Author´s response to the comments of A. Bahr (Referee)

Interactive comment on **"The last interglacial (MIS 5e) cycle at Little Bahama Bank: A history of climate and sea-level changes"** *by* **Anastasia Zhuravleva and Henning A. Bauch**

A. Bahr (Referee)

andre.bahr@geow.uni-heidelberg.de Received and published: 30 April 2018

Reviewer´s comment: GENERAL REMARKS: The authors present a comprehensive collection of faunal, stable isotope and sediment-geochemical data from Little Bahama Bank (LBB) core MD99-2202 encompassing MIS 5e in high temporal resolution. Such high-resolution low-latitude (27°N) records of the penultimate Interglacial are rare, but important to constrain the climatic variability of previous interglacials when compared to the Holocene. The authors argue that the surface ocean variability at LBB reflects changes in the position of the subtropical gyre and tropical warm pool, responding to latitudinal shifts of the ITCZ that are driven by insolation and AMOC changes. In addition, the sea level history at LBB is discussed, mainly based on the sedimentary composition (aragonite content) of the sediment. In general, the author's interpretations are well-founded by proxy evidence and supported by previous studies. Some problematic aspects of the interpretation are discussed below, but do not interfere with the general messages of the paper.

The manuscript is generally well-written and the study undoubtedly has its merits as a valuable contribution for the understanding of low-latitude climate variability during MIS 5e as well as the low-high-latitude feedbacks. However, the manuscript lacks a clear focus. This regards in particular the introduction - it should include more concise statements regarding the aims of the study, e.g. hypotheses to be tested and specific questions that should be solved. At the moment the introductory paragraphs (as well as the abstract ad conclusions) are very general, partly with a focus that hinges strongly on local aspects of sedimentary dynamics at LBB. Hence, I would strongly advocate to sharpen the focus of the manuscript, as the reader is left with the impression that the study confirms previous conceptual models (e.g. regarding the displacement of the ITCZ during MIS 5e) but wonders about the specific take-home-messages and new insights retrieved from this study. I therefore recommend the authors to rewrite the respective parts of their manuscript (in particular the introduction; see also specific comments below) to avoid underselling of their data.

Author´s response:

Please note that all changes in the manuscript are provided in a marked-up version (track changes in Word, converted into a *.pdf file). The line numbers used in the current Author´s response refer to the marked-up version, which is attached below.

The introduction has been rewritten, in attempt to provide a clearer focus of the study. Aims, methods and problematics are now also discussed.

Reviewer´s comment: SPECIFIC COMMENTS:

Abstract: As discussed above, the abstract should be more specific about what exactly the authors want to study. At present, the first three sentences concentrate on the local/regional aspects concerning LBB, but in fact the data can be used to infer much more general insights into low-high-latitude feedbacks and subtropical gyre dynamics and Gulf Stream variability. Hence, I suggest to reduce the reference to LBB but focus on the broader context.

Author´s response: The rewritten abstract focuses on millennial-scale teleconnections between high and low latitudes during the last interglacial. In addition, the strong freshening in the high latitudes during early MIS 5e is described as the main reason for the warm-cold switches, observed across various oceanic basins.

Reviewer´s comment: Introduction: line 40 and elsewhere: I would avoid abbreviating North Atlantic as "N. Atlantic"

Author´s response: Done.

Reviewer´s comment: l. 50: ". . .. we attempt to close this gap. . ." reflects the problem of the introduction - this is far too general. Data generation per se is important, but should be done with some hypothesis/question to be tackled in mind. At the moment I also miss a more specific lay out of the controversies that are mentioned. This would help to formulate specific questions and hypotheses at the end of the introduction.

Author´s response: The introduction has been rewritten (see the comment above).

Reviewer´s comment: Regional setting: l. 64: capitalize “intertropical convergence zone”

Author´s response: Done (ls. 15-16, 69-70, 1651).

Reviewer´s comment: l. 71: replace “tropical pool waters” with “tropical warm pool”

Author´s response: Replaced with “the Atlantic Pool Water” (ls. 117, 234).

Reviewer´s comment: l. 73: “thermocline layer” is too unspecific. Does this refer to the permanent thermocline?

Author´s response: Changed to the permanent thermocline (l. 237).

Reviewer´s comment: Methods: There should be a short statement in the introduction about the type of proxies used. In the present state, the purpose of the different proxies is unclear until the discussion. However, I would expect to read one or two sentences about the rational for XRF scanning, why δ18O of deep and shallow dwellers were used, and about the purpose of the faunal studies. Again, the mentioning of the proxies can be done in conjunction with the layout of the specific goals in the introduction (see comments above).

Author´s response: The used proxies are mentioned in the rewritten introduction together with their specific goals (ls. 119-128).

Reviewer´s comment: Results: l. 163: “physical sediment properties” should be replaced by “sedimentological properties”, this seems more appropriate as it refers to the grain size curve shown.

Author´s response: The text has been rephrased. Now “sedimentological records” are used (l. 389).

Reviewer´s comment: l. 174: I agree that the “significant sedimentological shift” mentioned here is no artifact as it displays in different, independent proxies. However, given its minute amplitude relative to the general fluctuations in the core it is an overstatement to call it “significant”. Considering the rather diffuse discussion in Section 6.4 I would skip the reference and discussion of this feature (see also respective comment below).

Author´s response: This section has been deleted from the results as well as from the discussion.

Reviewer´s comment: l. 178: “during the major deglacial transition . . . low isotopic gradients. . .” this statement does not fully reflect the data, as there is a steady trend to more stratification from 135-129 ka, reaching the MIS 5e level of well-stratified waters. As written in the text it sounds like the entire transition is characterized by a persistent low isotopic gradients.

Author´s response: We fully agree with the Reviewer´s comment. The statement has been changed to “During the penultimate glacial maximum <…> gradients <…> are very low, succeeded by a gradually increasing difference across the T2, ~135-129 ka” (ls. 425-427).

Reviewer´s comment: l. 181: please call out Fig. 6 after “species are observed”

Author´s response: Done (l. 431).

Reviewer´s comment: l. 185: please call out Fig. 5 after “abruptly increase”. Also note that the variations of G. trunca (sin) in Fig. 5e are within the 1-sigma error of their present-day abundances. Is it necessary to plot these G. trunca (sin) abundances?

Author´s response: Fig. 5 (now Fig. 4) is called out after “together with a reappearance of *G. inflata*” (ls. 433). For simplification and clarity, relative abundances of *G. truncatulinoides* (sin) as well as *G. falconensis* are not shown in figures any more.

Reviewer´s comment: Discussion: l. 192-211: I wonder about the necessity to discuss the Sr/Ca record. In principle this is a good proxy for aragonite, however, the authors make the convincing case that this record is biased by changes in porosity and water content. Considering that the authors present the XRD-based record of aragonite form Lantzsch et al. (2007), the discussion of Sr/Ca can be omitted without losing information.

Author´s response: The discussion of our Sr/Ca record, in particular, of the “problematic intervals” is retained, however, has been substantially shortened (ls. 440-544).

Reviewer´s comment: l. 222: Please add a reference for the subsidence rate of the LBB

Author´s response: Done (study by Carew and Mylroie (1995) is cited, l. 441)

Reviewer´s comment: l. 228: if I am correct, the sea level rise should be between 12-15 m (15 = 9 + 6 m) not 12-16 m. Please check.

Author´s response: Correct. This paragraph has been, however, deleted.

Reviewer´s comment: l. 256: "warm/cold conditions" – please specify what is meant here.

Author´s response: Has been changed to "temperature estimations during late MIS 6 so far reveal cold subsurface conditions" (l. 670).

Reviewer´s comment: l. 270-272: In principle I agree with the interpretation that G. truncatulinoides abundances strongly depend on the upper ocean stratification. However, in this respect, it is interesting that G. trunca. (dex) is still high during late MIS 5e, when δ18O is already low. Hence, vertical water column stratification is not the sole factor influencing the G. trunc. abundances.

Author´s response: We agree with the Reviewer´s comment. A paragraph, dealing with additional forcing factors controlling occurrences of *G. truncatulinoides* (dex) and *G. inflata* has been included (ls. 688-803).

Reviewer´s comment: l. 283-287: Fe appears to lag δ18O, hence, question is if dust is really the dominant factor that governs the Fe abundances if δ18O is supposed to be the prime proxy recording for wind-driven water column homogenization. Fe might also be influenced by diagenetic processes, hence, it would be worthwhile looking at Ti/Al as Ti is not influenced by diagenesis.

Author´s response: We have reconsidered our Fe data and has significantly restricted the interpretation, given the "variety of additional effects that may have influenced our Fe-record" (ls. 816-820). Ti content in the investigated sediment core appears to be very low, in addition, possibly strongly affected by seawater content (Fig. 1).

Reviewer´s comment: l. 287-291: to check if winnowing plays a role during the deglaciation elemental ratios such as Zr/Rb or Zr/Al might be used to check for high bottom current velocities (Bahr et al., 2014).

Author´s response: Increased winnowing at the northern slope of Little Bahama Bank during glacial times (a result of an intensified wind-driven Antilles Current) was previously suggested by Chabaud et al. (2016). As we could not prove the statement by using Zr/Rb or Zr/Al data (Fig. 1), as suggested above, this part has been removed.

Reviewer´s comment: l. 332: please add a reference after “only by ~124 ka”

Author´s response: Done (l. 1081-1082).

Reviewer´s comment: l. 355: correct for “Hofman et al.” (not Hofmann)

Author´s response: Done. Changed for Hoffman et al.

