$ values of planktonic foraminiferal shell calcite, Symbiosis, 4, 213-228, 1987.

Spero, H. J. and Lea, D. W.: Experimental determination of stable isotope variability in *Globigerina bulloides*: implications for paleoceanographic reconstructions, Marine Micropaleontology, 28, 231-246, 1996.

Stone, S. W.: Some ecologic data relating to pelagic foraminifera, Micropaleontology, 1956. 361-370, 1956.

Strain, P. M. and Tan, F. C.: Seasonal evolution of oxygen isotope-salinity relationships in high-latitude surface waters, Journal of Geophysical Research: Oceans (1978–2012), 98, 14589-14598, 1993.

Telford, R. J., Li, C., and Kucera, M.: Mismatch between the depth habitat of planktonic foraminifera and the calibration depth of SST transfer functions may bias reconstructions, Climate of the Past, 9, 859-870, 2013.

Thiede, J.: Planktonische Foraminiferen in sedimenten vom ibero-marokkanischen Kontinentalrand, Meteor Forschungsergebnisse C, 15-102, 1971.

Thiede, J.: Shell- and skeleton-producing plankton and nekton in the eastern North Atlantic Ocean, "Meteor" Forschungsergebnisse Herausgegeben von der Deutschen Forschungsgemeinschaft, C, 33-79, 1975.

Tolderlund, D. S. and Be, A. W. H.: Seasonal distribution of planktonic foraminifera in the western North Atlantic, Micropaleontology, 17, 297-329, 1971.

Vergnaud Grazzini, C.: Non-equilibrium isotopic compositions of shells of planktonic foraminifera in the Mediterranean Sea, Palaeogeography, Palaeoclimatology, Palaeoecology, 20, 263-276, 1976.

Vetter, L., Kozdon, R., Mora, C. L., Eggins, S. M., Valley, J. W., Hönisch, B., and Spero, H. J.: Micron-scale intrashell oxygen isotope variation in cultured planktic foraminifers, Geochimica et Cosmochimica Acta, 107, 267-278, 2013.

Vincent, E. and Berger, W. H.: Planktonic foraminifera and their use in palaeoceanography. In: The Sea, Emiliani, C. (Ed.), Wiley-Interscience, New York, 1981.

Volten, H., De Haan, J. F., Hovenier, J. W., Schreurs, R., Vassen, W., Dekker, A. G., Hoogenboom, H. J., Charlton, F., and Wouts, R.: Laboratory measurements of angular distributions of light scattered by phytoplankton and silt, Limnology and Oceanography, 43, 1180-1197, 1998.

Waelbroeck, C., Mulitza, S., Spero, H. J., Dokken, T., Kiefer, T., and Cortijo, E.: A global compilation of late Holocene planktonic foraminiferal ^{18}O: relationship between surface water temperature and ^{18}O, Quaternary Science Reviews, 24, 853-868, 2005.

Wefer, G., Berger, W. H., Bickert, T., Donner, B., Fischer, G., von Mücke, S. K., Meinecke, G., Müller, P. J., Mulitza, S., and Niebler, H.-S.: Late Quaternary surface circulation of the South Atlantic: The stable isotope record and implications for heat transport and productivity. In: The South Atlantic, Springer, 1996.

Weiner, S.: The carbon isotopic composition of the eastern Mediterranean planktonic foraminifera *Orbulina universa* and the phenotypes of *Globigerinoides ruber*, Palaeogeography, Palaeoclimatology, Palaeoecology, 17, 149-156, 1975.

Weinkauf, M. F. G., Moller, T., Koch, M. C., and Kučera, M.: Calcification intensity in planktonic Foraminifera reflects ambient conditions irrespective of environmental stress, Biogeosciences Discussions, 10, 11213-11253, 2013.

Weyl, P. K.: Micropaleontology and Ocean Surface Climate, Science, 202, 475-481, 1978.

Wilke, I., Bickert, T., and Peeters, F. J. C.: The influence of seawater carbonate ion concentration [CO_3^{2-}] on the stable carbon isotope composition of the planktic foraminifera species *Globorotalia inflata*, Marine Micropaleontology, 58, 243-258, 2006.

Williams, D. F., Bé, A. W. H., and Fairbanks, R.: Seasonal stable isotopic variations in living planktonic foraminifera from Bermuda plankton tows, Palaeogeography, Palaeoclimatology, Palaeoecology, 33, 71-102, 1981.

Williams, D. F., Bé, A. W. H., and Fairbanks, R. G.: Seasonal oxygen isotopic variations in living planktonic foraminifera off Bermuda, Science, 206, 447-449, 1979.

Williams, D. F., Ehrlich, R., Spero, H. J., Healy-Williams, N., and Gray, A. C.: Shape and isotopic differences between conspecific foraminiferal morphotypes and resolution of paleoceanographic events, Palaeogeography, Palaeoclimatology, Palaeoecology, 64, 153-162, 1988.

Wit, J. C., Reichart, G. J., and Ganssen, G. M.: Unmixing of stable isotope signals using single specimen $\delta^{18}O$ analyses, Geochemistry, Geophysics, Geosystems, 2013. n/a-n/a, 2013.

Wolfteich, C. M.: Satellite-derived sea surface temperature, mesoscale variability, and foraminiferal production in the North Atlantic, M.Sc., Massachusetts Institute of Technology/Woodshole Oceanographic Institution, 1994. 80pp., 1994.

Figure 1. Location map of the North Atlantic region. Location map of (1) piston core APNAP T90-9p and long term observation stations (2) sediment trap NABE 48 (Wolftreich, 1994) and (3) Ocean Station Delta (Be and Tolderlund, 1971) with main surface ocean currents overlain, colour indicates relative temperature of the dominant water mass with red to blue representing warmest to coolest.

