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Interactive comment

# *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.

**P. Burckel et al.**

burckel@ipgp.fr

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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



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

Referee #2 (R. Francois)

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Burckel et al combine new and published sediment Pa/Th and benthic d13C data with 2D simulations to assess the strength and geometry of the AMOC during 3 GIs and HS2 They chose these time intervals because they represent time periods with different ice sheet volumes. Their main conclusions are that AMOC during GIs consisted of a shallow northern overturning cell (likely weaker than the modern NADW) in the upper 2500m, above a deeper southern overturning cell whose volume flow would have been higher than modern AABW. During HS2, as per fig. 3, the circulation geometry stayed the same but was significantly more sluggish. To me, the take-home message of this study is that the Atlantic overturning circulation during glacial climatic extrema (i.e. Greenland intertadials and Heinrich stadials) had a similar geometry, and were differentiated only by the strength of the overturning cells, with stronger overturning cells during Greenland interstadials and weaker ones during Heinrich stadials. What may be the most surprising here is the apparent stability of AMOC geometry through the glacial period. However, I don’t think that circulation contrast between Greenland Interstadials and Greenland (non-Heinrich) Stadials has been clearly documented and discussed in the present manuscript.

General comments As indicated by the authors, the complete interpretation of sediment Pa/Th will require, to the extent possible, a synoptic database for each time slice of interest. The present study is a valuable contribution towards this end, but I have some questions and comments regarding some details of the interpretation of the data. Although I recommend "major revisions", I don’t think that the revisions I suggest are "major". However, as I am very interested in the topic, I would like to have the opportunity to see the replies of the authors.

Comparing sediment Pa/Th and the Greenland temperature record. If we accept that abrupt temperature changes in Greenland result from variations in heat transport coinciding with changes in the strength/geometry of the AMOC, one would not expect that changes in sediment Pa/Th would be concurrent with Greenland temperature changes. This is because of the response time of sediment Pa/Th to changes in circulation. For any abrupt change in overturning, the concentration of Pa and Th in the water column will adjust with an e-folding time equivalent to their residence time in the water column (ca. 100-200 y for Pa). It would thus take > 500 y to fully express the change in circulation in sedimentary Pa/Th. This may, in part, address the second question of the other reviewer, at least for GI 8 and 10. I suspect that GI3 may be too brief to yield a measureable Pa/Th signal. On the other hand, if d13C is truly a water mass tracer, then we would expect much less or no lag between the 13C signal and Greenland temperature. However, if decreases in d13C are due to accumulation of nutrients resulting from a sluggish circulation, we would also expect a lag. Another complication when comparing sediment circulation proxies with Greenland temperature is that the latter may also be modulated by the location of the site of deep water formation. Particularly striking is the lack of a Greenland temperature signal at the transition between GS3 and HS2 (as is the case between LGM and HS1).

*** We do not consider d13C as a perfect water mass tracer. The d13C of benthic foraminifera C. wuellerstorfi is a proxy of the nutrient content of bottom water masses, that we interpret as reflecting bottom water ventilation. For instance, reduced d13C at a site influenced by northern sourced waters could result from increased southern sourced water mass influence, or reduced deep water formation in the North Atlantic region. However, we would like to stress that we are not trying to resolve the timing between changes in deep water circulation and Greenland climate. Timing issues do not alter the interpretation of our time slices, as they are defined based on stable oceanic conditions during Greenland interstadials. ***

In fact, the present manuscript does not address another key question which is whether there are noticeable changes in AMOC between Greenland Stadials and Interstadials (they only contrast Greenland Interstadials and Heinrich Stadials). I would argue that Pa/Th distribution reported to GI3 is mostly a Greenland Stadial signal (because of the brevity of GI3), suggesting no or little changes in AMOC between Greenland Stadials and Interstadials. If this is the case, abrupt changes in Greenland temperature could reflect changes in the site of deep water formation, or northward transport of cooler/warmer surface water. This question could probably be directly addressed with another time slice to the discussion.

*** Because they span different depths on the Brazilian margin, cores MD09-3257 and MD09-3256Q Pa/Th records are particularly interesting to understand the geometry and strength of the AMOC during MIS3. Unfortunately we lack data in core MD09-3256Q during Greenland stadials. We therefore decided not to define stadial time slices. However, as we point out page 6, line 10, we agree that GI3 time slice might not reflect interstadial conditions. We have therefore added the following short paragraph (inserted P.9, l.20) to explain that this time slice may reflect stadial conditions and discuss the implications: "Based on our definition of Interstadial time slices, we assume that the GI3 time slice reflects interstadial conditions. However, because GI3 seen in Greenland ice cores is of relatively short duration, the Pa/Th signal of the studied sediment cores might not reflect full interstadial circulation conditions. Nonetheless, we consider it unlikely that the Pa/Th of GI3 reflects stadial conditions. Indeed, core MD09-3257 sedimentary Pa/Th values observed during GI3 are similar to those recorded during the GI8 and GI10 time slices that correspond to strict interstadials (Fig. 3).". ***

Additional comments Abstract; Line 21: "At the onset of HS2, the structure of the AMOC significantly changes" "Structure" is too vague a term. I think it is worth highlighting here that the present data set is interpreted to indicate that the geometry of the overturning circulation did not change (as per Fig. 7) but circulation was much weaker.