Reviewer´s comment: l. 364: Notably, the *ruber* (w) abundances are strikingly similar to the δ18Oivf-sw record of *G. ruber* (w) from ODP Site 1058 (Bahr et al, 2013). This supports the view that salinity is the main driver of *G. ruber* (w) abundances.

Author´s response: We agree with the comment above, however, a common temporal framework is needed for better core-to-core correlation and further climatic implications (Fig. 2).

Reviewer´s comment: l. 372-381: as mentioned above, the discussed changes in Sr and aragonite content are really minute compared to the other variations observed in the proxy records. Given that the authors make only very general inferences about the paleoclimatic implications I suggest to remove this paragraph.

Author´s response: Done. The paragraph has been removed.

Reviewer´s comment: Conclusions l. 387: “in the investigated core section”: this is much too local, especially for the conclusions (see also my general comments). The broader implications of this study should become clear here.

Author´s response: Conclusions have been rewritten to emphasize the broader implications of the study (particularly, the third paragraph).

Reviewer´s comment: l. 389-392: these statements regarding the local sedimentological processes on LBB are quite general and not novel considering the amount of publications dealing with this topic.

Author´s response: The statements have been removed from the conclusions.

Reviewer´s comment: l. 398: replace “depressed” by “shifted”

Author´s response: Done (l. 1191).

Reviewer´s comment: Figures: Fig. 4A-C is repetitive of Fig. 3 Fig. 4E: if Sr/Ca remains in the figure (see comments above): this record has been truncated at 0.3, please state this in the captions.

Author´s response: Fig. 4 has been deleted (XRF data and also #*G. menardii* are shown now in Fig. 3, plotted against age). We also note now that the Sr/Ca record has been truncated (l. 1666).

Reviewer´s comment: Fig. 7E-F: Is it necessary to show *G. ruber* and *G. sacculifer* abundances from ODP Site 1063 here?

Author´s response: Abundances of *G. ruber* and *G. sacculifer* from ODP Site 1063 have been removed.

Reviewer´s comment: Reference: Bahr, A., Jiménez-Espejo, F.J., Kolasinac, N., Grunert, P., Hernández- Molina, F.J., Röhl, U., Voelker, A.H., Escutia, C., Stow, D.A. and Hodell, D. (2014) Deciphering bottom current velocity and paleoclimate signals from contourite deposits in the Gulf of Cádiz during the last 140 kyr: An inorganic geochemical approach. Geochemistry, Geophysics, Geosystems, 15, 3145-3160.

Author´s response: References:

Bahr, A., Nürnberg, D., Karas, C. and Grützner, J.: Millennial-scale versus long-term dynamics in the surface and subsurface of the western North Atlantic Subtropical Gyre during Marine Isotope Stage 5, Glob. Planet. Change, 111, 77–87, doi:10.1016/j.gloplacha.2013.08.013, 2013.

Carew, J. L. and Mylroie, J. E.: Quaternary tectonic stability of the Bahamian archipelago: evidence from fossil coral reefs and flank margin caves, Quat. Sci. Rev., 14, 145–153, doi:10.1016/0277-3791(94)00108-N, 1995.

Chabaud, L., Ducassou, E., Tournadour, E., Mulder, T., Reijmer, J. J. G., Conesa, G., Giraudeau, J., Hanquiez, V., Borgomano, J. and Ross, L.: Sedimentary processes determining the modern carbonate periplatform drift of Little Bahama Bank, Mar. Geol., 378, 213–229, doi:10.1016/j.margeo.2015.11.006, 2016.

Author´s response to the comments of the Anonymous Referee #2

Interactive comment on **"The last interglacial (MIS 5e) cycle at Little Bahama Bank: A history of climate and sea-level changes"** *by* **Anastasia Zhuravleva and Henning A. Bauch**

Anonymous Referee #2

Received and published: 17 May 2018

Reviewer´s comment: SUMMARY: Zhuravleva and Bauch present a detailed consideration of the climate evolution of the Last Interglacial (LIg) for a core site on the Little Bahama Bank (LBB) using faunal assemblage and scanning XRF techniques. The high resolution faunal assemblages nicely resolve hydrographic oscillations at the site for the LIg reflecting both the insolation driven and AMOC modulated migration of the ITCZ for this region.

I would recommend the following amendments/clarifications: (a) change of title to better reflect the content of the paper; (b) removal or at the very least restructuring of the discussion of sea level. This section could be significantly trimmed and simplified (no new insights offered but a nice corroboration). Alternatively, if the authors wish to retain the sea-level discussion, then discussion of other sea level evidence from the region, glacio-isostatic adjustment (GIA) processes etc. are needed. (c) clearer discussion of the teleconnections between N Atlantic oceanic changes (i.e., variation in AMOC), the migration of the ITCZ and surface hydrographic change at MD99-2202.

Author´s response:

Please note that all changes in the manuscript are provided in a marked-up version (track changes in Word, converted into a *.pdf file). The line numbers used in the current Author´s response refer to the marked-up version, which is attached below.

a) The title has been changed to better reflect the main finding of the paper, i.e., subpolar forcing on the subtropical climate during the last interglacial;
b) The discussion about sea level is significantly reduced and focuses now exclusively on relative sea level changes in the Bahama region and its implications for regional sedimentary processes (ls. 440-544);

c) Links between AMOC strength and ITCZ shifts are discussed now in the introduction (ls. 68-78) as well as briefly mentioned in the discussion (ls. 986-1078).

Reviewer´s comment: GENERAL COMMENTS: The manuscript, in general, reads well. However, the structure and focus of the paper requires further thought. A clear statement of the research questions was missing and is reflected in the general tone of the introduction (and the manuscript generally).

Author´s response: The introduction has been rewritten, in attempt to outline the aims of the manuscript (ls. 95-110), used proxies (ls. 119-128) and testing hypothesis.

Reviewer´s comment: 1. Title

I found this to be somewhat misleading. The data in Zhuravleva and Bauch is not a sea-level record per se, rather a record of increased aragonite supply to the core site during interglacials, with these intervals of increased aragonite production/supply likely corresponding to < -6 m relative sea level (RSL) due to the generally shallow nature of Little Bahama Bank (i.e., you can infer periods of <-6 m relative sea level). This work nicely corroborates the Lantzsch et al., 2007 and Chabaud et al., 2016 studies but isn't a sea-level story. What is new and interesting the palaeoceanographic evolution of the Last Interglacial (LIg) at the site, and the interplay of interglacial climate (movement of the ITCZ etc.). I would suggest changing the title to better reflect this.

Author´s response: The title has been changed.

Reviewer´s comment: 2. Sea level

This section requires some restructuring to help the reader. The definition of the "flooding interval" (and corresponding relative sea level, <-6 m) is key to this section of the manuscript but I struggled to clearly follow the logic of how you defined the flooding interval using your records and why a -6 m RSL for this interval was appropriate. The connection between the flooding interval and inferred RSL of < -6 m was found al- most at the end of the section (line 222 to 226) when it should be at the start. All the information is there but the reader has to work hard to follow the argument.

Perhaps something along the lines of;

modern LBB lagoon is shallow, with an average water depth < 6 m (Williams, 1985); tectonic stability of the region (refs needed);

during the LIg, increasing RSL at the site floods the generally shallow bank and increases the area for aragonite production (i.e., the carbonate shedding model, Droxler and Schlager, 1985; Schlager et al., 1994);

Conversely, during glacial intervals, the top is exposed which limits the production and export of aragonite;

As such, we define the flooding interval (and inferred <-6 m RSL) is defined by an increase in the sedimentation rate, increase in wt % aragonite, increased Sr/Ca ratio, increase % *Globigerinoides*/decrease in numbers of *G. menardii*.

This could then usefully be followed with your discussion of very high values of Sr/Ca due to increased saltwater (lines 192 to 211). Perhaps shade these 'problematic' Sr/Ca intervals in subsequent figures? You should also note the truncation of the Sr/Ca record in caption of Figure 4.

I would suggest confining discussion of sea level in this section to that suggested above. If you wish to make more of the sea level story, then greater consideration of other Bahamas sea-level records, as well as those from the wider area is needed. For example, the +6m notch on Little Sale Cay (LLB) (Neumann and Hearty, 1996), other geomorphological records (e.g., Hearty and Kindler, 1995; Neumann and Hearty, 1996), the elevated Last Interglacial (LIg) coral records of Chen et al 1991, Hearty et al., 2007, Thompson et al., 2011 and the regionally extensive erosional surface that is suggestive of a sea-level oscillation within the LIg (Bahamas, Florida and Yucatan; Chen et al 1991, Hearty et al., 2007, Blanchon et al., 2009; Thompson et al., 2011).

How does the timing of the highstand from the coral/other records from the Bahamas compare to the timing of the interval of enhanced aragonite production (and inferred sea levels < -6 m)? How do changes in hydrography (variations in faunal assemblages) at the site compare to the timing of the Bahamas LIg highstand? The broad correspondence between climate (δ18OG.ruber) and relative sea level (RSL) (weight % aragonite) is hinted at in lines 138 to 141 but could be developed further if you wish to keep the sea-level discussion.

Any discussion of the LIg highstand in a general sense (i.e., the eustatic record) (lines 227 to 231) and Bahamas RSL will need to consider glacio-isostatic (GIA) processes, given the intermediate location of the site on the peripheral bulge of the former Lauren- tide Ice Sheets. There will be a regional expression of the LIg highstand; the Bahamas would "see" a "late" LIg highstand compared to eustatic sea level (e.g., Figure 6 in Stirling et al., 1998). There seems to be good correspondence between the age of your "flooding interval" at the site (i.e., sea level < -6 m) and the predictions of RSL (Stirling et al., 1998, their Figure 6).