Figure 2. Taxonomy and size of species analysed in this paper. Apertural view of (*Top row*) the 'surface dweller' *Globigerina bulloides*, (*Middle row*) 'intermediate dweller' *Globorotalia inflata* and (*Bottom row*) the 'deep dweller' *Globorotalia truncatulinoides* for the following size fractions: 212-250 μm, 250-300 μm, 300-355 μm and 355-400 μm from a 756 cm depth in core. Scale bar (100 μm) is the same for all images, highlighting the offset between the various size fractions.

Figure 3. Relative abundance and average ~~S~~size of planktonic foraminifera across MIS7 to 8. For reference (~~a~~A) *G. bulloides* single specimen $\delta^{18}O$ values, dashed line represent average $\delta^{18}O$ values. (~~b~~B) Relative abundance of whole sample of *G. bulloides* (blue), *G. inflata* (red) and *G.*

truncatulinoides (green) used to calculate (~~c~~C) the average size, arrows in (~~c~~C) denote the upper and lower limits of the size fractions used in this study. In comparison with abundance and average size (~~d~~D) the relative monthly insolation for the time period has been plotted. Arrows in (~~d~~D) represent expansion and contraction of increased Summer insolation. Dashed vertical lines indicate the minima and maxima in insolation, horizontal bars at top specify samples that contain Heinrich/I.R.D. debris

Figure 4. Single specimen oxygen isotope values. Raw $\delta^{18}O$ values, the symbol size denotes size fraction, for convenience the data points are offset from one another. Shaded regions represent periods where ice rafted debris is present within the core, this envelope however is larger than the actual duration of a Heinrich event as it is difficult to constrain the precise date of such 'old' events.

Figure 5. Mean oxygen isotope values with 95% confidence intervals. Mean $\delta^{18}O$ values for (~~a~~Top panel) *G. bulloides*, (~~b~~Middle panel) *G. inflata* and (~~c~~Bottom panel) *G. truncatulinoides*, colour denotes size fraction. Confidence intervals are based upon using the outlier corrected single specimen data to compute a t based confidence interval ($n < 30$) at the 95% level ($\alpha = 0.05$), assuming that the sample is normally distributed. Insets in (~~b~~Middle panel) show the size versus oxygen isotope for (i) 220.9 kyr reminiscent of the study of Ravelo and Fairbanks (1992) (ii) 239.1 kyr, (iii) 208.9 kyr and (iv) 216.3 kyr. A one sample t-test shows that (i) and (iv) do not have sufficient evidence to reject the null hypothesis (H_0) that the means are different, whereas (ii) and (iii) have sufficient evidence to accept the alternative hypothesis (H_1). ~~(d) Mean insolation for 45°N.~~

Figure 6. Isotope differences for each species between the smallest and largest size fraction. Isotope difference between the mean of the smallest (212-250 μm) and largest (355-400 μm) size fractions of (*Top panel*) $\delta^{18}O$ and (*Bottom panel*) $\delta^{13}C$. The 1:1 (δ-iso line) relationship (grey dashed line) is presented~~, equations of~~ to compare the linear regressions (coloured dashed lines), for the equations of each linear regression and the resultant t-test values ~~are presented~~see ~~in~~ Table 4. The δ-iso lines of *G. truncatulinoides* from Wefer et al. (1996) are presented for comparison.

Figure 7. Single specimen carbon isotope values. Raw $\delta^{13}C$ values, symbol size denotes size fraction, for convenience the data points are offset from one another. Highlighted regions represent the glacial and interglacial Heinrich events (H14 and H15) and Termination III.

Figure 8. Mean carbon isotope values with 95% confidence intervals. (a) For comparative purposes the mean $\delta^{18}O$ values for *G. bulloides*, *G. inflata* and *G. truncatulinoides*. Mean $\delta^{13}C$ values for (b) *G. bulloides*, (c) *G. inflata* and (d) *G. truncatulinoides*, colour denotes size fraction. Highlighted regions represent the glacial and interglacial Heinrich events (H14 and H15) and Termination III.

Figure 9. Crossplot of oxygen and carbon values. Crossplot between mean $\delta^{18}O$ and $\delta^{13}C$ for all size fractions of (a) *G. bulloides* (b) *G. inflata* (c) *G. truncatulinoides* and (d) all species. For (a-c) symbol colour represents size fraction as per figure 5 and 8: 212-250 μm (green), 250-300 μm (red), 300-355 μm (blue) and 355-400 μm (black).

Figure 10. Previous size-isotope relationship. Previously published size isotope trends (i-iii) $\delta^{18}O$ and (iv-vi) $\delta^{13}C$ compared with four samples that represent, based upon the ratio between *Neogloboquadrina pachyderma* and *N. incompta* (Feldmeijer et al., submitted) cold and warm periods of MIS 8 and MIS 7. Additionally an average size-isotope curve was constructed for comparison. Unpublished work of Ganssen ~~is~~ from Indian Ocean core samples.

Figure 11. Schematic diagram of the key hydrological parameters at the core site and the insolation pattern for the studied interval. Ocean reanalysis dataset of (a) Monthly temperatures and (b) Monthly salinity at 5 m water depth for the years 1959-2009, excluding the warming since 2009 (Balmaseda et al., 2013). Using (a) and (b) the (c) oxygen isotope equilibrium was calculated for 5 m (black line), for reference (red line). (d) Oxygen isotope equilibrium ($\delta^{18}O_{eq}$) representing the water structure plotted against time based upon 'an average year' using values of World Ocean Atlas (WOA09) extracted from Ocean Data View (ODV). The main foraminiferal flux, as determined by the North Atlantic Bloom Experiment (NABE) the initial pilot study of the Joint Global Ocean Flux Study (JGOFS), lies between March and July. Maximum insolation occurs in June however the warmest month is later in September/October. Estimated depth habitat of *G. bulloides*, *G. inflata* and *G. truncatulinoides* is 100 m, 400 m and 800 m respectively. Schematically, foraminifera that calcify in (e) the Winter mixed layer are likely to

record similar values for each successive chamber in comparison with those foraminifera that calcify in the (f) seasonal thermocline.

