Thermocline state change in the Eastern Equatorial Pacific during the late Pliocene/early Pleistocene intensification of Northern Hemisphere Glaciation

- Response to Reviewer #2 -

We thank Reviewer #2 for his/her careful and thorough assessment of our manuscript. Below, we provide a point-by-point response to all comments and suggestions made by Reviewer #2.

Response to general comments

R.2.1: "The paper by Jakob et al focusses on a new high resolution paleoceanographic record of the onset of the large Northern Hemisphere Glaciations at the Plio-Pleistocene transition 2.6 Myrs ago. The authors have documented changes in the surface hydrography at Site 849, in the Eastern Equatorial Pacific, based on coupled δ^{18}O and Mg/Ca in *G. ruber*, record mostly published in previous papers by the same group, and compare this record with a new *G. crassaformis* δ^{18}O/Mg/Ca record interpreted as a deep-thermocline species. Those geochemical datasets are augmented with a record of sediment fluxes and with some countings of *G. crassaformis* and *G. menardii/G. tumida*. Using the difference in the temperature records and δ^{18}O, the authors describe what they think changes in the EEP thermocline, with a thermocline shoaling until 2.55 Myr followed by a stable thermocline. The article is a welcome addition as it does document in the EEP a Mg/Ca record for a deep-dwelling species.

The manuscript is well written and the figures are also generally well crafted. As this is the third manuscript on the same record, the paper also details what are the novelties compared to the previous records. I do feel that the technical issues are well thought out, e.g. the potential impact of Mn crusts on the Mg composition of the foraminiferal calcite is ruled out with some backed up arguments (but missing the Pena et al., 2005 study which worked in the EEP to estimate the impact of these crusts on the Mg/Ca of foraminifera). On the choice of the calibration used, the authors are also quite careful, and do pick the Cléroux et al. calibration quite sensibly."

We thank the reviewer for this positive assessment.

R.2.2: "My main comment on the manuscript, is that it does miss a real discussion. Symptomatically, the authors did not compare their records to any other records either from the same region or from more remote sites, which would have lent some weight to their hypothesis."

We agree with Reviewer #2 and acknowledge that our original manuscript has not presented a comparison of thermocline data from our study site with other datasets revealing thermocline evolution for the same time interval. To account for this comment made by both reviewers, we will compare thermocline data from Site 849 to the following datasets of the same time interval (to provide maximum clarity for the readers, we plan to also modify Figure 1 by showing – in addition to the two maps already presented – a global map indicating the location of all sites that will be mentioned in the text):

(i) Geochemical (δ^{18}O and Mg/Ca) data of *G. crassaformis* from eastern tropical Indian Ocean Site 214 (Karas et al., 2009; Fig. S2.1c). For a detailed discussion see our response to comment R.2.3.

(ii) Geochemical (δ^{18}O and Mg/Ca) data of *G. tumida* from eastern tropical Pacific Site 1241 (Steph et al., 2010; Fig. S2.1c). For a detailed discussion see our response to comment R.1.2 by Reviewer #1.

(iii) Surface-to-thermocline (*G. sacculifer* to *N. dutertrei*) Mg/Ca-based temperature gradients from eastern tropical Pacific Site 1241 (Groeneveld et al., 2014; Fig. S2.1a,b). For a detailed discussion see our response to comment R.1.3 by Reviewer #1.

(iv) Alkenone-based sea-surface temperatures (SSTs) from Site 1090 in the Southern Ocean (i.e., the source region for waters upwelled in the Eastern Equatorial Pacific [EEP]) (Martínez-Garcia et al., 2010). For a detailed discussion see our response to comment R.2.3.

We note that in comparison to the Mg/Ca-based temperature data of *G. tumida* yet available for our study site and target interval (~15.5–17.5 °C; Ford et al. [2012]; Fig. S2.1c) our *G. crassaformis* temperatures (1.0–11.6 °C) appear to be relatively low. The *G. tumida*-based temperature record of Ford et al. (2012) is, however, of low temporal resolution, with only six datapoints for the 2.75–2.4 Ma interval. Therefore we argue that this comparison is not robust enough to warrant further discussion in the revised version of the manuscript.