Given that the records presented are not strictly a sea level record, rather incidence of increased aragonite production/export, and seems to corroborate previous studies rather than adding anything new, I would confine this section to just a brief consideration of the timing of your "flooding interval".

Author´s response: We agree on the importance of consideration of glacio-isostatic adjustment processes for interpretation of our aragonite-related records in terms of eustatic sea level change and also for comparison with other sea level reconstructions and curves (ls. 746-749). Therefore, we have restructured the sea-level discussion, in accordance with the Reviewer´s comment and significantly reduced this part, restricting the discussion to the relative sea level change, defining the "flooding interval" and associated changes in geochemical and sedimentary data around Bahama Banks (ls. 440-544).

The study by Carew and Mylroie (1995) was cited with regard to the tectonic stability of the Bahama region (l. 441). Truncation of the Sr/Ca record is now mentioned in the figure caption (Fig. 3, l. 1666).

Reviewer´s comment: 3. Palaeoceanographic reconstruction

This section is much more coherent and well written. I would recommend this as the focus of the manuscript.

The discussion, while nicely documenting the site/regional changes during the LIG, was lacking in consideration of the mechanisms. This section would be strengthened by a clearer exposition of the mechanisms linking ITCZ position, insolation (precession and the migration of the ITCZ to the warming hemisphere) and AMOC (i.e., modification of the thermal condition at the surface, due to interactions with the ocean, that in turn act to drive atmospheric circulation). This is well documented for the last deglaciation and glacial period (and in modelling studies), where N. hemisphere extra-tropical cooling (brought about by variations in the AMOC, forced by freshwater inputs) lead to an interhemispheric thermal gradient and a southward shift in the ITCZ (e.g., review of Chiang and Friedman, 2012 or Schneider et al., 2014). This would help the reader to place the different records (Cariaco, MD99-2202 and Site 1063) within a broader climatological context. Again, all the 'threads' of the story are there, it just needs a stranger framework.

For example, I found the correspondence between the % *G. ruber* and *G. sacculifer* and the XRF Mo count of the Caricao Basin striking (demonstrating the clear record of ITCZ shifts at the LBB) but the link to N. Atlantic surface density changes (AMOC slowdown with surface freshening e.g., Galaasen et al., 2014 etc.) and positive the δ18O *G. ruber* excursion and faunal changes at MD99-2202 and southward migration of the ITCZ (Cariaco Mo, MD99-2202 decrease in % *Globigerinoides*) weak. A short introductory paragraph should fix this.

Author´s response: We have included information on coupling between high-latitude forcing (AMOC strength) on the ITCZ position with its further influence on upper ocean properties in the introduction (ls. 68-78) and as well as briefly in the discussion (ls. 986-1078).

Reviewer´s comment: A southward shift of the ITCZ, strengthens of the trade winds increases the eolian input from the Sahara, resulting in reduced Al/Ti in Cariaco. These episodes of decreased Al/Ti ratios in Cariaco correspond to elevated salinities in the Caribbean (e.g., Yarincik et al 2000). I assume there is clear correspondence between the Cariaco Al/Ti and Mo records and hence to your % of tropical species?

Author´s response: Despite similar approach for age model construction (alignment of stable isotope data to SPECMAP/benthic stack), there is no correspondence between the Al/Ti record from Yarincik et al. (2000) and the Mo-data from Gibson and Peterson (2014) and, therefore, our relative abundance of the tropical species. This is likely due to low-resolution of the first record, providing general information about atmospheric circulation changes mainly on glacial-interglacial timescales (Fig. 1).

Reviewer´s comment: Do you see an increase in iron (with increased dust transport) in your record during the positive the δ18OG.ruber excursion ~ 127 ka? (plotting this on a log scale for the LIg might help).

Author´s response: We don’t find any response in iron accumulation during the 127-ka event.

Reviewer´s comment: Dust inputs are probably better reflected in the XRF core scanning Ti record, given that your Fe inputs could change with a number of factors.

Author´s response: We agree with this statement, but our XRF Ti measures appear to be very low and could be strongly influenced by Cl content (Fig. 2), therefore they were not considered in the study. We agree on the comment and restrict the interpretation of our Fe content, due to the “variety of additional effects that may have influenced our Fe-record” (ls. 816-820).

Reviewer´s comment: It would be interesting to compare to your faunal assemblages and a calculated δ18Oseawater for MD99-2202.

Author´s response: Please, see further below.

Reviewer´s comment: Additionally, is there any correspondence to the dated palaeosols on the Bahamas (Muhs et al., 2007)?

Author´s response: Study of Muhs et al. (2007) reveals two major sources for the dated palaeosols (~125 ka) on the Bahamas: African dust and Mississippi River valley loess. Today particularly strong input of African aerosols occurs during summer time, when the ITCZ position is to the north. The study, thus, suggests variable parent materials for eolian inputs, possibly with a greater role of Mississippi River valley loess at times of southward ITCZ shifts (glaciations). The text has been improved accordingly (ls. 816-820).

Reviewer´s comment: Given you have faunal assemblage data, could you calculate a transfer function/MAT sea surface temperature? From this you could then calculate δ18Oseawater at the site to think about density changes during the LIg.

Author´s response: While we agree with the suggestion to look at density changes and inferred calculated salinities, we assume that the use of Mg/Ca-based temperatures, derived from similar species used to obtain d18O values, would be more plausible. As we don’t have Mg/Ca-ratios for the investigated samples, we rather suggest considering proportions of selected species for relative temperature/salinity change reconstructions.

Reviewer´s comment: lines 372 to 381 – I found this paragraph to be highly speculative and not well supported by your data (I struggled to see the change in the sedimentological properties in your figures, even with the help of the white arrows). I would suggest removing this section.

Author´s response: The section has been removed.

Reviewer´s comment: TECHNICAL CORRECTIONS

Referencing: greater care needed with referencing. Please check manuscript. For example, the depth of submersion of the LBB (and origin of the -6 m quoted often in the paper) is Neumann and Land, 1975. Similarly the carbonate shedding model (upon which the inferred sea-level story is based) comes from Droxler and Schlager, 1985; Schlager et al., 1994

Author´s response: We tried to improve the referencing. Neumann and Land, 1975 and Droxler and Schlager, 1985 are cited (l. 444 and ls. 244, 250, 283, 444, respectively).

Reviewer´s comment: line 124 – what potential biases are you refereeing to? Please give appropriate references for these.

Author´s response: PhD thesis of Chabaud, 2016 has been cited (l. 336). This study extensively discusses the potential biases for XRF measurements in periplatform sediments, related e.g., to coarse-grained intervals, increased sediment porosity and/or seawater content.

Reviewer´s comment: line 242 – what is the derivation of "minimal ice volume interval" and it's reference?

Author´s response: This part has been removed.

Reviewer´s comment: line 332 - reference required for the "full resumption of the AMOC. . . only by ~124 ka"

Author´s response: Studies of Hodell et al. (2009) and Barker et al. (2015) are cited (l. 1081-1082).

Reviewer´s comment: 2. Other: line 64 – capitalisation of "intertropical convergence zone"

Author´s response: Done (ls. 15-16, 69-70, 1651).

Reviewer´s comment: line 133 – unit of measurement missing, add “m”.

Author´s response: Done (l. 344).

Reviewer´s comment: line 330 - please clarify or add examples of the “additional forcing” or add “as discussed below”.

Author´s response: The term “additional forcing” (now changed to “other forcing factors at play”, l. 986) is clarified (i.e., AMOC control on the ITCZ position, ls. 986-1078).

Reviewer´s comment: line 324-325 - Clarification of the age of the cooling/increase salinity event ~ 127 ka is needed. The ~127 ka age for this event is derived from your age model, whereas the U-series ages for the correlative event in core 152JPC (Bahamas, Slowey et al., 1996), dated (in duplicate) above and below the event to ~121 ± 3 ka and 125.6 ka (mean of 127 ± 4.8 and 124.1 ± 5.1) respectively. (Note, the relatively large age uncertainties associated with these U-series ages)

Author´s response: We agree with the Reviewer´s comment both with regard to only subtle agreement between our age estimates and direct U-Th dating of the cooling/salinification event, as well as large age uncertainties associated with U-series ages. Therefore, this section has been removed.

Reviewer´s comment: 3. Figures: typo - Axis label in Figure 4D should read “# G. menardii” rather than “# G. menradii” I would remove the sea level records (H), or if you choose to retain these and your discussion of sea level, then you should remove the dashed blue line “RSL above -6 m” from the lowermost panel (H).

Author´s response: Fig. 4 has been removed, instead XRF data and # G. menardii are shown together in Fig. 3, plotted against age.

Reviewer´s comment: REFERENCES CITED: Blanchon, P., Eisenhauer, A., Fietzke, J. and Liebetrau, V., 2009. Rapid sea-level rise and reef back-stepping at the close of the last interglacial highstand. Nature, 458, 881.

Chabaud, L., Ducassou, E., Tournadour, E., Mulder, T., Reijmer, J. J. G., Conesa, G., Giraudeau, J., Hanquiez, V., Borgomano, J. and Ross, L.: Sedimentary processes determining the modern carbonate periplatform drift of Little Bahama Bank, Mar. Geol., 378, 213–229.

Chen, J.H., Curran, H.A., White, B., Wasserburg, G.J. 1991. Precise chronology of the last interglacial period: 234U-230Th data from fossil coral reefs in the Bahamas. Geological Society of America Bulletin 103, 82-97.