Figure 12. Oxygen isotope of smallest size fraction and differences. (a) The oxygen isotopes between small sized specimens of *G. bulloides*, *G. inflata* and *G. truncatulinoides* and (b) the calculated difference between species ($\Delta\delta^{18}O$).

Table 1. T-test values of oxygen isotope values.

Table 2. Smallest (212-250 µm) -and largest (355-400 µm) size fraction linear regression and T-test values.

Table 3. T-test values of carbon isotope values.

Table 4. Covariance of studied planktonic foraminifera. Test values for covariance and correlation coefficient of *G. bulloides.*

Formatted: Adjust space between Latin and Asian text, Adjust space between Asian text and numbers, Font Alignment: Auto

Formatted: Font color: Black, German (Germany)

1 Table 5. Covariance of studied planktonic foraminifera. Test values for covariance and
2 correlation coefficient of *G. inflata*.
3

Table 1. T-test values of oxygen isotope values.

t-Test values for Oxygen isotopes

	Age (ka)	203.4	204.4	205.7	207.0	208.9	210.7	212.6	214.5	216.3	218.6	220.9	223.2	225.5	227.8	230.1	232.3	234.6	236.8	239.1	240.9	242.8	244.6	246.5	248.4	250.2	252.1	Mean	Standard deviation	T-value for dependent samples§
	Depth in core (cm)	729	732	736	740	744	748	752	756	760	764	768	772	776	780	784	788	792	796	800	804	808	812	816	820	824	828			
Globigerina bulloides	212-250	-0.195	-0.056	-0.256	-1.095	-0.996	-0.201	-0.128	-0.581	-0.427	*-0.462*	-0.373	-0.277	0.072	-0.322	-0.571	-0.044	-0.142	0.157	0.325	-0.529	-0.342	-0.848	-0.420	-0.051	0.138	-0.108	-0.297	0.342	***-4.440***
	212-300	-0.602	-0.493	-0.395	-1.137	-1.199	-0.067	-0.509	-0.501	-0.225	*-0.624*	-0.390	-0.488	-0.258	-0.088	-0.543	-0.326	0.036	-0.126	0.128	-0.756	-0.402	-1.069	-0.600	-0.451	0.055	0.025	-0.423	0.354	***-6.099***
	212-355	-0.232	0.008	0.195	-0.852	-0.537	0.411	0.167	0.166	-0.020	*-0.470*	-0.005	-0.178	0.206	-0.039	-0.707	-0.055	-0.259	-0.101	-0.277	-0.253	-0.196	-1.048	0.080	-0.425	-0.171	0.040	-0.175	0.341	***-2.619***
	250-300	-0.407	-0.437	-0.138	-0.043	-0.203	0.134	-0.382	0.080	0.202	*-0.163*	-0.018	-0.211	-0.330	0.234	0.028	-0.282	0.178	-0.283	-0.197	-0.227	-0.060	-0.221	-0.180	-0.400	-0.083	0.133	-0.126	0.200	***-3.206***
	250-355	-0.036	0.064	0.452	0.242	0.459	0.612	0.294	0.747	0.407	*-0.008*	0.367	0.099	0.134	0.284	-0.136	-0.011	-0.118	-0.258	-0.602	0.276	0.146	-0.200	0.500	-0.374	-0.310	0.149	0.122	0.324	*1.924*
	300-355	0.371	0.501	0.590	0.285	0.663	0.478	0.676	0.667	0.205	*0.155*	0.385	0.310	0.464	0.049	-0.164	0.271	-0.295	0.025	-0.405	0.503	0.206	0.021	0.680	0.026	-0.227	0.016	0.248	0.315	***4.023***
	Mean	-0.184	-0.069	0.074	-0.433	-0.302	0.228	0.020	0.096	0.024	*-0.262*	-0.006	-0.124	0.048	0.020	-0.349	-0.075	-0.100	-0.098	-0.172	-0.164	-0.108	-0.561	0.010	-0.279	-0.100	0.042			
	One sample t-value†	-1.347	-0.463	0.458	-1.588	-0.978	1.725	0.108	0.421	0.187	***-2.110***	-0.041	-1.069	0.395	0.216	**-2.891**	-0.849	-1.364	-1.426	-1.224	-0.845	-1.055	**-2.849**	0.048	**-3.263**	-1.428	1.120			
	p value	0.236	0.663	0.666	0.173	0.373	0.145	0.918	0.691	0.859	***0.089***	0.969	0.334	0.709	0.837	**0.034**	0.435	0.231	0.213	0.276	0.437	0.340	**0.036**	0.963	**0.022**	0.213	0.314			
Globorotalia inflata	212-250	-0.923	*-1.194*	*-1.001*	*-0.758*	-0.833	-0.377	-1.231	*-1.491*	-1.271	*-1.081*	-1.290	-0.684	-0.858	-1.272	-0.835	-1.066	-0.391	0.013	-0.047	*-1.567*	*-1.702*	-1.407	-1.052	-0.954	-1.209	-0.295	-0.953	0.446	***-10.891***
	212-300	-0.617	*-1.390*	*-1.194*	*-0.824*	-1.419	-0.759	-1.713	*-1.299*	-0.621	*-1.047*	-1.306	-0.802	-1.026	-1.201	-0.752	-0.846	-0.484	-0.283	-0.835	*-1.251*	*-1.561*	-1.364	-0.610	-0.899	-0.945	-0.607	-0.987	0.360	***-13.982***
	212-355	-0.739	*-1.183*	*-1.109*	*-0.803*	-1.720	-0.611	-1.495	*-1.630*	-1.313	*-1.192*	-0.999	-0.421	-0.769	-1.555	-0.947	-1.305	-1.070	-0.663	-1.088	*-1.496*	*-1.580*	-1.657	-1.098	-1.444	-1.800	-1.134	-1.185	0.374	***-16.150***
