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Climate of the Past Discussions

Interactive comment on "Changes in the geometry and strength of the Atlantic Meridional Overturning Circulation during the last glacial (20–50 ka)" *by* P. Burckel et al.

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Full point by point response to reviewers' comments on manuscript "Changes in the geometry and strength of the Atlantic Meridional Overturning Circulation during the last glacial (20-50 ka)".

We would like to thank the reviewers for their constructive comments. Our point by point response is outlined below. The reviewer's comments are displayed, and our answers are highlighted by asterisks "***". As requested by the editor, we will provide a revised version of the manuscript later in the revision process. Note that page and line numbers that we provide are those associated with the PDF downloaded from http://www.clim-past-discuss.net/cp-2016-26/#discussion. The line numbers the first reviewer provided

in the "Technical points" section appear to be different from those that appear on the PDF. Thank you for your understanding.

Referee #1 (Anonymous)

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In their manuscript "Changes in the geometry and strength of the Atlantic Meridional Overturning Circulation during the last glacial (20-50 ka)", Burckel et al. use 231Pa and 230Th ratios and 13C to assess the past state of deep ocean circulation in the Atlantic Ocean at several intervals during the past glaciation. After attempting to assess the geometry and strength of the overturning cell of the Atlantic, they conclude that the deep ocean circulation was very different from the modern in all four of their study intervals. The interstadial circulation was different in being relatively shallow, with a deep inflow from the south. Southward flowing waters at mid-depth would therefore have been the return flow of southern-sourced waters. At the time of Heinrich Stadial 2, yet another different circulation is inferred, with southern waters filling the deep Atlantic and a slow, southward-flowing water mass occupying the intermediate depths. This is a potentially valuable contribution to the literature on past states of the ocean circulation. It presents new geochemical data in a spatial array that may provide insights into changes at different depths and locations. The isotopic method is a promising and exciting approach, although it seems still in development in comparison to modern measurements. The data are compared to model output, which although limited in resolution and lacking a third dimension, nevertheless provides useful constraints on potential interpretations. The conclusions are not inconsistent with the relatively limited data presented. In terms of the specific criteria, the paper certainly addresses relevant questions within the scope of CP. It does not present novel approaches, but builds well upon existing techniques, data, and ocean modeling output. Substantial conclusions are reached regarding the configuration and rate of ocean circulation. The conclusions are not inconsistent with the data, although there are too many gaps at relevant locations and depths for them to be any more convincing than many alternatives which are not discussed. Figures are relatively clear, and text is a reasonable length. The text is fluent and the authors give adequate credit to the previous studies that they utilize and discuss. The two largest issues with the paper in its present form are related to its justification and chronology. This is a study of four time slices that are widely distributed within the last glacial. They are neither the most extreme, nor the most characteristic. Nor do they include important transitions or intervals of special climatic interest. It is therefore not clear to the reader why this seemingly arbitrary assortment of time slices was chosen. The authors should provide a much better explanation of the rationale for their selection. It is possibly related to what may be understandable difficulties with a challenging geochemical method, although others, notably Hall, also Negre, McManus, Lippold and Böhm have demonstrated that it is possible to produce continuous highly resolved records of the same isotope systems for specific intervals. Or it may be related to the quality or continuity of the sediment cores. These are acceptable reasons if they are confronted and explained, although it would be most satisfactory if some greater level of scientific rationale were presented. This is currently inadequate, beyond the mention of an interval that was not included. A section of a paragraph or two that would better explain the reasons for the scattered data intervals might seem to the authors to be an acknowledgement of a shortcoming, but in the end it would increase the interest and potential impact of the published study.

*** Pa/Th measurements were focused on relevant MIS3 time slices. HS2 and HS4 in particular were selected because these intervals are characterized by significantly different ice sheet volumes (Lambeck and Chappell, 2001) (see P.2, l.23 of the manuscript). Oceanic circulation around these time periods could therefore reasonably be expected to be different. Unfortunately, it is difficult to disentangle the sedimentary from the oceanic influences on the Pa/Th signal during HS4 in core MD09-3257, as high Pa/Th values are correlated to high 232Th fluxes (Burckel et al., 2015). We therefore focused our study on the time intervals during which the Pa/Th signal of core MD09-3257 can be interpreted in terms of circulation changes, i.e. HS2 and on the DO climate variability encompassing HS2 and HS4. ***