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Last interglacial ocean changes in the Bahamas: climate teleconnections between low and high latitudes

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Abstract. Paleorecords and modeling studies suggest that instabilities in the Atlantic Meridional Overturning Circulation (AMOC) strongly affect the low-latitude climate, namely via feedbacks on the Atlantic Intertropical Convergence Zone (ITCZ). Despite pronounced millennial-scale climatic variability documented in the subpolar North Atlantic during the last interglacial (MIS 5e), studies on the cross-latitudinal teleconnections remain to be very limited, precluding full understanding of the mechanisms controlling subtropical climate evolution across the last warm cycle. Here, we present new planktic foraminiferal assemblage data combined with $\delta^{18}O$ values in surface and thermocline-dwelling foraminifera from the Bahama region, which is ideally suited to study past changes in subtropical ocean and atmosphere. Our data reveal that the peak sea surface warmth during early MIS 5e was intersected by an abrupt millennial-scale cooling/salinification event, which was possibly associated with a sudden southward displacement of the mean annual ITCZ position. This atmospheric shift, which could have left its imprint on the low-latitude upper ocean properties, is ascribed to the transitional climatic regime of early MIS 5e characterized, by persistent ocean freshening in the high latitudes and, therefore, an unstable AMOC mode.

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1 Introduction

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In the low-latitude North Atlantic, wind patterns, precipitation-evaporation balance as well as sea surface temperatures (SSTs) and salinities (SSSs) are strongly dependent on the position of the Atlantic Intertropical Convergence Zone (ITCZ) and its associated rainfall (Peterson and Haug, 2006). Based on paleorecords and modelling studies, past positions of the ITCZ are thought to be related to the interhemispheric thermal contrast, changes of which could be driven by two principal mechanisms: the precessional cycle and, associated with it, a cross-latitudinal distribution of solar insolation and millennial-scale climatic variability brought about by Atlantic Meridional Overturning Circulation (AMOC) instabilities (Wang et al., 2004; Broccoli et al., 2006; Arbuszewski et al., 2013; Schneider et al., 2014). Specifically, millennial-scale cold events in the high northern latitudes were linked with reduced convection rates of the AMOC, accounting for both a decreased oceanic transport of the tropical heat towards the north and a southward shift of the mean annual position of the ITCZ (Vellinga and Wood, 2002; Chiang et al., 2003; Broccoli et al., 2006). Reconstructions from the low-latitude North Atlantic confirm southward displacements of the ITCZ coeval with AMOC reductions and reveal a complex hydrographic response within the upper water column, generally suggesting an accumulation of heat and salt in the (sub)tropics (Schmidt et al., 2006a; Carlson et al., 2008; Bahr et al., 2011; 2013). There are, however, opposing views on the subtropical sea surface development at times of high-latitude cooling events. While some studies suggest stable or increasing SSTs (Schmidt et al., 2006a; Bahr et al., 2011; 2013), others imply an atmospheric-induced (evaporative) cooling (Chang et al., 2008; Chiang et al., 2008).

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The last interglacial (MIS 5e), lasting from about ~130 to 115 thousand years before present (hereafter [ka]), is often referred to as a warmer-than-preindustrial interval, associated with significantly reduced ice sheets and a sea level rise up to 6-9 meters above the present levels (Dutton et al., 2015; Hoffman et al., 2017). This time period has attracted a lot of attention as a possible analog for future climatic development as well as a critical target for validation of climatic models (Masson-Delmotte et al., 2013). Proxy data from the North Atlantic demonstrate that the climate of the last interglacial was relatively unstable, involving one or several cooling events (Maslin et al., 1998; Fronval and Jansen, 1997; Bauch et al., 2012; Irvali et al., 2012, 2016; Zhuravleva et al., 2017a, b). This climatic variability is thought to be strongly related to changes in the AMOC strength (Adkins et al., 1997). Thus, recent studies reveal that the AMOC abruptly recovered after MIS 6 deglaciation (Termination 2 or T2), i.e., at the onset of MIS 5e, at ~ 129 ka, but it was interrupted around 127-126 ka (Galaasen et al., 2014; Deaney et al., 2017). Despite the pronounced millennial-scale climatic variability documented in the high northern latitudes, studies on the cross-latitudinal links are very limited (but see e.g., Cortijo et al., 1999; Schwab et al.,

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2013; Kandiano et al., 2014; Govin et al., 2015; Jiménez-Amat and Zahn, 2015). This precludes the full understanding of the mechanisms, regulating subtropical climate across the last interglacial, i.e., insolation, oceanic and/or atmospheric forcing versus high-low-latitudes feedbacks.

Given its critical location near the origin of the Gulf Stream, sediments from downslope the shallow-water carbonate platforms of the Bahamian archipelago (Fig. 1) have been previously investigated in terms of oceanic and atmospheric variability (Slowey and Curry, 1995; Roth and Reijmer, 2004; 2005; Chabaud et al., 2016). However, a thorough study of the last interglacial climatic evolution underpinned by a critical stratigraphical insight is lacking so far. Here, a sediment record from the Little Bahama Bank (LBB) region is investigated for possible links between the AMOC variability and the ITCZ during the last interglacial cycle. Today the LBB region lies at the northern edge of the influence of the Atlantic Warm Pool, which expansion is strongly related to the ITCZ movements (Wang and Lee, 2007; Levitus et al., 2013), making our site particularly sensitive to monitor past shifts of the ITCZ. Given that geochemical properties of marine sediments around carbonate platforms vary in response to sea level fluctuations (e.g., Lantzsch et al., 2007), X-ray fluorescense (XRF) data are being used together with stable isotope and faunal records to strengthen the temporal framework. Planktic foraminiferal assemblage data complemented by $\delta^{18}O$ values, measured on surface- and thermocline-dwelling foraminifera, are employed to reconstruct the upper ocean properties (stratification, trends in temperature and salinity), specifically looking at mechanisms controlling the foraminiferal assemblages. Assuming a coupling between foraminiferal assemblage data and past mean annual positions of the ITCZ (Poore et al., 2003; Vautravers et al., 2007), our faunal records are then looked at in terms of potential geographical shifts of the ITCZ. Finally, we compare our new proxy records with published evidence from the regions of deep water formation to draw further conclusions on the subpolar forcing on the low-latitude climate during MIS 5e.

2 Regional Setting

2.1 Hydrographic context

Core MD99-2202 (27°34.5′ N, 78°57.9′ W, 460 m water depth) was taken from the upper northern slope of the LBB, which is the northernmost shallow-water carbonate platform of the Bahamian archipelago. The study area is at the western boundary of the wind-driven subtropical gyre (STG), in the vicinity to the Gulf Stream (Fig. 1a). The Gulf Stream supplies both heat and salt to the high northern latitudes thereby constituting the upper cell of the AMOC.

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In the western subtropical North Atlantic two distinctly different layers can be distinguished within the upper 500 m of the water column (Fig. 1c). The uppermost mixed layer (upper 50-100 m) is occupied by warm and comparatively fresh waters (T>24° C, S<36.4 psu), predominantly coming from the equatorial Atlantic (Schmitz and McCartney, 1993; Johns et al., 2002). Properties of this water mass vary significantly on seasonal timescales and are closely related to the latitudinal migration of the ITCZ (Fig. 1b). During boreal winter (December-April), when the ITCZ is in its southernmost position, the Bahama region is dominated by relatively cool, stormy weather with prevailing northern and northeastern trade winds and is affected by cold western fronts, that increase evaporation and vertical convective mixing (e.g., Wilson and Roberts, 1995). During May to November, as the ITCZ moves northward, the LBB region is influenced by relatively weakened trade winds from the east and southeast, increased precipitation and very warm waters of the Atlantic Warm Pool (T >28.5° C), which expand into the Bahama region from the Caribbean Sea and the equatorial Atlantic (Stramma and Schott, 1999; Wang and Lee, 2007; Levitus et al., 2013).

The mixed layer is underlain by the permanent thermocline, which is comprised of a homogeneous pool of comparatively cool and salty (T <24° C, S >36.4 psu) water (Schmitz and Richardson, 1991). These "mode" waters are formed in the North Atlantic STG through wintertime subduction of surface waters generated by wind-driven Ekman downwelling and buoyancy flux (Slowey and Curry, 1995).

2.2 Sedimentological context

Along the slopes of the LBB, sediments are composed of varying amounts of sedimentary input from the platform top and from the open ocean, depending on the global sea level state (Droxler and Schlager, 1985; Schlager et al., 1994). During interglacial highstands, when the platform top is submerged, the major source of sediment input is the downslope transport of fine-grained aragonite needles, precipitated on the platform top. This material incorporates significantly higher abundances of strontium (Sr), than found in pelagic-derived aragonite (e.g., pteropods) and calcite material from planktic foraminifera and coccoliths (Morse and MacKenzie, 1990). Given that in the periplatform interglacial environment modifications of the aragonite content due to sea floor dissolution and/or winnowing of fine-grained material are minimal (Droxler and Schlager, 1985; Schlager et al., 1994; Slowey et al., 2002), thicker sediment packages accumulate on the slopes of the platform, yielding interglacial climate records of high resolution (Roth and Reijmer, 2004; 2005). During glacial lowstands on the contrary, as the LBB bank top is exposed, aragonite production is limited, sedimentation rates are strongly reduced and coarser-grained

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consolidated sediments are formed from the pelagic organisms (Droxler and Schlager, 1985; Slowey et al., 2002; Lantzsch et al., 2007).