	250-300	0.305	*-0.195*	*-0.194*	*-0.066*	-0.586	-0.383	-0.482	*0.192*	0.650	*0.035*	-0.016	-0.117	-0.168	0.071	0.084	0.219	-0.093	-0.296	-0.788	*0.316*	*0.141*	0.043	0.442	0.054	0.264	-0.312	-0.034	0.325	-0.532
	250-355	0.184	*0.012*	*-0.108*	*-0.045*	-0.887	-0.235	-0.264	*-0.139*	-0.042	*-0.111*	0.291	0.263	0.090	-0.283	-0.112	-0.239	-0.679	-0.676	-1.041	*0.071*	*0.122*	-0.250	-0.046	-0.490	-0.590	-0.839	-0.232	0.362	***-3.272***
	300-355	-0.121	*0.207*	*0.085*	*0.021*	-0.301	0.148	0.219	*-0.331*	-0.691	*-0.145*	0.307	0.381	0.258	-0.353	-0.196	-0.459	-0.586	-0.380	-0.253	*-0.245*	*-0.019*	-0.293	-0.489	-0.545	-0.855	-0.527	-0.199	0.331	***-3.063***
	Mean	-0.318	*-0.624*	*-0.587*	*-0.413*	-0.958	-0.369	-0.828	*-0.783*	-0.548	*-0.590*	-0.502	-0.230	-0.412	-0.766	-0.460	-0.616	-0.551	-0.381	-0.675	*-0.695*	*-0.766*	-0.821	-0.475	-0.713	-0.856	-0.619			
	One sample t-value†	-1.523	***-2.160***	***-2.504***	***-2.403***	**-4.459**	**-2.873**	**-2.651**	***-2.454***	-1.786	***-2.532***	-1.579	-1.151	-1.866	**-2.845**	**-2.583**	**-2.672**	**-4.154**	**-3.585**	**-3.866**	***-2.029***	***-2.015***	**-2.744**	-1.961	**-3.434**	**-3.059**	**-4.695**			
	p value	0.188	***0.083***	***0.054***	***0.061***	**0.007**	**0.035**	**0.045**	***0.058***	0.134	***0.052***	0.175	0.302	0.121	**0.036**	**0.049**	**0.044**	**0.009**	**0.016**	**0.012**	***0.098***	***0.100***	**0.041**	0.107	**0.019**	**0.028**	**0.005**			
Globorotalia truncatulinoides (dextral)	212-250	-1.211	-1.311	-1.223	*-1.477*	-0.979	-1.896	*-1.367*	*-1.889*	-1.882	*-1.604*	*-1.837*	-1.766	-1.447	-1.818	*-1.152*	-2.586	*-1.890*	*-1.772*	-1.655	-1.259	-1.659	-1.407	-1.274	-0.868	-0.759	-0.472	-1.479	0.444	***-16.993***
	212-300	-1.299	-1.619	-1.165	*-1.022*	-1.459	-2.020	*-1.180*	*-2.001*	-2.026	*-1.531*	*-1.851*	-1.390	-1.597	-1.895	*-0.785*	-2.688	*-1.895*	*-1.767*	-1.892	-1.240	-2.104	-1.675	-2.223	-1.560	-1.569	-1.599	-1.656	0.414	***-20.418***
	212-355	-1.469	-1.722	-1.707	*-1.623*	-1.730	-2.155	*-1.504*	*-1.981*	-2.116	*-1.627*	*-1.967*	-1.663	-1.715	-2.148	*-1.431*	-2.132	*-1.964*	*-1.933*	-2.021	-1.881	-1.964	-1.794	-2.121	-1.515	-1.309	-1.426	-1.793	0.257	***-35.602***
	250-300	-0.088	-0.308	0.058	*0.455*	-0.479	-0.125	*0.187*	*-0.111*	-0.144	*0.072*	*-0.013*	0.376	-0.150	-0.076	*0.367*	-0.101	*-0.004*	*0.005*	-0.236	0.019	-0.446	-0.268	-0.949	-0.692	-0.809	-1.126	-0.176	0.388	***-2.318***
	250-355	-0.259	-0.411	-0.484	*-0.146*	-0.750	-0.260	*-0.137*	*-0.092*	-0.233	*-0.023*	*-0.130*	0.103	-0.267	-0.329	*-0.279*	0.455	*-0.073*	*-0.161*	-0.366	-0.622	-0.306	-0.386	-0.847	-0.647	-0.549	-0.954	-0.314	0.302	***-5.293***
	300-355	-0.170	-0.102	-0.542	*-0.601*	-0.271	-0.135	*-0.324*	*0.019*	-0.089	*-0.096*	*-0.117*	-0.272	-0.118	-0.253	*-0.646*	0.556	*-0.069*	*-0.166*	-0.129	-0.641	0.140	-0.118	0.102	0.045	0.260	0.172	-0.137	0.277	***-2.527***
	Mean	-0.749	-0.912	-0.844	*-0.736*	-0.945	-1.098	*-0.721*	*-1.009*	-1.082	*-0.801*	*-0.986*	-0.769	-0.882	-1.086	*-0.654*	-1.083	*-0.983*	*-0.966*	-1.050	-0.937	-1.057	-0.941	-1.219	-0.873	-0.789	-0.901			
	One sample t-value†	**-2.869**	**-3.106**	**-3.247**	***-2.252***	**-4.102**	**-2.643**	***-2.466***	***-2.377***	**-2.601**	***-2.275***	***-2.447***	-1.985	**-2.780**	**-2.773**	***-2.502***	-1.715	***-2.351***	***-2.505***	**-2.876**	**-3.471**	**-2.683**	**-3.016**	**-3.433**	**-3.553**	**-3.028**	**-3.364**			
	p value	**0.035**	**0.027**	**0.023**	***0.074***	**0.009**	**0.046**	***0.057***	***0.063***	**0.048**	***0.072***	***0.058***	0.104	**0.039**	**0.039**	***0.054***	0.147	***0.065***	***0.054***	**0.035**	**0.018**	**0.044**	**0.030**	**0.019**	**0.016**	**0.029**	**0.020**			

† A t distribution two tailed of an α value of 0.05 (95% confidence interval) for n = 6 (d.f. = 5) is 2.571. Shaded columns represent those samples where the null hypothesis, that the samples are not different from one another, is rejected. Italisised columns are those that are rejected at a α value of 0.1 (90% confidence level) of 2.015.