R.2.3: "The Mg/Ca values measured in *G. crassaformis* are quite low, and give some very low temperature range, mostly between 1 to 6 °C (regardless of the calibration used is the one by Cléroux or the one by Regenberg). Those temperatures appear to be even colder than modern temperature at the sites, and it is unlikely that the LGM temperatures were much colder than 1. I am thus puzzled by those extremely low temperatures, though one might argue that they are close to the Tcrassa inferred at site DSDP214. Moreover the temperatures at the site 849 are much colder than surface subantarctic waters during the same time interval (site 1090). I would like to have some sense of the process by which the water masses where
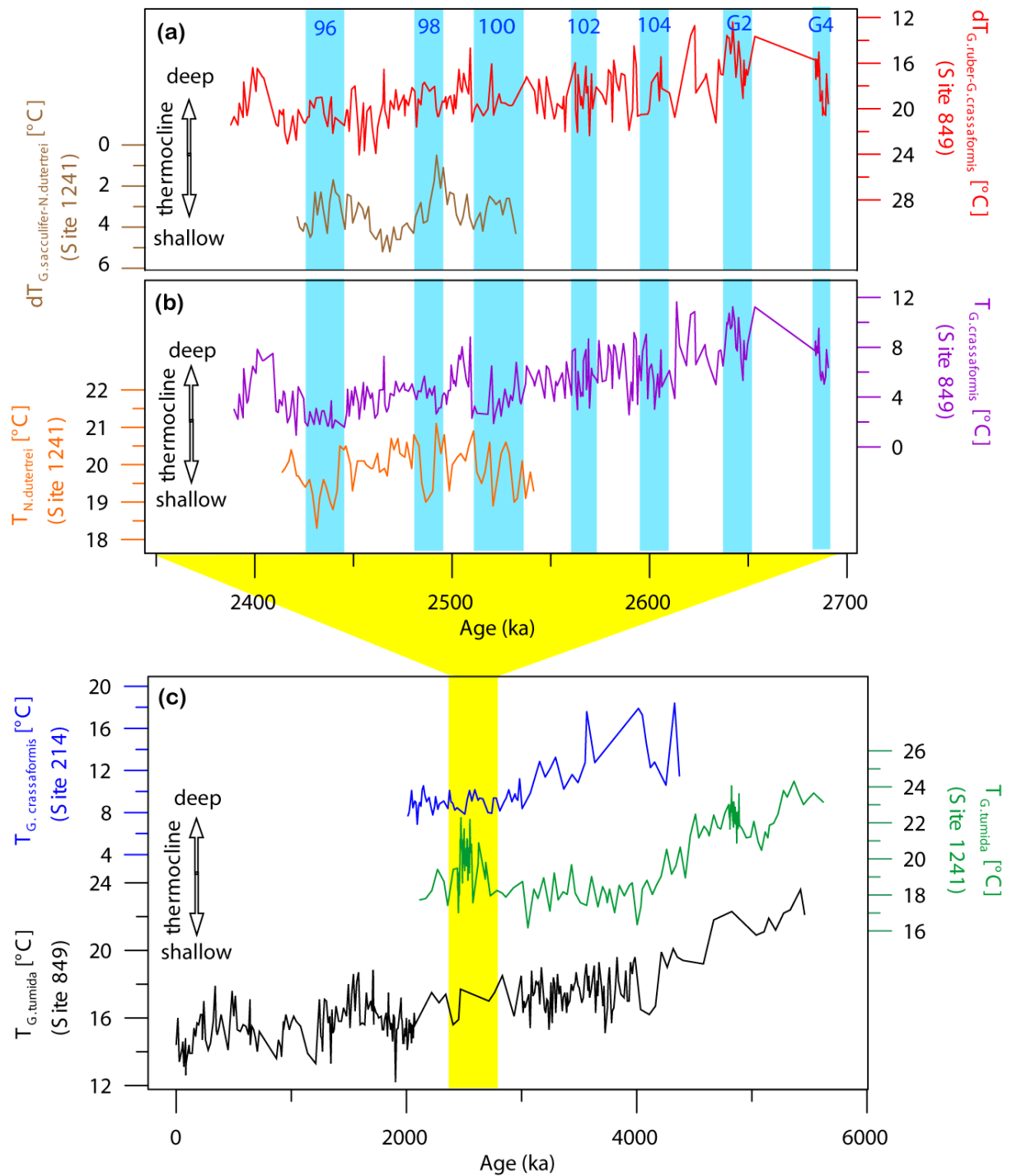
Figure S2.1: Comparison of thermocline proxy records. (a) Stratification data (surface-to-thermocline temperature gradient) for Site 849 in the EEP upwelling regime (this study; red) and Site 1241 in the East Pacific Warm Pool (Groeneveld et al., 2014; brown) for ~2.7–2.4 Ma. (b) Thermocline temperatures based on *G. crassaformis* at Site 849 in the EEP upwelling regime (this study; purple) and based on *N. dutertrei* at Site 1241 in the East Pacific Warm Pool (Groeneveld et al., 2014; orange) for ~2.7–2.4 Ma (c) Thermocline temperatures from Site 214 in the tropical eastern Indian Ocean (based on *G. crassaformis*; Karas et al., 2009; blue), Site 1241 in the East Pacific Warm Pool (based on *G. tumida*; Steph et al., 2010; green) and Site 849 in the EEP upwelling regime (based on *G. tumida*; Ford et al., 2012; black) for the past ~6 Myr. Blue bars in (a) and (b) highlight glacial periods. Yellow bar in (c) marks our study interval.