3 Methods

3.1 Foraminiferal counts and stable isotopes analyses

Planktic foraminiferal assemblages were counted on representative splits of the 150-250 µm fraction containing at least 300 individual specimens. Counts were also performed in the >250 µm fraction. The census data from the two size fractions were added up and recalculated into relative abundance of planktic foraminifera in the fraction >150 µm. Faunal data were obtained at each 2 cm for the core section between 508.5 and 244.5 cm and at each 10 cm between 240.5 and 150.5 cm. According to a standard practice, *Globorotalia menardii* and *Globorotalia tumida* as well as *Globigerinoides sacculifer* and *Globigerinoides trilobus* were grouped together, and referred to as *G. menardii* and *G. sacculifer*, respectively (Poore et al., 2003; Kandiano et al., 2012; Jentzen et al., 2018). New oxygen isotope data were produced at 2 cm steps using ~10-30 tests of *Globorotalia truncatulinoides* (dex) and ~5-20 tests of *Globorotalia inflata* for depths 508.5-244.5 cm and 508.5-420.5 cm, respectively. Analyses were performed using a Finnigan MAT 253 mass spectrometer at the GEOMAR Stable Isotope Laboratory. Calibration to the Vienna Pee Dee Belemnite (VPDB) isotope scale was made via the NBS-19 and an internal laboratory standard. The analytical precision of in-house standards was better than 0.07‰ (1σ) for $\delta^{18}O$. Isotopic data derived from the deep-dwelling foraminifera *G. truncatulinoides* (dex) and *G. inflata* could be largely associated with the permanent thermocline and linked to winter conditions (Groeneveld and Chiessi, 2011; Jonkers and Kučera, 2017; Jentzen et al., 2018). However, as calcification of their tests starts already in the mixed layer and continues in the main thermocline (Fig. 1c), the abovementioned species are thought to accumulate in their tests hydrographic signals from different water depths (Groeneveld and Chiessi, 2011; Mulitza et al., 1997).

3.2 XRF scanning

XRF analysis was performed in two different runs using the Aavatech XRF Core Scanner at Christian-Albrecht University of Kiel (for technical details see Richter et al., 2006). To obtain intensities of elements with lower atomic weight (e.g., calcium (Ca), chlorine (Cl)), XRF scanning measurements were carried out with the X-ray tube voltage of 10 kv, the tube current of 750 µA and the counting time of 10 seconds. To analyze heavy elements (e.g., iron (Fe), Sr), the X-ray generator setting of 30 kv and 2000 µA and the counting time of 20 seconds were used; a palladium thick filter was placed in the X-ray tube to reduce the high background radiation generated by

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the higher source energies. XRF Core Scanner data were collected directly from the split core sediment surface, that had been flattened and covered with a 4 µm-thick ULTRALENE SPEXCerti Prep film to prevent contamination of the measurement unit and desiccation of the sediment (Richter et al., 2006; Tjallingii et al., 2007). The core section between 150 and 465 cm was scanned at 3 mm step size, whereas the coarser-grained interval between 465 and 600 cm was analyzed at 10 mm resolution.

To account for potential biases related to physical properties of the sediment core (see e.g., Chabaud, 2016), XRF intensities of Sr were normalized to Ca, the raw total counts of Fe and Sr were normalized to the total counts of the 30kv-run; counts of Ca and Cl were normalized to the total counts of 10kv-run, excluding Rh intensity, because this element intensities are biased by the signal generation (Bahr et al., 2014).

4 Age model

By using our foraminiferal assemblage data, we were able to refine the previously published age model of core MD99-2202 (Lantzsch et al., 2007). To correctly frame MIS 5e, stratigraphic subdivision of the unconsolidated aragonite (Sr)-rich sediment package between 190 and 464 m is essential (Fig. 2). In agreement with Lantzsch et al. (2007), we interpret this core section to comprise MIS 5, which is supported by key biostratigraphic markers used to identify the well-established faunal zones of late Quaternary (Ericson and Wollin, 1968). Thus, the last occurrence of *G. menardii* at the end of the aragonite-rich sediment package is in agreement with the estimated late MIS 5 age (ca. 80-90 ka; Boli and Saunders, 1985; Slowey et al., 2002; Bahr et al., 2011; Chabaud, 2016). The coherent variability in the ~200-300 cm core interval, observed between aragonite content and relative abundances of warm surface-dwelling foraminifera of *Globigerinoides* genus (*G. ruber,* white and pink varieties, *G. conglobatus* and *G. sacculifer*), points to simultaneous climate and sea level-related changes and likely reflects the warm/cold substages of MIS 5. The identified substages were then correlated with the global isotope benthic stack LS16 (Lisiecki and Stern, 2016) using AnalySeries 2.0.8 (Paillard et al., 1996). Further, boundaries between MIS 6/5e and 5e/5d as well as the penultimate glaciation (MIS 6) peak, defined from $\delta^{18}O$ record of *G. ruber* (white), were aligned to the global benthic stack (Lisiecki and Stern, 2016).

Given that sedimentation rates at the glacial/interglacial transition could have changed drastically due to increased production of Sr-rich aragonite material above the initially flooded carbonate platform top (Roth and Reijmer, 2004), we applied an additional age marker to better frame the onset of the MIS 5e "plateau" (Masson-Delmotte et al., 2013) and to allow for a better core-to-core comparison. Thus, we tied the increased relative abundances of warm surface-dwelling foraminifera of *Globigerinoides* genus, which coincides with the rapid decrease in

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foraminiferal $\delta^{18}O$ record at 456 cm, with the onset of MIS 5e "plateau" at ~129 ka (Masson-Delmotte et al., 2013). This age is in good agreement with many marine and speleothem records, dating a rapid post-stadial warming and monsoon intensification to 129-128.7 ka (Govin et al., 2015; Jiménez-Amat and Zahn, 2015; Deaney et al., 2017), coincident with the sharp methane increase in the EPICA Dome C ice core (Loulergue et al., 2008; Govin et al., 2012). Although we do not apply a specific age marker to frame the decline of the MIS 5e "plateau", the resulting decrease in the percentage of warm surface-dwelling foraminifera of *Globigerinoides* genus as well as the initial increase in the planktic $\delta^{18}O$ values dates back to ~117 ka (Figs. 3-5), which broadly coincides with the cooling over Greenland (NGRIP community members, 2004). A similar subtropical-polar climatic coupling was proposed in earlier studies from the western North Atlantic STG (e.g., Vautravers et al., 2004; Schmidt et al., 2006a; Bahr et al., 2013; Deaney et al., 2017).

5 Results

5.1 XRF data in the lithological context

In Fig. 3, XRF-derived elemental data are plotted against lithological and sedimentological records. Beyond the intervals with low Ca counts and correspondingly high Cl intensities (at 300-325 cm and 395-440 cm), Ca intensities do not vary significantly, which is in line with a stable carbonate content of about 94 % Wt (Lantzsch et al., 2007). Our Sr record closely follows the aragonite curve, demonstrating that the interglacial minerology is dominated by aragonite. Beyond the intervals containing reduced Ca intensities, a good coherence between Sr/Ca and aragonite content is observed. The rapid increase in Sr/Ca and aragonite is found at the end of the penultimate deglaciation (T2), coeval with the elevated absolute abundances of *G. menardii* per sample (Fig. 3). The gradual step-like Sr/Ca and aragonite decrease characterizes both the glacial inception and the later MIS 5 phase. Intensities of Fe abruptly decrease at the beginning of the last interglacial, but gradually increase during the glacial inception (Fig. 4). Between ~112 and 114.5 ka, the actual XRF measurements were affected by a low sediment level in the core tube.

5.2 Climate-related proxies

To calculate $\delta^{18}O$ gradients across the upper water column, we also used the published $\delta^{18}O$ data by Lantzsch et al. (2007) which were measured on the surface-dwelling foraminifera *G. ruber* (white). These isotopic data can be generally associated with mean annual conditions (Tedesco et al., 2007), however, during colder time intervals productivity peak of *G. ruber* (white) could shift towards warmer months, leading to underestimation of the actual

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environmental change (Schmidt et al., 2006a, b; Jonkers and Kučera, 2015). During the penultimate glacial maximum (MIS 6), $\delta^{18}O$ gradients between *G. ruber* (white) and *G. truncatulinoides* (dex) and *G. inflata* are very low (Fig. 4), succeeded by a gradually increasing difference across T2, ~135-129 ka. Changes in the isotopic gradient between surface- and thermocline-dwelling foraminifera closely follow variations in the relative abundances of *G. truncatulinoides* (dex) and *G. inflata* (Fig. 4). Across MIS 5e species of *Globigerinoides* genus dominate the total assemblage, however, significant changes in the proportions of three main *Globigerinoides* species are observed (Fig. 5): *G. sacculifer* and *G. ruber* (pink) essentially dominate the assemblage during early MIS 5e (129-124 ka), whereas *G. ruber* (white) proportions are at their maximum during late MIS 5e (124-117 ka). At around 127 ka, all $\delta^{18}O$ records abruptly increase together with a reappearance of *G. inflata* (Fig. 4) and a relative abundance decrease of *G. ruber* (pink) and *G. sacculifer* (Fig. 5). After 120 ka, $\delta^{18}O$ values in *G. ruber* (white) and *G. truncatulinoides* (dex) become unstable (Fig. 4). That instability coincides with an abrupt drop in *G. sacculifer* relative abundances (Fig. 5).

6 Discussion

6.1 Platform sedimentology and relative sea level change

The modern LBB lagoon is shallow with an average water depth between 6-10 m (Williams, 1985). Despite some possible isostatic subsidence of 1-2 m per hundred thousand years (Carew and Mylroie, 1995), the LBB region is generally regarded as tectonically stable (Hearty and Neumann, 2001). Considering this, a relative sea level (RSL) rise above -6 m of its present position is required to completely flood the platform top and allow for a drastic increase in platform-derived (Sr-rich aragonite) sediment particles (Neumann and Land, 1975; Droxler and Schlager, 1985; Schlager et al., 1994; Carew and Mylroie, 1997). As such, the LBB flooding periods exceeding -6 m RSL can be defined from downcore variations in Sr/Ca intensity ratio (Chabaud et al., 2016).