‡ Smallest size fraction minus the larger size fraction

§ A t distribution two tailed of an α value of 0.05 (95% confidence interval) for n = 26 (d.f. = 25) is 2.060. Shaded columns represent those samples where the null hypothesis, that the samples are not different from one another, is rejected. Italisised columns are those that are rejected at a α value of 0.1 (90% confidence level) of 1.708.

Table 2. Smallest and largest size fraction linear regression and T-test values.

Test values for smallest-largest crossplot					
Species	**y = ax+b**		**r^2**	**T test value for r^2†**	**T value‡**
	a	**b**			
Oxygen isotope values					
G. bulloides	0.8033	0.4535	0.6432	6.5776	-1.305
G. inflata	0.5687	1.5919	0.3433	3.5421	-1.288
G. truncatulinoides	0.8929	1.8467	0.6626	6.853	-1.669
Carbon isotope values					
G. bulloides	0.2345	-0.324	0.1315	1.9063	-2.319
G. inflata	0.1277	0.6448	0.1107	1.7284	-3.393
G. truncatulinoides	0.2231	0.7924	0.0775	1.42	-2.887

†Where, H_0: p = 0, H_1: p ≠ 0. Two tailed t-test value for α 0.05 is 2.064

‡Where, H_0: slope = 1, H_1: p ≠ 1. Two tailed t-test value for α 0.05 is 2.064

Table 3. T-test values of carbon isotope values.