The issue of chronology may be even more crucial, as the authors draw potentially important conclusions about intervals that do not appear to coincide with their data exactly, or in one crucial instance, at all. Figure 3 makes this very clear. None of the shaded intervals truly represent interstadials. The red shaded intervals all cover some portion of one interstadial or another, but the oldest begins at the peak of GI10 and extends beyond the peak of the next stadial, the subsequent shading covers solely a portion of the transition from GI 8 to the next stadial, without including the interstadial peak at all, and the youngest of the three is the only one to cover the entire interstadial GI3, but also includes two times as much duration of full stadial conditions. This does not appear to be just a drafting issue, which might be easily remedied. The shading is well aligned with the sediment data, which largely do not coincide with the ice core evidence.

*** In figure 3, it is clear that every GI (in particular GI10, 8 and 7) is associated with a Pa/Th decrease (i.e. increased circulation intensity). The GI8 and GI10 time slices are well defined as periods of stable oceanic circulation (see section 2.3). Because GI3 is of shorter duration, it is possible that the GI3 time slice does not represent average interstadial conditions, as highlighted page 6, line 10 (see also comments from and answers to Roger François, 2nd reviewer). ***

In the case of the fourth time slice, HS2, the blue shading in Figure 3 aligns well with the new data, until there is an abrupt data gap above the most extreme values, apparently due to a turbidite layer. But the shaded interval is centered on 26 ka, when the published age for HS2 is more than one to two thousand years younger (Naafs et al., 2013, Hodell et al., 2008, Hemming, 2004). Because this interval is well dated, it seems that the new data are older than HS2, which might instead correspond and even be related to the turbidite interval.

*** It is important to distinguish the Heinrich Stadial (defined as the stadial (cold) period during which a Heinrich Event (HE) occurs) and the event itself, characterized by the sedimentary IRD layers. The Pa/Th increase that we observe and that is concurrent with the increase observed in core ODP1063 occurs during GS2, the cold period in the Greenland temperature record during which HE2 is observed in marine sediment cores. ***

A related question is how there appear to be data from this same interval, which is presented as a several thousand year gap in the supplemental figure S2.

*** Turbiditic layers were identified in core MD09-3256Q between 24.16 and 20.88 ka (gap in Figure S2). However, no sedimentary Pa/Th data from this core corresponding to this interval are presented in Figure 3 (last Pa/Th data at 24.16 ka). ***

The authors very reasonably identified intervals of stability in the circulation based on their data, to make the most informative comparison with the model results. These choices did not lead to direct comparisons with the Greenland climate variations, which they accurately describe as important intervals for which the past circulation is not fully or well understood At the very least these chronological issues should be confronted. If they can be adjusted or adequately explained, it will greatly enhance the significance of this study.

*** The fact that oceanic and Greenland signals do not align perfectly could be due to (i)-chronological uncertainties (ii)-real leads or lags of one signal compared to the other (iii)-the response time of geochemical proxies to changes in oceanic circulation. Note that chronological uncertainties were accounted for in calculating the uncertainties associated with the Pa/Th values of each time slice (see supplementary material). ***

Specific comments-

As mentioned in the introduction, the 13C data should have complications due to carbon cycling as well as ocean circulation. These can also be better addressed when interpreting the different time slices, and may help to explain differences in the data not due to circulation.

*** We lack data on changes in marine productivity at the studied sites so we cannot investigate what fraction of the benthic d13C might reflect these changes. We thus follow the classical assumption that d13C reflects changes in bottom water ventilation. ***

The authors describe an important change at the onset of HS2. Aside from the chronological issues, do they infer that the observed changes relate only to the HS2 interval, or do they establish the LGM condition that is the focus of so many studies? If it was only during HS2, was the configuration and strength then different from LGM?

*** The change that we observe at the onset of HS2 in core MD09-3257 specifically relates to the HS2 interval, as we observe an increased Pa/Th at the beginning of GS2. Based on Pa/Th and d13C data in cores MD09-3257 and GeoB3910, the onset of the LGM appears to be characterized by an active circulation, however not as active as that of the Holocene. ***

The changes at various depths appear to be under-constrained by the data, in particular because some time slices utilize four sites and others more, but never more than six locations, and no two time slices utilize the same set of locations. This limits the confidence bounds possible in the interpretations, and must allow other consistent alternatives, which should be mentioned and possibly discussed.