While our Sr record likely represents a non-affected signal because of good coherence with the aragonite record, some of the Ca intensity values are reduced due increased seawater content, as evidenced by simultaneously measured elevated Cl intensities (Fig. 3). Because enhanced seawater content in the sediment appears to reduce only Ca intensities, which leaves elements of higher atomic order (e.g., Fe, Sr) less affected (Tjallingii et al., 2007; Hennekam and de Lange, 2012), normalization of Sr counts to Ca results in very high Sr/Ca intensity ratios across the Cl-rich intervals. Regardless of these problematic intervals described above, the XRF-derived Sr/Ca values agree well with the actually measured aragonite values that it seem permissible to interpret them in terms of RSL variability.

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Around 129 ka, Sr/Ca rapidly reach maximum values, indicating the onset of the LBB flooding interval with the inferred RSL above –6 m (Fig. 3). Absolute abundance of *G. menardii* per sample support the inferred onset of the flooding interval, since amounts of planktic foraminifera in the sample can be used to assess the relative accumulation of platform-derived versus pelagic sediment particles (Slowey et al., 2002). After *G. menardii* repopulated the (sub)tropical waters at the end of the penultimate glaciation (Bahr et al., 2011; Chabaud, 2016), its increased absolute abundances are found around Bahamas between ~131-129 ka. This feature could be attributed to a reduced input of fine-grained aragonite at times of partly flooded platform. Consequently, as the platform top became completely submerged, established aragonite shedding gained over pelagic input, thereby reducing the number of *G. menardii* per given sample. Our proxy records further suggest that the aragonite production on top of the platform was abundant until late MIS 5e (unequivocally delimited by foraminiferal $\delta^{18}O$ and faunal data). The drop in RSL below -6 m only during the terminal phase of MIS 5e (~117-115 ka on our timescale) is corroborated by a coincident changeover in the aragonite content and an increase in absolute abundance of *G. menardii*, further supporting the hypothesis that aragonite shedding was suppressed at that time, causing relative enrichment in foraminiferal abundances.

The exact timing of the last interglacial global sea level peak is a rather controversial matter of debate as studies place it into either early (Grant et al., 2012; Lisiecki and Stern, 2016), mid or late MIS 5e (Hearty and Neumann, 2001; Hearty et al., 2007; Kopp et al., 2009; O´Leary et al., 2013; Spratt and Lisiecki, 2016). Although the Bahama region is located quite away from the former Laurentide Ice Sheet, there still could have been some influence by glacio-isostatic adjustments, causing our RSL signals to deviate from the global sea level during MIS 5e (Stirling et al., 1998). Therefore, we refrain from making any further evaluation of this issue at this point.

6.2 Deglacial changes in the vertical water mass structure

Particularly high proportions of thermocline-dwelling foraminifera *G. inflata* and *G. truncatulinoides* (dex) are found off LBB during late MIS 6 and T2 (Fig. 4). To define mechanisms controlling the faunal assemblage, we look at $\delta^{18}O$ values in those foraminiferal species which document hydrographic changes across the upper water column, i.e., spanning from the uppermost mixed layer down to the permanent thermocline. The strongly reduced $\delta^{18}O$ gradients between surface-dwelling species *G. ruber* (white) and two thermocline-dwelling foraminifera *G. truncatulinoides* (dex) and *G. inflata* during T2 and particularly during late MIS 6 could be interpreted in terms of decreased water column stratification, a condition which is favored by thermocline-dwelling foraminifera (e.g., Mulitza et al., 1997). Specifically, for *G. truncatulinoides* (dex) this hypothesis is supported by its increased

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abundance within the regions characterized by deep winter vertical mixing (Siccha and Kučera, 2017). Such environmental preference may be explained by species ontogeny, given that *G. truncatulinoides* (dex) requires reduced upper water column stratification to be able to complete its reproduction cycle with habitats ranging from c. 400-600 m to near-surface depths; in well-stratified waters, however, reproduction of *G. truncatulinoides* (dex) would be inhibited by a strong thermocline (Lohmann and Schweizer, 1990; Hilbrecht, 1996; Mulitza et al., 1997; Schmuker and Schiebel, 2000).

To explain the inferred reduced upper water mass stratification during late MIS 6 and T2, sea surface cooling/salinification and/or subsurface warming could be invoked (e.g., Zhang, 2007; Chiang et al., 2008). While Mg/Ca-based temperature estimations during late MIS 6 so far reveal cold subsurface conditions for the subtropical western North Atlantic (Bahr et al., 2011; 2013), it should be noted that species-specific signals (i.e., $\delta^{18}O$ values, Mg/Ca-ratios) could be complicated due to adaptation strategies of foraminifera, such as seasonal shifts in the peak foraminiferal tests flux and/or habitat changes (Schmidt et al., 2006a, b; Cléroux et al., 2007; Bahr et al., 2013; Jonkers and Kučera, 2015). However, further insights into the past hydrographic changes could be provided from the conspicuous millennial-scale reversion found at 131 ka (Fig. 4), associated with a shift towards lower surface-thermocline isotopic gradients (i.e., reduced stratification). When compared to the abrupt increase in *G. ruber* (white) $\delta^{18}O$ values at 131 ka, which indicates sea surface cooling or salinification, the isotopic response in thermocline-dwelling species remains rather muted. The latter could be explained either by foraminiferal adaptation strategies, stable subsurface conditions and/or incorporation of opposing signals during foraminiferal ontogenetic cycle that would mitigate the actual environmental change. Regardless of the exact mechanism, there is a good coherence between $\delta^{18}O$ values in *G. ruber* (white) and relative abundances of *G. inflata* and *G. truncatulinoides* (dex), suggesting a possible link between thermocline species abundance and conditions occurring nearer to the sea surface (Mulitza et al., 1997; Jonkers and Kučera, 2017). Specifically, steadily increasing upper water column stratification across glacial-interglacial transition could have suppressed reproduction of *G. truncatulinoides* (dex) and *G. inflata*, while the short-term stratification reduction at 131 ka may have promoted favorable conditions for the thermocline-dwelling species through sea surface cooling and/or salinification.

It should be noted, however, that stratification is not a sole mechanism for explaining variability in the thermocline-associated assemblage. Thus, while relative abundances of *G. inflata* become strongly reduced at the onset of MIS 5e, there is no such response in the *G. truncatulinoides* (dex) proportions (Fig. 4). Whereas *G. inflata* is generally regarded as subpolar to transitional species, preferring little seasonal variations in salinity (Hilbrecht,

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1996), *G. truncatulinoides* (dex) was shown to dwell in warmer temperatures (Siccha and Kučera, 2017) and occurs in small amounts also in the modern tropical Atlantic (Jentzen et al., 2018). However, an abrupt increase in the latter species proportions during the sea surface cooling/salinification event at ~127 ka (see further below), coupled with reduced upper water column stratification, supports the underlying "sea surface" control on the general abundance of *G. truncatulinoides* (dex).

A southern position of the mean annual ITCZ during the penultimate (de)glaciation could be inferred based on previous studies (Yarincik et al., 2000; Wang et al., 2004; Schmidt et al., 2006a; Carlson et al., 2008; Arbuszewski et al., 2013; Bahr et al., 2013). By analogy with the modern atmospheric forcing in the region, a southern location of the ITCZ could have caused enhanced upper water column mixing and evaporative cooling through intensified trade winds (e.g., Wilson and Roberts, 1995). Acknowledging the fact that our study region lies too far north to be influenced by changes in the winter position of the ITCZ (Ziegler et al., 2008) – this would be of primary importance for modern-like winter-spring reproduction timing of *G. truncatulinoides* (dex) and *G. inflata* (Jonkers and Kučera, 2015) - we suggest that a southern location of the mean annual position of the ITCZ during the penultimate (de)glaciation could have facilitated favorable conditions for the latter species through generally strong sea surface cooling/salinification in the subtropical North Atlantic.

Previous studies attributed increased Fe content in the Bahamas sediments to enhanced trade winds strength, given that siliclastic inputs by other processes than wind transport are very limited (Roth and Reijmer, 2004). Accordingly, elevated XRF-derived Fe counts in our record during T2 (Fig. 4) may support intensification of the trade winds and possibly increased transport of Saharan dust at times of enhanced aridity over Northern Africa (Muhs et al., 2007; Helmke et al., 2008). We, however, refrain from further interpretations of our XRF record due to a variety of additional effects that may have influenced our Fe-record (e.g., diagenesis, change in the source and/or properties of eolian inputs, sensitivity of the study region to atmospheric shifts, *etc.*).

6.3 MIS 5e climate in the subtropics: orbital versus subpolar forcing

Various environmental changes within the mixed layer (SST, SSS, nutrients) can account for the proportional change in different *Globigerinoides* species (Fig. 5). *G. sacculifer* – it makes up less than 10 % of the planktic foraminiferal assemblage around the LBB today (Siccha and Kučera, 2017) – is abundant in the Caribbean Sea and tropical Atlantic and commonly used as a tracer of tropical waters and geographical shifts of the ITCZ (Poore et al., 2003; Vautravers et al., 2007). Also, *G. ruber* (pink) shows rather coherent abundance maxima in the tropics, while no such affinity is observed for *G. ruber* (white) and *G. conglobatus* (Siccha and Kučera, 2017; Schiebel

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Deleted: ¶ This is in contrast to the subtropical N. Atlantic where winter sea surface cooling (T<23°C) and deep mixing occur alongside with increase of *G. truncatulinoides* up to 15% (Levitus et al., 2013; Siccha and Kučera, 2017). It could, therefore, be proposed that the overall abundance of *G. truncatulinoides* in our subtropical settings was at least partly controlled by oceanic conditions occurring nearer to the sea surface (Mulitza et al., 1997; Jonkers and Kučera, 2016). ¶ elevated occurrences of transitional to subpolar species *G. inflata* indicate generally cold-water conditions off the LBB ... [22]
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and Hemleben, 2017). Therefore, fluctuations in relative abundances of *G. sacculifer* and *G. ruber* (pink) are referred here as to represent a warm "tropical" end-member (Fig. 1b).