t-Test values for Carbon isotopes

	Age (ka)	203.4	204.4	205.7	207.0	208.9	210.7	212.6	214.5	216.3	218.6	220.9	223.2	225.5	227.8	230.1	232.3	234.6	236.8	239.1	240.9	242.8	244.6	246.5	248.4	250.2	252.1	Mean	Standard deviation	T-value for dependent samples§
	Depth in core (cm)	729	732	736	740	744	748	752	756	760	764	768	772	776	780	784	788	792	796	800	804	808	812	816	820	824	828			
Globigerina bulloides	**212-250**	-0.317	0.028	-0.226	-0.331	-0.272	0.138	0.094	0.053	0.197	*0.139*	*-0.567*	-0.394	-0.515	*-0.382*	-0.296	-0.008	0.085	0.357	0.078	*-0.015*	-0.378	-0.612	*-0.766*	0.157	*-0.079*	-0.191	-0.155	0.289	***-2.726***
	212-300	-0.277	-0.079	-0.542	-0.694	-0.917	-0.521	-0.425	-0.256	-0.278	*-0.369*	*-0.475*	-0.278	-0.234	*-0.547*	-0.632	-0.328	0.177	0.070	0.280	*-0.244*	-0.676	-1.020	*-1.156*	-0.412	*-0.021*	-0.285	-0.390	0.341	***-5.838***
	212-355	-0.281	-0.203	-0.513	-0.593	-0.852	-0.607	-0.503	-0.108	-0.122	*-0.346*	*-0.578*	-0.525	-0.587	*-0.421*	-0.574	-0.322	0.098	0.215	-0.030	*-0.154*	-0.820	-0.919	*-0.879*	-0.329	*-0.270*	-0.488	-0.412	0.295	***-7.130***
	250-300	0.041	-0.108	-0.316	-0.363	-0.645	-0.659	-0.519	-0.309	-0.475	*-0.509*	*0.091*	0.116	0.281	*-0.165*	-0.337	-0.321	0.091	-0.287	0.203	*-0.229*	-0.298	-0.409	*-0.390*	-0.570	*0.058*	-0.093	-0.235	0.267	***-4.501***
	250-355	0.036	-0.231	-0.288	-0.262	-0.581	-0.745	-0.596	-0.161	-0.319	*-0.485*	*-0.011*	-0.131	-0.072	*-0.039*	-0.278	-0.315	0.013	-0.142	-0.108	*-0.139*	-0.442	-0.307	*-0.113*	-0.486	*-0.191*	-0.297	-0.257	0.201	***-6.526***
	300-355	-0.005	-0.123	0.029	0.101	0.065	-0.086	-0.077	0.148	0.156	*0.023*	*-0.102*	-0.247	-0.353	*0.126*	0.059	0.006	-0.079	0.145	-0.311	*0.090*	-0.144	0.102	*0.277*	0.083	*-0.249*	-0.204	-0.022	0.160	***-0.699***
	Mean	-0.134	-0.119	-0.309	-0.357	-0.534	-0.413	-0.338	-0.105	-0.140	*-0.258*	*-0.274*	-0.243	-0.247	*-0.238*	-0.343	-0.215	0.064	0.060	0.019	*-0.115*	-0.459	-0.527	*-0.505*	-0.259	*-0.125*	-0.260			
	One sample t-value†	-1.882	**-3.154**	**-3.633**	**-3.136**	**-3.519**	**-2.851**	**-2.966**	-1.461	-1.271	***-2.318***	***-2.233***	**-2.691**	-1.895	***-2.279***	**-3.402**	**-3.175**	1.800	0.617	0.212	***-2.180***	**-4.526**	**-3.112**	***-2.327***	**-2.081**	***-2.325***	**-4.747**			
	p value	0.119	**0.025**	**0.015**	**0.026**	**0.017**	**0.036**	**0.031**	0.204	0.260	***0.068***	***0.076***	**0.043**	0.117	***0.072***	**0.019**	**0.025**	0.132	0.564	0.841	***0.081***	**0.006**	**0.026**	***0.067***	**0.092**	***0.068***	**0.005**			
Globorotalia inflata	**212-250**	-0.644	*-1.022*	-0.817	-0.496	-0.736	-0.307	-0.854	-1.149	-0.754	-0.954	-0.788	*-0.804*	-0.838	-0.841	-0.560	-0.916	-0.589	-0.694	-0.556	-1.086	*-1.083*	-1.273	-0.502	-0.691	-0.788	0.146	-0.754	0.288	***-13.328***
	212-300	-0.454	*-1.075*	-0.913	-0.684	-0.961	-0.499	-1.165	-1.204	-0.821	-1.212	-1.046	*-0.683*	-0.948	-0.842	-0.791	-0.757	-0.585	-0.676	-0.834	-1.038	*-1.230*	-1.394	-0.357	-0.595	-0.595	-0.001	-0.821	0.314	***-13.329***
	212-355	-0.501	*-1.041*	-1.082	-0.651	-1.171	-0.546	-1.227	-1.426	-0.895	-1.217	-0.976	*-0.850*	-1.054	-1.356	-1.167	-1.400	-1.159	-1.039	-1.138	-1.512	*-1.159*	-1.711	-0.676	-0.966	-1.044	-0.288	-1.048	0.325	***-16.444***
	250-300	0.190	*-0.053*	-0.095	-0.188	-0.225	-0.191	-0.312	-0.056	-0.067	-0.258	-0.258	*0.121*	-0.110	-0.001	-0.231	0.159	0.004	0.018	-0.278	0.048	*-0.147*	-0.120	0.145	0.096	0.193	-0.147	-0.068	0.155	***-2.230***
	250-355	0.143	*-0.020*	-0.264	-0.155	-0.435	-0.238	-0.373	-0.277	-0.141	-0.262	-0.188	*-0.046*	-0.217	-0.515	-0.607	-0.484	-0.570	-0.345	-0.582	-0.426	*-0.076*	-0.438	-0.175	-0.276	-0.256	-0.434	-0.295	0.188	***-7.982***
	300-355	-0.047	*0.033*	-0.169	0.033	-0.210	-0.047	-0.062	-0.222	-0.074	-0.004	0.071	*-0.167*	-0.107	-0.515	-0.376	-0.643	-0.574	-0.363	-0.304	-0.474	*0.071*	-0.318	-0.320	-0.372	-0.449	-0.287	-0.227	0.207	***-5.580***
	Mean	-0.219	*-0.529*	-0.557	-0.357	-0.623	-0.305	-0.665	-0.722	-0.459	-0.651	-0.531	*-0.405*	-0.546	-0.678	-0.622	-0.674	-0.579	-0.516	-0.615	-0.748	*-0.604*	-0.876	-0.314	-0.467	-0.490	-0.168			
	One sample t-value†	-1.494	***-2.290***	**-3.179**	**-2.966**	**-3.835**	**-3.936**	**-3.363**	**-2.947**	**-2.789**	**-2.961**	**-2.793**	***-2.342***	**-2.995**	**-3.670**	**-4.623**	**-3.207**	**-3.855**	**-3.460**	**-4.602**	**-3.245**	***-2.418***	**-3.235**	**-2.727**	**-3.109**	**-2.783**	-1.940			
	p value	0.195	***0.071***	**0.025**	**0.031**	**0.012**	**0.011**	**0.020**	**0.032**	**0.038**	**0.032**	**0.038**	***0.066***	**0.030**	**0.014**	**0.006**	**0.024**	**0.012**	**0.018**	**0.006**	**0.023**	***0.060***	**0.023**	**0.041**	**0.027**	**0.039**	0.110			
Globorotalia truncatulinoides (dextral)	**212-250**	-0.656	-0.645	-0.421	-0.715	-0.242	-0.753	-0.587	-1.043	-0.941	-0.656	-0.789	-0.761	-0.735	-0.614	-0.234	-0.916	-0.857	-0.943	-0.627	-0.360	-0.600	0.019	-0.482	-0.264	-0.003	-0.215	-0.578	0.288	***-10.237***
	212-300	-0.805	-0.839	-0.597	-0.684	-0.747	-1.119	-0.680	-1.286	-0.954	-0.946	-1.004	-0.831	-0.999	-0.994	-0.560	-1.021	-1.139	-1.091	-1.004	-0.555	-0.986	-0.651	-1.113	-0.621	-0.491	-0.502	-0.855	0.226	***-19.274***
	212-355	-0.968	-1.039	-0.938	-1.050	-1.023	-1.042	-0.966	-1.296	-1.292	-1.212	-1.208	-0.900	-1.039	-1.012	-0.750	-1.088	-1.415	-1.282	-1.073	-0.858	-0.998	-0.725	-1.111	-0.822	-0.507	-0.700	-1.012	0.208	***-24.814***
	250-300	-0.149	-0.194	-0.175	0.031	-0.506	-0.366	-0.093	-0.243	-0.013	-0.291	-0.215	-0.071	-0.264	-0.379	-0.326	-0.105	-0.282	-0.148	-0.377	-0.195	-0.386	-0.670	-0.631	-0.357	-0.487	-0.286	-0.276	0.174	***-8.084***
	250-355	-0.312	-0.393	-0.517	-0.335	-0.782	-0.289	-0.379	-0.252	-0.351	-0.556	-0.419	-0.140	-0.304	-0.397	-0.516	-0.172	-0.559	-0.339	-0.446	-0.498	-0.398	-0.745	-0.629	-0.557	-0.504	-0.485	-0.434	0.155	***-14.267***
	300-355	-0.163	-0.199	-0.341	-0.366	-0.276	0.077	-0.286	-0.010	-0.338	-0.266	-0.204	-0.069	-0.040	-0.018	-0.190	-0.067	-0.276	-0.191	-0.069	-0.303	-0.012	-0.074	0.002	-0.200	-0.016	-0.199	-0.157	0.127	***-6.312***
	Mean	-0.509	-0.552	-0.498	-0.520	-0.596	-0.582	-0.498	-0.688	-0.648	-0.655	-0.640	-0.462	-0.563	-0.569	-0.430	-0.561	-0.755	-0.666	-0.599	-0.462	-0.563	-0.474	-0.661	-0.470	-0.335	-0.398			
	One sample t-value†	**-3.574**	**-3.880**	**-4.689**	**-3.385**	**-4.734**	**-3.045**	**-3.928**	**-2.891**	**-3.266**	**-4.320**	**-3.700**	**-2.780**	**-3.297**	**-3.603**	**-4.866**	**-2.786**	**-3.968**	**-3.277**	**-3.808**	**-4.831**	**-3.607**	**-3.329**	**-3.857**	**-4.846**	**-3.253**	**-4.932**			
	p value	**0.016**	**0.012**	**0.005**	**0.020**	**0.005**	**0.029**	**0.011**	**0.034**	**0.022**	**0.008**	**0.014**	**0.039**	**0.022**	**0.015**	**0.005**	**0.039**	**0.011**	**0.022**	**0.013**	**0.005**	**0.015**	**0.021**	**0.012**	**0.005**	**0.023**	**0.004**			