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G. crassaformis do live would be much colder in the equatorial Pacific than in subantarctic waters."

We agree with Reviewer #2 that temperatures reconstructed from *G. crassaformis* (~1–11.6 °C; Fig. 5d) are difficult to reconcile with

(i)   thermocline temperatures of the Last Glacial Maximum in the eastern tropical Pacific (~14 to 16 °C inferred from Mg/Ca data of *N. dutertrei* from the Cocos and Carnegie Ridges [Hertzberg et al., 2016] and of *G. tumida* from Site 849 [Ford et al., 2015], respectively);

(ii) modern bottom-water temperatures at our study site of about ~1.5 °C (Locarnini et al., 2013) – note that because the exact calcification depth of *G. crassaformis* in the EEP remains unclear, a direct comparison to modern temperatures of an assumed *G. crassaformis* calcification depth (~400–800 m, equal to ~5–8 °C at Site 849; Fig. 1b) is not straight forward (for details see our response to comment R.2.15);

(iii) SSTs of ~10.5–17 °C during our study interval at Site 1090 (Martínez-Garcia et al., 2010) in the Southern Ocean that provides source waters for the EEP upwelling region (we are aware that Site 1090 is not on the direct trajectory from the Southern Ocean to the EEP; however, this site is accepted as the best end member of Southern Ocean waters currently available [Billups et al., 2002; Pusz et al., 2011]).

Although our temperature record of *G. crassaformis* appears to be too cold in comparison to the above-mentioned data, it is close to the temperature range inferred for Site 214 in the tropical eastern Indian Ocean for the same species and time interval (~8–10 °C; Karas et al, 2009; Fig. S2.1). This makes it reasonable to assume that our *G. crassaformis*-based temperature record indeed reflects realistic values. However, thermocline temperatures of ~1–11.6 °C at low-latitude Sites 214 and 849 are difficult to reconcile with SSTs of ~10.5–17 °C at high-southern-latitude Site 1090 during the same time interval. This temperature difference implies that there must have been substantial cooling of Southern Ocean surface-waters (i) either when being downwelled and transported to the lower latitudes and/or (ii) through mixing with Antarctic Bottom Waters, which presently has a bottom-water temperature of about 0 °C (Craig and Gordon, 1965). In this context, it is important to note that very low *G. crassaformis*-based temperatures at Site 849 of ~1 °C result from only one datapoint, while temperatures typically higher than 2–3 °C during the remaining target interval even during most prominent glacials of the intensification of Northern Hemisphere Glaciation can be reconciled better with the mixing hypothesis presented above.

To account for the reviewer's comment, we will briefly elaborate on absolute temperature estimates derived from *G. crassaformis* in comparison to other datasets. This discussion will go into Section 5.3 ("Stable-isotope and Mg/Ca records of *G. crassaformis* and *G. ruber* at Site 849").

R.2.4: "The location of the Site ODP849 is at the edge of the cold tongue. Deglacial studies have shown that this cold tongue did migrate both longitudinally, but also latitudinally (e.g. Koutavas et al. 2003). I wonder if one might not interpret the subtle changes in the record as a long term shift the EEP rather than a subsurface process."