Relative abundances of the tropical foraminifera (here and further in the text *G. ruber* (pink) and *G. sacculifer* calculated together) in our core suggest an early thermal maximum (between ~129 and 124 ka), which agrees well with the recent compilation of global MIS 5e SST (Hoffman et al., 2017). The sea surface warming could be related to a northward expansion of the Atlantic Warm Pool (Ziegler et al., 2008), in response to a northern location of the mean annual position of the ITCZ. The latter shift in the atmospheric circulation is explained by the particularly strong northern hemisphere insolation during early MIS 5e (Fig. 6), resulting in a cross-latitudinal thermal gradient change, and in turn, forcing the ITCZ towards a warming (northern) hemisphere (Schneider et al., 2014). A northern location of the mean annual position of the ITCZ during the first phase of the last interglacial is supported by the XRF data from the Cariaco Basin, showing highest accumulation of the redox-sensitive element molybdenum (Mo) during early MIS 5e (Fig. 6). At that latter location, high Mo content is found in sediments deposited under anoxic conditions, occurring only during warm interstadial periods associated with a northerly shifted ITCZ (Gibson and Peterson, 2014).

Further, our data reveal a millennial-scale cooling/salinification event at ~127 ka, characterized by decreased proportions of the tropical foraminifera and elevated planktic $\delta^{18}O$ values (Fig. 6). That this abrupt cooling characterized the entire upper water column at the onset of the event is indicated by the re-occurrence of cold-water species *G. inflata* coincident with the brief positive excursions in $\delta^{18}O$ values in the shallow and thermocline-dwelling foraminifera (Fig. 4). Simultaneously, the XRF record from the Cariaco Basin reveals a stadial-like Mo-depleted (i.e., southward ITCZ shift) interval (Fig. 6). The close similarity between the tropical-species record from the Bahamas and the XRF data from the Cariaco Basin supports the hypothesis that the annual displacements of the ITCZ are also documented in our faunal counts. Thus, a southward shift in the mean annual position of the ITCZ at ~127 ka could have restricted influence of the Atlantic Warm Pool in the Bahama region, reducing SST and possibly increasing SSS, and in turn, affecting the foraminiferal assemblage. Moreover, because the aforementioned abrupt climatic shift at ~127 ka cannot be reconciled with insolation changes, other forcing factors at play during early MIS 5e should be considered. Studies from the low-latitude Atlantic reveal strong coupling between the ITCZ position and the AMOC strength associated with millennial-scale climatic variability (Rühlemann et al., 1999; Schmidt et al., 2006a; Carlson et al., 2008). In particular, model simulations and proxy data suggest that freshwater inputs as well as sea-ice extent in the (sub)polar North Atlantic can affect the ITCZ

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As shown in Fig. 7B, relative abundances of tropical species (here and further in the text *G. ruber* (pink) and *G. sacculifer* calculated together) increased before the onset of the last interglacial "plateau" at ~129 ka. This transition was

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a gradual northward migration of the mean annual position of the ITCZ at the onset of MIS 5e could be implied. In line with increasing low latitude summer insolation (Fig. 7C), this ITCZ displacement would also promote a northward expansion of tropical pool waters (Ziegler et al., 2008). Because core MD99-2202 is located at the northern edge of ITCZ influence, the rapid shift in foraminiferal proportions at ~130 ka could, in fact, represent the onset of warm pool waters influence, which resulted from a gradual northward-directed ITCZ movement.Accordingly, a gradual northward migration of the mean annual position of the ITCZ at the onset of MIS 5e could be implied. In line with increasing low latitude summer insolation (Fig. 7C), this ITCZ displacement would also promote a northward expansion of tropical pool waters (Ziegler et al., 2008). Because core MD99-2202 is located at the northern edge of ITCZ influence, the rapid shift in foraminiferal proportions at ~130 ka could, in fact, represent the onset of warm pool waters influence, which resulted from a gradual northward-directed ITCZ movement. Similarly, the pronounced increase in the tropical species ... [25]

position through feedbacks on the thermohaline circulation and associated change in the cross-latitudinal heat redistribution (e.g., Chiang et al., 2003; Broccoli et al., 2006; Gibson and Peterson, 2014). It is well-established that the deepwater overflow from the Nordic Seas, which constitutes the deepest southward-flowing branch of the AMOC today (e.g., Stahr and Sanford, 1999), strengthened (deepened) only during the second phase of MIS 5e (at ~124 ka), and after the deglacial meltwater input into the region ceased (Hodell et al., 2009; Barker et al., 2015). Nevertheless, several studies show that the deep-water ventilation and presumably the AMOC abruptly recovered at the beginning of MIS 5e, at ~129 ka (Fig. 6), possibly linked to a deepened winter convection in the Northwestern Atlantic (Adkins et al., 1997; Galaasen et al., 2014; Deaney et al., 2017). Accordingly, the resumption of the AMOC could have added to a meridional redistribution of the incoming solar heat, changing cross-latitudinal thermal gradient and, thus, contributing to the inferred "orbitally-driven" northward ITCZ shift during early MIS 5e (see above). In turn, the millennial-scale climatic reversal between 127 and 126 ka could have been related to the known reductions of deep water ventilation (Galaasen et al, 2014; Deaney et al., 2017), possibly attributed to a brief increase in the freshwater input into the subpolar North Atlantic and accompanied by a regional sea surface cooling (Irvali et al., 2012; Zhuravleva et al., 2017b). A corresponding cooling and freshening event, referred here and elsewhere as to a Younger Dryas-like event, is captured in some high- and mid-latitude North Atlantic records (Sarnthein and Tiedemann, 1990; Bauch et al., 2012; Irvali et al., 2012; Schwab et al., 2013; Govin et al., 2014; Jiménez-Amat and Zahn, 2015). Coherently with the Younger Dryas-like cooling and the reduction (shallowing) in the North Atlantic Deep Water formation, an increase in the Antarctic Bottom Water influence is revealed in the Southern Ocean sediments, arguing for the existence of an "interglacial" bipolar seesaw (Hayes et al., 2014). The out-of-phase climatic relationship between high northern and high southern latitudes, typical for the last glacial termination (Barker et al., 2009), could be attributed to a strong sensitivity of the transitional climatic regime of early MIS 5e due to persistent high-latitude freshening (continuing deglaciation, Fig. 6) and suppressed overturning in the Nordic Seas (Hodell et al., 2009). This assumption seems of crucial importance as it might help explain a relatively "late" occurrence of the Younger Dryas-like event during the last interglacial when compared to the actual Younger Dryas during the last deglaciation (Bauch et al., 2012). The recognition of the transitional phase during early MIS 5e is not new, but only few authors have pointed out its importance for understanding the last interglacial climatic evolution beyond the subpolar regions (e.g., Govin et al., 2012; Schwab et al., 2013; Kandiano et al., 2014).

As insolation forcing decreased during late MIS 5e and the ITCZ gradually moved southward, the white variety of *G. ruber* started to dominate the assemblage (Fig. 5), arguing for generally colder sea surface conditions in the

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Although the full resumption of the AMOC from a shallow or weak mode during T2 occurred only by ~124 ka,
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Bahama region. The inferred broad salinity tolerance of this species, also to neritic conditions (Bé and Tolderlund, 1971; Schmuker and Schiebel, 2002), was used in some studies to link high proportions of *G. ruber* (pink and white varieties) with low SSS (Vautravers et al., 2007; Kandiano et al., 2012). The plots of the global distribution pattern of *G. ruber* (white) and *G. ruber* (pink), however, suggest that when relative abundances of these two species are approaching maximum values (40% and 10%, respectively), the SSSs would be higher for specimens of the white variety of *G. ruber* (Hilbrecht, 1996). Therefore, the strongly dominating white versus pink *G. ruber* variety observed in our records during late MIS 5e could be linked not only to decreasing SSTs, but also to increasing SSSs.

In their study from the western STG, Bahr et al. (2013) also reconstruct sea surface salinification during late MIS 5e in response to enhanced wind stress at times of deteriorating high-latitude climate and increasing meridional gradients. Accordingly, our isotopic and faunal data (note the abrupt decrease in *G. sacculifer* proportion at 120 ka; Fig. 5) suggest a pronounced climatic shift that could be attributed to the so-called "neoglaciation", consistent with the sea surface cooling in the western Nordic Seas and the Labrador Sea (Van Nieuwenhove et al., 2013; Irvali et al., 2016) as well as with a renewed growth of terrestrial ice (Fronval and Jansen, 1997; Zhuravleva et al., 2017a).

7 Conclusions

New faunal, isotopic and XRF evidence from the Bahama region were studied for past subtropical climatic evolution, with special attention given to (a) the mechanisms controlling the planktic foraminiferal assemblage and (b) the climatic feedbacks between low and high latitudes.

During late MIS 6 and glacial termination, strongly reduced $\delta^{18}O$ gradients between surface- and thermocline-dwelling foraminifera suggest decreased water column stratification, which promoted high relative abundances of *G. truncatulinoides* (dex) and *G. inflata*. The lowered upper water column stratification, in turn, could be a result of sea surface cooling/salinification and intensified trade winds strength at times of the ITCZ being shifted far to the south.