† At distribution two tailed of an α value of 0.05 (95% confidence interval) for n = 6 (d.f. = 5) is 2.571. Shaded columns represent those samples where the null hypothesis, that the samples are not different from one another, is rejected. Italisised columns are those that are rejected at a α value of 0.1 (90% confidence level) of 2.015.

‡ Smallest size fraction minus the larger size fraction

§ At distribution two tailed of an α value of 0.05 (95% confidence interval) for n = 26 (d.f. = 25) is 2.060. Shaded columns represent those samples where the null hypothesis, that the samples are not different from one another, is rejected. Italisised columns are those that are rejected at a α value of 0.1 (90% confidence

Table 4. Covariance of studied planktonic foraminifera. Test values for covariance and correlation coefficient of *G. bulloides.*

Depth in Core (cm)	Age (kyr)	*G. bulloides*														
		Covariance				Product of Standard Deviations				Correlation Coefficient				Combined		
		212-250 µm	250-300 µm	300-355 µm	355-400 µm	212-250 µm	250-300 µm	300-355 µm	355-400 µm	212-250 µm	250-300 µm	300-355 µm	355-400 µm	CoVar	StDev. Pr.	Co
729	203.4	0.00	-0.02	0.07	0.19	0.20	0.26	0.27	0.30	0.01	-0.06	0.24	0.65	0.08	0.29	
732	204.4	-0.04	0.01	0.06	0.09	0.19	0.39	0.19	0.36	-0.21	0.02	0.33	0.26	0.03	0.30	
736	205.7	-0.02	0.13	0.20	0.09	0.59	0.52	0.28	0.21	-0.03	0.26	0.72	0.41	0.11	0.43	
740	207.0	0.48	0.16	0.16	0.15	0.72	0.39	0.29	0.33	0.67	0.41	0.55	0.45	0.34	0.55	
744	208.9	0.23	-0.04	-0.09	0.22	0.57	0.40	0.24	0.41	0.41	-0.11	-0.37	0.52	0.14	0.58	
748	210.7	0.17	0.24	0.07	-0.04	0.64	0.48	0.23	0.18	0.27	0.50	0.30	-0.20	0.05	0.44	
752	212.6	-0.03	0.11	0.07	0.13	0.26	0.32	0.29	0.33	-0.12	0.35	0.26	0.40	0.06	0.39	
756	214.5	0.00	0.20	0.12	0.07	0.19	0.38	0.21	0.27	0.00	0.53	0.57	0.27	0.09	0.31	
760	216.3	0.32	0.08	0.04	0.00	0.56	0.25	0.17	0.22	0.56	0.34	0.22	-0.01	0.09	0.33	
764	218.6	0.22	0.09	0.11	0.20	0.31	0.31	0.22	0.32	0.71	0.28	0.48	0.64	0.17	0.32	
768	220.9	0.25	0.11	-0.01	0.07	0.34	0.24	0.22	0.19	0.75	0.45	-0.03	0.35	0.12	0.30	
772	223.2	0.37	0.08	0.02	0.12	0.63	0.29	0.24	0.18	0.58	0.27	0.09	0.65	0.14	0.37	
776	225.5	0.34	0.20	0.05	0.11	0.59	0.39	0.34	0.21	0.58	0.51	0.16	0.51	0.14	0.42	
780	227.8	0.14	0.07	-0.03	0.02	0.33	0.40	0.29	0.21	0.44	0.17	-0.12	0.08	0.08	0.34	
784	230.1	0.24	0.07	0.02	0.09	0.52	0.29	0.33	0.29	0.47	0.24	0.05	0.32	0.16	0.44	
788	232.3	0.08	0.14	0.01	0.02	0.24	0.42	0.34	0.33	0.32	0.34	0.04	0.07	0.07	0.34	
792	234.6	0.52	-0.06	-0.04	0.04	0.66	0.28	0.20	0.16	0.79	-0.23	-0.20	0.26	0.12	0.35	
796	236.8	0.42	0.17	0.01	0.02	0.66	0.41	0.19	0.26	0.64	0.42	0.03	0.09	0.15	0.39	
800	239.1	0.15	0.38	0.04	0.06	0.40	0.46	0.28	0.12	0.38	0.83	0.13	0.49	0.15	0.33	
804	240.9	0.27	0.13	0.00	0.09	0.53	0.33	0.13	0.15	0.51	0.38	0.01	0.58	0.14	0.33	
808	242.8	0.10	0.22	0.07	0.01	0.35	0.31	0.25	0.27	0.27	0.71	0.27	0.03	0.11	0.36	
812	244.6	0.07	0.15	-0.06	0.07	0.41	0.24	0.35	0.24	0.16	0.64	-0.17	0.28	0.22	0.47	
816	246.5	0.13	0.05	0.16	0.04	0.38	0.20	0.29	0.22	0.35	0.26	0.53	0.17	0.15	0.38	
820	248.4	0.00	0.10	0.08	0.06	0.57	0.47	0.44	0.26	0.01	0.22	0.19	0.24	0.10	0.49	
824	250.2	0.09	-0.06	0.01	-0.02	0.41	0.31	0.26	0.18	0.23	-0.19	0.03	-0.10	0.01	0.29	
828	252.1	-0.08	-0.05	0.07	0.01	0.39	0.26	0.25	0.11	-0.20	-0.20	0.30	0.12	-0.01	0.26	
									Average	**0.33**	**0.28**	**0.18**	**0.29**		Average	