We agree that there is a migration of the cold tongue over glacial-interglacial timescales that can be reconstructed using an approach as exemplified in the study of Koutavas et al. (2003). For the studied time interval, however, the amount of sites (both with the required temporal resolution and preservation of foraminiferal tests) that would be required for such a study is simply not available. Furthermore, the migration mentioned by Reviewer #2 occurs on a glacial-interglacial timescale, while the changes inferred from our data show no significant changes on these short timescales, but rather a long-term shift in thermocline depth. Therefore, we acknowledge the comment of Reviewer #2, but are unfortunately not able to include this kind of information in our contribution.

R.2.5: "I am puzzled by the number of *G. crassaformis* found in the record, reaching at sometimes close to 30 % of the >250 μm. Though the comparison with modern and LGM census of planktonic foraminifera is not straight forward, as late Pleistocene counts are based on the >150 μm fraction, I am surprised that core-top data show extremely low percentages of *G. crassaformis* (typically below 1 %, exceptionally reaching 5 %), far less with results from this study. I understand that the authors do have some arguments that the dissolution is limited at this site (fragmentation index for example), yet I cannot find an alternate process that would selectively get rid of most of the surface to subsurface species."

We respectfully disagree with the reviewer that high percentages of *G. crassaformis* within the planktic foraminiferal assemblage observed at Site 849 can only be explained by selective dissolution of less resistant planktic foraminifera such as *Globigerinoides* (Dittert et al., 1999). The overall good preservation and lack of significant changes in preservation between glacials and interglacials (Fig. 3) along with the low fragmentation index (Jakob et al., 2017) argue against preservation playing a significant role. Another possibility might be that living conditions (e.g., oxygen content in case of *G. crassaformis* [Jones, 1967; Kemle von Mücke

and Hemleben, 1999]) changed over time. In our manuscript we argue that increasing *G. crassaformis* abundances from ~2.64 Ma (MIS G2) onward (Fig. 6c) can be explained by changing environmental conditions that were more favourable for this species. This line of argument can also be used to explain lower percentages of *G. crassaformis* in the modern as opposed to our target interval assuming less favourable living conditions.

R.2.6: "The ΔT record does not show any glacial/interglacial dynamics. This is quite surprising as there are a large number of studies (modelling and observational) that have shown some changes in the thermocline depth during the most recent glacial/interglacial transitions. I wonder then if the choice of picking a quite deep species (see below) and a shallow species such as *G. ruber* does really reflect changes in the thermocline. Species such as *G. tumida, G. menardii,* or *N. dutertrei* living closer to the thermocline would have been more sensitive to changes. I would therefore be grateful if the authors could add some lines on how they can groundcheck their proxy of the thermocline?"

Again, we thank the reviewer for this constructive comment. First, we want to shed light onto the applicability of our approach for surface-to-thermocline (i.e., *G. ruber* to *G. crassaformis*) gradient calculation. Subsequently, we present a more detailed discussion of our ΔT record also in comparison to previous studies:

(i) To reconstruct thermocline changes, we decided to focus on $\delta^{18}O$ and temperature gradients between sea-surface and thermocline waters. *Globigerinoides ruber* lives in the mixed layer, and as one of the shallowest-dwelling species among modern planktic foraminifera it is typically used as recorder for surface-water (mixed-layer) conditions (e.g., Dekens et al., 2002; Rippert et al., 2016); therefore we decided for this species as surface-water recorder.

As a recorder for thermocline waters, we selected *G. crassaformis* because ongoing studies suggest that this species is rather conservative in its preferred calcification depths, although the life cycle of deep-dwelling planktic foraminifera can involve a vertical migration through the water column of several hundred meters. Instead, *G. crassaformis* specimens are suggested to mainly calcify below the thermocline (Regenberg et al., 2009, Steph et al., 2009, and references therein) by maintaining a more constant depth habitat near the base of the thermocline through time compared to other deep-dwellers (Cléroux and Lynch-Stieglitz, 2010). Therefore, it is reasonable to assume that this species is a suitable recorder for deep-thermocline conditions, which led us to compare surface-water records of *G. ruber* to records of the deep-thermocline-dwelling species *G. crassaformis*

rather than to intermediate-dwelling species such as *G. tumida*, *G. menardii*, or *N. dutertrei* as a proxy for thermocline state changes.