Computed together, relative abundances of the tropical foraminifera *G. sacculifer* and *G. ruber* (pink) agree well with the published ITCZ-related Cariaco Basin record (Gibson and Peterson, 2014), suggesting a climatic coupling between the regions. Based on these data, a northward/southward displacement of the mean annual ITCZ position, in line with strong/weak northern hemisphere insolation, could be inferred for early/late MIS 5e. Crucially, an abrupt Younger Dryas-like sea surface cooling/salinification event at ~127 ka intersected the early MIS 5e warmth (between ~129 and 124 ka) and could be associated with a sudden southward displacement of the

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ITCZ. This atmospheric shift, could be, in turn, related to a millennial-scale instability in the ocean overturning, supporting a cross-latitudinal teleconnection that influenced the subtropical climate via ocean-atmospheric forcing. These observations lead to an inference that the persistent ocean freshening in the high northern latitudes (i.e., continuing deglaciation) and, therefore, unstable deep water overturning during early MIS 5e accounted for a particularly sensitive climatic regime, associated with the abrupt warm-cold switches that could be traced across various oceanic basins.

[Deleted: This so-called Younger Dryas type cooling event likely involved AMOC-related forcing that influenced (sub)tropical climate. The relatively late occurrence of Younger Dryas type cooling event, when compared to the actual Younger Dryas in the last deglaciation, is attributed to the transitional climatic regime of early MIS 5e, characterized by persistent high-latitude freshening and unstable deep-water overturning in the N. Atlantic.
Late MIS 5e: Overall sea surface cooling and possibly salinification is reconstructed for the Bahama region, in accordance with insolation decrease and a gradual southward displacement of the mean annual ITCZ. A coherent change is observed in faunal, isotopic and sedimentological proxies, arguing for coupled oceanic and northern hemisphere cryospheric reorganizations before the end of the major flooding period.]

Data availability

All data will be made available in the online database PANGAEA (www.pangaea.de).

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Figure captions

Figure 1: Maps showing positions of investigated sediment records and oceanic/atmospheric circulation. (**a**) Simplified surface water circulation in the (sub)tropical North Atlantic and positions of investigated core records: MD99-2202 (27°34.5′ N, 78°57.9′ W, 460 m water depth; *this study*), Ocean Drilling Program (ODP) Site 1002 (10°42.7′ N, 65°10.2′ W, 893 m water depth; Gibson and Peterson, 2014), MD03-2664 (57°26.3′ N, 48°36.4′ W, 3442 m water depth, Galaasen et al., 2014) and PS1243 (69°22.3′ N, 06°33.2′ W, 2710 m water depth, Bauch et al., 2012). (**b**) Relative abundances of the tropical foraminifera *G. sacculifer* and *G. ruber* (pink) (Siccha and Kučera, 2017) and positions of the Intertropical Convergence Zone (ITCZ) during boreal winter and summer. (**c**) Summer and winter hydrographic sections (as defined by the black line in **b**), showing temperature and salinity obtained from the World Ocean Atlas (Levitus et al., 2013). Vertical bars denote calcification depths of *G. ruber* (white) and *G. truncatulinoides* (dex). Note, that *G. truncatulinoides* (dex) reproduce in winter time and due to its life cycle with changing habitats (as shown with arrows) accumulate signals from different water depths. Maps are created using Ocean Data View (Schlitzer, 2016).

Figure 2: The age model for MIS 5 in core MD99-2202. The temporal framework is based on alignment of (**b**) planktic $\delta^{18}O$ values (Lantzsch et al., 2007) and (**d**) relative abundance record of *Globigerinoides* species with (**a**) global benthic isotope stack LS16 (Lisiecki and Stern, 2016). (**c**) Aragonite content in black (Lantzsch et al., 2007) and normalized elemental intensities of Sr in lilac as well as (**e**) relative abundances of *G. menardii* are shown to support the stratigraphic subdivision of MIS 5.

Figure 3: XRF-scan results, sedimentological and foraminiferal data from core MD99-2202 for the period 140-100 ka. (**a**) $\delta^{18}O$ values in *G. ruber* (white); (**b**) aragonite content; (**a-b**) is from Lantzsch et al. (2007). Normalized elemental intensities of (**c**) Sr, (**e**) Ca and (**f**) Cl, (**d**) Sr/Ca intensity ratio (truncated at 0.6) and (**g**) absolute abundances of *G. menardii* per sample. Green bars denote core intervals with biased elemental intensities due to high seawater content. The inferred platform flooding interval (see text) is consistent with the enhanced production of Sr-rich aragonite needles and a RSL above -6 m (**d**). T2 – refers to the position of the penultimate deglaciation (Termination 2).

Figure 4: Proxy records from core MD99-2202 over the last interglacial cycle. (**a**) $\delta^{18}O$ values in *G. ruber* (white) (Lantzsch et al., 2007), (**b**) $\delta^{18}O$ values in *G. truncatulinoides* (dex) (black) and *G. inflata* (blue), (**c-d**)

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Figure 3…: The age model for MIS 5Chronology…of…n core MD99-2202.… The temporal framework Age model…is based on alignment of (**b**) planktic $\delta^{18}O$ values (Lantzsch et al., 2007) and (**D**) …**d**) relative abundance record of *Globigerinoides* species and (**B**) planktic $\delta^{18}O$ values (Lantzsch et al., 2007) …ith (**A…**) global benthic isotope stack LS16 (Lisiecki and Stern, 2016). (**C…**) Aragonite content in black (Lantzsch et al., 2007) and normalized elemental intensities of Sr in lilac and …s well as (**E…**) relative abundances of *G. menardii* and *G. menardii* flexuosa ... [34]

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isotopic gradients between $\delta^{18}O$ values in *G. ruber* (white) and *G. truncatulinoides* (dex) and *G. ruber* (white) and *G. inflata*, respectively, (**e-f**) relative abundances of *G. inflata* and *G. truncatulinoides* (dex), respectively, (**g**) normalized Fe intensities. Also shown in (**e**) and (**f**) are modern relative foraminiferal abundances (average value ±1σ) around Bahama Bank, computed using 7 nearest samples from Siccha and Kučera (2017) database. T2 – Termination 2.

Figure 5: Relative abundances of main *Globigerinoides* species in core MD99-2202 over the last interglacial cycle. (**a**) $\delta^{18}O$ values in *G. ruber* (white) (Lantzsch et al., 2007), relative abundances of (**b**) *G. sacculifer*, (**c**) *G. ruber* (pink), (**d**) *G. conglobatus* and (**e**) *G. ruber* (white). Also shown in (**b-e**) are modern relative foraminiferal abundances (average value ±1σ) around Bahama Bank, computed using 7 nearest samples from Siccha and Kučera (2017) database. T2 – Termination 2.

Figure 6: Comparison of proxy records from tropical, subtropical and subpolar North Atlantic over the last interglacial cycle. (**b**) $\delta^{18}O$ values in *G. ruber* (white) in core MD99-2202 (Lantzsch et al., 2007), (**c**) relative abundances of the tropical species *G. sacculifer* and *G. ruber* (pink) in core MD99-2202, (**d**) molybdenum record from ODP Site 1002 (Gibson and Peterson, 2014), (**e**) $\delta^{13}C$ values measured in benthic foraminifera from core MD03-2664 (Galaasen et al., 2014, age model is from Zhuravleva et al., 2017b), (**f**) Ice-rafted debris in core PS1243 (Bauch et al., 2012, age model is from Zhuravleva et al., 2017b). Also shown is (**a**) boreal summer insolation (21 June, 30° N), computed with AnalySeries 2.0.8 (Paillard et al., 1996) using Laskar et al. (2004) data. Shown in (**c**) are modern relative abundances of *G. sacculifer* and *G. ruber* (pink) (average value ±1σ) around Bahama Bank, computed using 7 nearest samples from Siccha and Kučera (2017) database. The blue band suggests correlation of events (Younger Dryas-like cooling) across tropical, subtropical and subpolar North Atlantic (see text). T2 – Termination 2.

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Deleted: **7…: Comparison of proxy records from (sub)…ropical, subtropical and subpolar North.…Atlantic over the last interglacial cycle.** (**A**) …**b**) $\delta^{18}O$ values in *G. ruber* (white) in core MD99-2202 (Lantzsch et al., 2007), (**B…**) relative abundances of the tropical species *G. sacculifer* and *G. ruber* (pink) in core MD99-2202, (**C**) boreal summer insolation (21 June, 30° N), computed with AnalySeries 2.0.8 (Paillard et al., 1996) using Laskar et al. (2004) data, …**D…**) molybdenum (Mo) …ecord from ODP Site 1002 (Gibson and Peterson, 2014), (**E…-F**… $\delta^{13}C$ values measured in benthic foraminifera from core MD03-2664 (Galaasen et al., 2014, age model is from Zhuravleva et al., 2017b), (**f**) Ice-rafted debris in core PS1243 (Bauch et al., 2012, age model is from Zhuravleva et al., 2017b)and relative abundances of *G. ruber* (total) and *G. sacculifer* from ODP Site 1063 (Deaney et al., 2017)… Also shown is (**a**) boreal summer insolation (21 June, 30° N), computed with AnalySeries 2.0.8 (Paillard et al., 1996) using Laskar et al. (2004) data. Also s…hown in (**B…**) are modern relative abundances of *G. sacculifer* and *G. ruber* (pink) (average value ±1σ) around Bahama Bank, computed using 7 nearest samples from Siccha and Kučera (2017) database. The blue arrows …and and the dashed line …uggests correlation of events ((so-called …ounger Dryas- type …ike cooling))…in…cross the …ropical, subtropical and tropical…ubpolar North.…Atlantic (see text). Shaded in lilac is the platform flooding interval (as defined in Fig. 4).… [40]