Table 5. Covariance of studied planktonic foraminifera. Test values for covariance and correlation coefficient of *G. inflata*.

Depth in Core (cm)	Age (kyr)	***G. inflata***														
		Covariance				Product of Standard Deviations				Correlation Coefficient				Combined		
		212-250 µm	250-300 µm	300-355 µm	355-400 µm	212-250 µm	250-300 µm	300-355 µm	355-400 µm	212-250 µm	250-300 µm	300-355 µm	355-400 µm	CoVar	StDev. Pr.	Corr. Coef.
729	203.4	0.18	0.04	0.00	0.01	0.26	0.08	0.14	0.05	0.67	0.47	0.01	0.24	0.17	0.24	0.69
732	204.4	0.13	0.04	-0.02	0.06	0.26	0.16	0.09	0.11	0.51	0.22	-0.18	0.55	0.29	0.39	0.74
736	205.7	0.25	0.07	0.01	0.06	0.30	0.13	0.07	0.08	0.84	0.52	0.17	0.70	0.26	0.33	0.81
740	207.0	0.15	0.02	0.06	0.00	0.25	0.11	0.10	0.08	0.60	0.15	0.56	-0.04	0.14	0.24	0.60
744	208.9	0.18	0.07	0.00	0.03	0.27	0.16	0.14	0.09	0.67	0.43	-0.03	0.32	0.34	0.44	0.76
748	210.7	0.28	0.10	0.07	0.01	0.38	0.29	0.19	0.07	0.73	0.34	0.36	0.10	0.16	0.28	0.56
752	212.6	0.23	0.05	0.02	0.04	0.34	0.13	0.08	0.09	0.67	0.42	0.20	0.43	0.42	0.49	0.84
756	214.5	0.18	0.02	0.01	0.11	0.27	0.10	0.08	0.18	0.68	0.20	0.17	0.60	0.46	0.54	0.84
760	216.3	0.24	0.47	0.02	0.05	0.35	0.60	0.07	0.16	0.69	0.79	0.21	0.30	0.40	0.56	0.71
764	218.6	0.44	0.28	0.02	0.07	0.51	0.52	0.15	0.10	0.87	0.55	0.11	0.70	0.49	0.61	0.80
768	220.9	0.17	0.03	0.01	0.03	0.24	0.09	0.12	0.09	0.71	0.29	0.07	0.36	0.30	0.40	0.75
772	223.2	0.21	0.04	0.06	0.02	0.25	0.14	0.10	0.08	0.83	0.30	0.57	0.26	0.20	0.29	0.68
776	225.5	0.16	0.05	0.05	0.09	0.24	0.16	0.12	0.16	0.65	0.29	0.45	0.57	0.28	0.39	0.73
780	227.8	0.08	0.04	0.07	0.01	0.13	0.12	0.18	0.08	0.59	0.31	0.39	0.08	0.36	0.46	0.78
784	230.1	0.11	0.02	0.02	0.03	0.20	0.11	0.08	0.12	0.54	0.16	0.20	0.28	0.23	0.34	0.69
788	232.3	0.37	0.01	0.09	0.06	0.55	0.17	0.26	0.27	0.67	0.03	0.33	0.23	0.41	0.57	0.72
792	234.6	0.10	0.08	0.05	-0.01	0.19	0.29	0.19	0.11	0.56	0.28	0.28	-0.12	0.21	0.36	0.58
796	236.8	0.24	0.11	0.00	0.05	0.36	0.56	0.11	0.12	0.67	0.20	-0.01	0.42	0.20	0.51	0.39
800	239.1	0.23	0.40	0.02	0.11	0.55	0.54	0.19	0.14	0.42	0.75	0.08	0.78	0.39	0.61	0.64
804	240.9	0.34	0.03	0.01	0.10	0.52	0.21	0.18	0.24	0.66	0.12	0.06	0.42	0.42	0.60	0.70
808	242.8	0.39	0.16	-0.02	0.03	0.45	0.26	0.12	0.10	0.86	0.62	-0.17	0.30	0.45	0.58	0.78
812	244.6	0.35	0.20	0.14	0.01	0.46	0.29	0.23	0.10	0.75	0.70	0.60	0.09	0.60	0.72	0.82
816	246.5	0.27	0.02	0.01	-0.03	0.54	0.19	0.11	0.13	0.51	0.08	0.05	-0.23	0.15	0.33	0.45
820	248.4	0.37	0.04	0.00	0.08	0.48	0.24	0.09	0.21	0.77	0.15	-0.02	0.37	0.29	0.43	0.68
824	250.2	0.07	0.04	0.03	0.03	0.15	0.17	0.18	0.13	0.45	0.25	0.17	0.25	0.30	0.41	0.72
828	252.1	0.01	0.02	0.08	0.10	0.27	0.27	0.21	0.18	0.04	0.07	0.39	0.54	0.11	0.35	0.30
									Average	**0.64**	**0.33**	**0.19**	**0.33**		Average	**0.68**