Moreover, the selected approach has been successfully applied to previous studies on surface-water structure and thermocline evolution (e.g., Karas et al., 2009; Bahr et al., 2011). To account for the reviewer's comment and to enhance clarity for the readers, we will include information on the overall applicability of the selected approach for tracing thermocline changes into Sections 3 ("Investigated foraminiferal species") and 5.4.1 ("Geochemical evidence").

(ii) The reviewer is correct in stating that a number of previous studies showed thermocline changes on glacial-interglacial timescales across the Last Glacial Maximum in the tropical Pacific. However, it remains unclear whether the thermocline shoaled (e.g., Andreasen and Ravelo, 1997; Lynch-Stieglitz et al., 2015) or deepened (DiNezio et al., 2011) during the Last Glacial Maximum. Across our study interval, there are both model- and proxy-based studies that indicate no glacial-interglacial changes in thermocline depth in the EEP (Lee and Poulson, 2005; Bolton et al., 2010; Jakob et al., 2017). In accordance with these studies, we therefore suggest that our new ΔT (and $\Delta\delta^{18}O$) records indeed reflect a true signal of thermocline development for the EEP cold tongue, i.e., no change in thermocline depth on the glacial-interglacial timescale during the late Pliocene to early Pleistocene (Fig. 6b). Instead, work of Groeneveld et al. (2014), which hints at glacial-interglacial changes in thermocline depth at Site 1241 (Fig. S2.1), is based on a site located outside the equatorial upwelling regime. Data from this site might reflect a more local signal than sites from the EEP cold tongue, possibly rather being related to glacioeustatically induced openings and closures of the Central American Seaway during that time (for details see our response to comment R.1.3 by Reviewer #1).

To account for the comment of Reviewer #2, we will extend the paragraph dealing with the glacial-interglacial evolution of the thermocline at Site 849 and its comparison to other datasets from the same time interval (Section 5.4.1, "Geochemical evidence").

R.2.7: "The living depth of *G. crassaformis* in this study is supposed to be within the 500 to 1000 m range. To set the record straight, the authors have to be clear that they think that the "calcification range" of *G. crassaformis* is within this range. All the studies quoted by the paper to posit this range come from surface sediment samples, in which the authors have made the assumption that the isotopic temperature reflects the calcification depth. This is different from the actual mean living depth. As a couple of examples, the paper by Jones (1967)

in the equatorial Atlantic did find most *G. crassaformis* at depths ranging 200 to 300 meters, not below 500 meters. The authors also quote Wejnert et al. 2013 indicating a calcification depth below 500 meters. This is not what the paper states, as they indicate that the range is above 300 meters. Please correct accordingly."

We agree with Reviewer #2 and have to acknowledge that we incorrectly mixed the terms "habitat depth" and "calcification depth"; the relevant paragraph will be corrected as follows:

(i)   In accordance with our response to comment R.2.6, we will state that *G. crassaformis* lives at the bottom of the thermocline (Niebler et al., 1999; Regenberg et al., 2009, Steph et al., 2009, and references therein) with a rather conservative calcification depth as opposed to other deep-dwelling foraminiferal species (Cléroux and Lynch-Stieglitz 2010).

(ii) Since the exact calcification depth of *G. crassaformis* in the EEP is unclear, we will use calcification depths of this species determined by $\delta^{18}O$ values in the (sub-)tropical Atlantic and Caribbean Sea (~400 to 800 m water depth) (Steph et al., 2006; Regenberg et al., 2009; Steph et al., 2009; Cléroux et al., 2013).

(iii) Finally, we will also note that there are other parts in the ocean where the calcification depth of *G. crassaformis* seems to be shallower (<300 m), such as in the Cariaco Basin (Tedesco et al., 2007; Wejnert et al., 2013).

Response to line by line remarks:

R.2.8: "note [page 2]: One might also consider the last major tipping climate history: The Holocene to Anthropocene transition or the last deglaciation. Please reword more carefully."
We agree with Reviewer #2 and will reword the relevant sentences as suggested.

R.2.9: "note [page 2]: I would tend to think that it is not the shallow depth of the thermocline that exerts a role in the ENSO, but rather the reverse. So please reword in thinking the Eastern Pacific Ocean as a part of the ocean where atmospheres and surface oceanic layers are subtlety interconnected."
Again, we agree with the reviewer and will rephrase the respective paragraphs in the abstract and introduction as suggested.