*** We agree with reviewer #1's comment and added the following two sentences at the end of section 2.4 to clarify our argumentation: "Note that due to the limited number of sedimentary Pa/Th records during MIS3, we can only provide an approximate estimate of water mass boundary positions. Our equatorial transect is however ideally located to record shifts in the position of the transition between southern and northern sourced water masses." ***

The contrast between the inferred interstadial mode and HS2 mode appears to be related to which direction the waters were moving below 2500 meters. Does that mean that the deep Atlantic was influenced by southern source waters below 2500 in both scenarios?

*** Based on our results, we infer that the Atlantic was likely influenced by southern sourced waters below 2500 m during HS2 but we lack data to determine the precise vertical extent of this southern-sourced water mass. In contrast, during Greenland Interstadials, the transition between southern- and northern-sourced water masses was probably located between 3500 and 2500 m, which would explain the low Pa/Th gradient between our equatorial sediment cores. ***

Many schematic and model representations of the deep Atlantic display a boundary between northern and southern waters that is inclined as a function of latitude. Do the authors consider that also to be possible in their reconstructions?

*** The models representing the deep Atlantic (i.e. streamfunctions, Fig.2, b, d, f), do not display an inclined boundary as a function of latitude. However, the simulated sedimentary Pa/Th (Fig.2, a, c, e) do show increasing sedimentary Pa/Th with latitude along the flow path of any newly formed water mass. We explain this effect page 5 line 11. ***

The presented model shows that boundary to slope deeper to the south in the Holocene, which might suggest that northern waters influence more of the volume of the south Atlantic than the north. Perhaps this can be explained and clarified for those less familiar with this type of geochemical modeling.

*** We are afraid we do not fully understand this question. To render our argumentation accessible to the non-specialized audience, we describe the behavior of dissolved Pa and Th and how this influences the output of the model (see section 2.1.2 and 2.2.1). For a more thorough explanation, we refer the reader to the chapter book by Francois, 2007 (main principles of Pa/Th as a proxy of oceanic circulation intensity) and to the Luo et al., 2010 paper (description of the 2D Pa/Th model). ***

Is the southward flowing mass at intermediate depth GNAIW? Several studies men-

tioned have inferred a vigourous circulation by this water mass, at least at the LGM. The contrasting conclusion of a sluggish intermediate circulation here is largely based on 13C from the productive equatorial region. Nevertheless, it would be useful to have a more direct discussion in the context of previous interpretations.

*** We make sure not to describe the southward flowing water as GNAIW, as it is indeed defined for the LGM and our study concerns earlier time periods. Our conclusion concerning the sluggish intermediate water mass only relates to HS2. We then see a decrease in Pa/Th (i.e. likely an increase in the overturning intensity) at the onset of the LGM.

Also, we made a few minor changes in order to make clear that we were careful not to over-interpret benthic d13C:

P.5, l.28: the sentence “Moreover, benthic foraminiferal d13C measurements, which reflect the DIC of the water mass directly above the sediment interface, allows confirming or infirming the geometry information contained in measured Pa/Th values.” was removed.

P.8, l.30: the sentence “the high d13C values of core SU90-03 and MD09-3257 indicate that northern sourced waters were present at $\sim$2500 m in the North and equatorial Atlantic” was changed to “the high d13C values of core SU90-03 and MD09-3257, and low d13C values of core MD02-2594 (< 0.5‰ Negre et al., 2010), indicate that northern sourced waters were present at $\sim$2500 m in the North and equatorial Atlantic”.

P.11, l.13: “deep waters likely dominated the deep Atlantic Ocean” was replaced by “deep waters likely filled the deep Atlantic Ocean”. We also removed the word “direct” in the sentence : ”The direct influence of the southern-sourced water mass likely extended. . .”.

P.11, l.17: we removed “and their associated return flow” from the sentence “. . .it is difficult to assess the exact position of the southern sourced waters and their associated return flow.”

P.11, l.17: we removed the word “directly” in the sentence “This water mass probably directly affected the equatorial Atlantic. . .”.***

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