R.2.10: "note [page 2]: I understand the framing in two alternate hypotheses, but there is also a mid-ground solution where the state of the equatorial Pacific did play a substantial role,

without being the main climatic ruler. Moreover, if one would really test the role of the EEP, he would have to reconstruct the dynamics of the equator to pole gradient."

Indeed, such a test of the role of the EEP would require a much larger dataset and comparison to other sites and records. Since this would be beyond the scope of our contribution, we will rephrase the respective paragraph to account for this comment by Reviewer #2.

R.2.11: "note [page 2]: 'We use planktic (both sea-surface- and thermocline-dwelling) foraminiferal geochemical (^{18}O, ^{13}C and Mg/Ca) proxy records in combination with sedimentlogical (sand-accumulation rates) and faunal (abundance data of thermocline-dwelling foraminiferal species) information to reconstruct thermocline depth for the final phase of the late Pliocene/early Pleistocene iNHG from 2.75 to 2.4 Ma (MIS G7–95)': This final sentence of the introduction, which sums up the methods should be either moved in the methods, or argumented."

In line with the reviewer's comment, this paragraph will be moved to Section 4 ("Material and methods").

R.2.12: "note [page 6]: The use of this very large size fraction is not regularly used. Could you elaborate on this choice?"

We are admittedly not sure if Reviewer #2 refers to the size fraction of *G. crassaformis* tests (315–400 µm) used for geochemical analyses or the size fraction selected for foraminiferal abundance counts (>250 µm). Therefore we will briefly elaborate on both aspects in the following:

(i) Geochemical analyses of *G. crassaformis* tests (315–400 µm):

A study that explores the relationship between the shell size of *G. crassaformis* and δ^{18}O, δ^{13}C and Mg/Ca shows less variations for all parameters for the >300 µm fraction as opposed to the <300 µm fraction (Elderfield et al., 2002) and validates the use of a size fraction >300 µm. Finally, the 315–400 µm fraction has been selected in order to keep ontogenetic effects as small as possible (Elderfield et al., 2002; Friedrich et al., 2012), but at the same time to allow a sufficient number of *G. crassaformis* tests per sample. Moreover, the selected size fraction has also typically been used for geochemical analyses of *G. crassaformis* tests in earlier studies (e.g., Steph et al., 2006; Karas et al., 2011).

It is further important to note that the geochemical records of *G. crassaformis* presented in Jakob et al. (2016) to be complemented in this study are based on the 315–400 µm

size fraction as well. To remain consistent, we used the same size fraction in this study. To provide maximum clarity for the readers, we will rephrase the relevant sentences.

(ii) Foraminiferal abundance counts (>250 µm):

There are studies in which the >250 µm fraction is used for abundance counts of thermocline-dwelling species (e.g., Sexton and Norris, 2008). However, the reviewer is correct in stating that for abundance counts of the entire planktic foraminiferal assemblage (i.e., thermocline- and surface-dwelling species) smaller fractions (>63 µm or >125 µm) are typically investigated (e.g., Jehle et al., 2015; Luciani et al., 2017). The use of different size fractions for the purpose of abundance counts on thermocline-dwelling *versus* all planktic species is justified by the fact that test sizes are typically larger (smaller) in thermocline-dwelling (surface-dwelling) species (e.g., Davis, et al., 2013, and references therein; Feldmeijer et al., 2015). To account for the reviewer's comment, relevant references will be added.

R.2.13: "note [page 7]: A low fragmentation index might also correspond to the selective preservation of only resistant species. Please rephrase this sentence."

The reviewer is correct in stating that a low planktic foraminiferal fragmentation index might indicate either a good preservation of the entire planktic foraminiferal assemblage or the selective preservation of only resistant species, while less resistant species have been dissolved. However, we suggest that a low planktic foraminiferal fragmentation index at Site 849 indicates a generally good foraminiferal preservation, because also less resistant species such as *Globigerinoides* (see for example Tab. 1 in Dittert et al., 1999) occur in large numbers in these samples and are also well preserved (Fig. 3). Instead, if a low planktic foraminiferal fragmentation index indicated selective preservation of only resistant species, a substantially reduced number of *Globigerinoides* (and a poor preservation state of those individuals preserved) would be expected.

To account for the reviewer's comment, the relevant sentence in Section 5.1 ("Foraminiferal test preservation at Site 849") will be rephrased as suggested.

R.2.14: "note [page 7]: Please be more specific: What is the seasonality at the location of the site? Even though it might be significantly different, it cannot be ruled out without testing it."

Modern seasonal changes in SSTs at Site 849 have an amplitude of about ~0.4 °C (~24 °C during summer [June] *versus* ~23.6 °C during winter [January]; Locarnini et al. [2013]). The same seasonality (amplitude of ~0.4 °C) has been observed for 20 m water depth (Locarnini

et al., 2013), i.e, the assumed mean depth habitat of the herein investigated foraminiferal species *G. ruber* (Wang, 2000). Determining seasonal temperature variations at a depth corresponding to the calcification depth of *G. crassaformis* is not straight forward since its calcification depth remains uncertain in the EEP (for details see our response to comment R.2.15). We suggest, however, seasonality to decrease with increasing water depth and therefore to be less than ~0.4 °C.

The above-mentioned data indicate that seasonal temperature variability is relatively low at our study site; therefore the geochemical signatures of the investigated foraminiferal species are considered not to be seasonally biased (Lin et al., 1997; Tedesco et al., 2007; Mohtadi et al., 2009; Jonkers and Kučera, 2015). As suggested by the reviewer, more specific information on seasonality at our study site as described above will be added to Section 5.3 ("Stable-isotope and Mg/Ca records of *G. crassaformis* and *G. ruber* at Site 849").

R.2.15: "note [page 8]: What is the mean temperature at the site?"

Modern mean annual SSTs at Site 849 are ~23.5 °C (Locarnini et al., 2013) at 20 m water depth, i.e., the assumed mean depth habitat of *G. ruber* (Wang, 2000) (see also Fig. 1b). Mean SSTs reflected by *G. ruber* (~24 °C [Jakob et al., 2017]) indicate slightly warmer values, supporting the overall notion of a warmer-than-present EEP during the late Pliocene and early Pleistocene (e.g., Lawrence et al., 2006; Groeneveld et al., 2014). A comparison between modern and reconstructed Plio-/Pleistocene SSTs at Site 849 has already been presented in Jakob et al. (2017) and therefore will not be repeated in our manuscript.

While the depth habitat of *G. ruber* is relatively well understood (e.g., Wang, 2000) and therefore a comparison of *G. ruber*-based temperature estimates with modern values is possible, a comparison of *G. crassaformis*-based temperatures with modern values is not straight forward since the calcification depth of this species in the EEP has yet remained unclear. In the (sub-)tropical Atlantic, *G. crassaformis* typically calcifies between 400 and 800 m water depth (Steph et al., 2006; Regenberg et al., 2009; Steph et al., 2009, and references therein; Cléroux et al., 2013). Assuming the same calcification depth range for this species in the EEP, this corresponds to a modern temperature range of about ~5–8 °C (Fig. 1b). *Globorotalia crassaformis*-based temperatures reconstructed for our study interval are similar to or somewhat higher than these values until MIS 100 (~5–15 °C); thereafter, thermocline temperatures became somewhat lower (~0–10 °C) (Fig. 5d). This would indicate that thermocline temperatures of the late Pliocene (early Pleistocene) were slightly higher (lower) than modern values, reflecting an overall warmer-than-present (colder-than-present)

EEP at thermocline depth. We are fully aware that this comparison is not straight forward in light of the uncertainties in the calcification depth of *G. crassaformis*. Therefore we decided not to include this comparison (i.e., modern *versus* late Pliocene/early Pleistocene thermocline temperatures) into our manuscript.

R.2.16: "note [table1 page 17]: Add the number of samples processed for each site and study to give a sense of the effort included in this study."

We appreciate this suggestion. We will include the number of samples processed (dried, weighed, washed) and geochemically analysed ($\delta^{13}C$, $\delta^{18}O$, Mg/Ca) per study. Note that the number of samples analysed is somewhat lower than the number of samples processed depending on the availability of foraminiferal (*G. crassaformis* and *G. ruber*) material.

R.2.17: "note [Figure 1 page 18, panel B]: A latitudinal transect would be more useful to test whether the front did change as in Koutavas et al."

We agree with Reviewer #2 that a latitudinal transect would be more useful to test changes in the frontal position. Given the amount of data that would be needed for such an approach, however, this would be clearly beyond the scope of this contribution (see also our response to comment R.2.4).

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