*** While this is indeed a possibility, we do not conclude that the geometry of the AMOC did not change between Heinrich Stadial 2 and Greenland Interstadials. We cannot say if the southern sourced water mass influence extended above 2500 m during HS2 (page 11, line 13). We removed the term structure and wrote “At the onset of Heinrich Stadial 2, the AMOC intensity and geometry likely changed”. ***

P2; line 4-5: “.. suggesting that other mechanisms could be required to explain Greenland temperature millennial scale variability” The accepted mechanism is heat transport by the AMOC. The presence of a shallow circulation cell during HS is not inconsistent with this mechanism and does not require an alternative explanation.

*** We agree with your point and therefore chose to use the terms “could be required”. In order to clarify the text, we modified the sentence as follows “. . . suggesting that Greenland temperature millennial scale variability might be related to more complex changes in Atlantic circulation than simply switching between “on” and “off” circulation modes.” ***

P2; line 14 – 15: I would suggest: However, interpretation of sediment Pa/Th from a single core can be ambiguous because similar values can result from different geometry and overturning strength (Luo et al., 2010). Reconstructing past circulation thus requires combining Pa/Th records from multiple sites over a wide range of latitudes and depths (refs).

*** Your suggestion makes the issue of interpreting a single core clearer by pointing the possibility of having multiple circulation intensities for a single sedimentary Pa/Th value. We modified the sentence following your suggestion. ***

P2; line 22: I would suggest: The streamfunction under Heinrich Stadial conditions* were simulated with the Earth System model Iloveclim (ref) while the Holocene streamfunction was derived from geostrophic velocity estimates (ref) *later on, this is becoming confusing, since the HS simulation does not fit the HS data..

*** We changed the sentence to: “One streamfunction is derived from present day geostrophic velocity estimates (Talley et al., 2003) and two others were simulated with





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the Earth System model iLOVECLIM under different climatic conditions (Roche et al., 2014)." As described below, we agree with your comment on the confusing nature of the terminology used and changed "HS1 streamfunction" into "Shallow overturning streamfunction". ***

P3; line 6 – 8: This should be moved to section 2.1.2.

*** Although we understand the potential issue of mentioning Pa/Th in the "Sediment cores" section, we prefer to group all cores at the beginning of the paper for the sake of clarity. ***

I note that the South Atlantic record of Jonkers et al is not mentioned. Is it because this core sedimentation rate is to low? It would still be worth checking if their glacial values are consistent with the AMOC scenarios presented here.

*** Unfortunately, none of Jonkers et al.'s Pa/Th data are within our time slices. However, the low sedimentary Pa/Th values that they describe fit very well with our assumptions of intensified deep water formation in the South Atlantic (it would help to systematically exclude the Holocene streamfunction). ***

P3; line 34: "Pa/Th records renewal rates of water masses ca. 1000m above the seafloor" While it is correct that sediment Pa/Th records Pa and Th scavenging mostly coming from the water ca. 1000m above the seafloor, it does not record renewal rates of this water mass. The scavenging of Pa and Th from this water mass is in part controlled by its Pa and Th concentration, which is influenced by the overall geometry and strength of the AMOC. That is why, as indicated by the authors, interpretation of sediment Pa/Th requires a synoptic database for each time slice of interest.

*** We agree that the sentence: "Pa/Th is a relatively recent tracer that records the renewal rate of water masses occupying the first $\sim$1000 m above the seafloor (Thomas et al., 2006)" could be misleading and we replaced it by "Pa/Th is a relatively recent tracer that can be used to estimate the renewal rate of water masses occupying the







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first ∼1000 m above the seafloor (Thomas et al., 2006, Luo et al., 2010)". ***

P3; line 40 I suggest "High (low) rate of overturning" rather than "High (low) flow rates.."If circulation was only horizontal and scavenging intensity uniform in the ocean, sediment Pa/Th would not be dependent on flow rate

*** We agree that overturning is indeed required for sedimentary Pa/Th. We changed the sentence following your suggestion. ***

P5; line 13: I would suggest: ..Pa/Th increases along the flow path of any newly-formed deep water masses*, as initially low dissolved Pa concentrations increase: : : *it is not true that Pa/Th increase along the flow path of any water mass.

*** We agree and changed the sentence following your suggestion. ***

P5; line 18-19: While there is no explicit parameterization of diffusive transport in the 2D model, it is present in the model and it is controlled by horizontal velocities and horizontal grid spacing. In the model used by Luo et al., the inherent mixing is about 800msôĂĂĂ2, which is in the upper range of the along-isopycnal tracer diffusivities. Therefore, it is not the lack of diffusive transport that prevents the model from simulating boundary scavenging. Instead, it is simply because it is a 2D model and there are no margins. Including boundary scavenging at ocean margins would require a 3D model (or an open 2D model).

*** Thank you very much for your input concerning the 2D Pa/Th model. We changed the paragraph into the following: : "The absence of margins in the simple 2D Pa/Th model (Luo et al., 2010) prevents it from simulating boundary scavenging, which is the transfer of dissolved protactinium from open ocean regions of high Pa concentrations to coastal regions of low Pa concentration such as in upwelling zones (Christl et al., 2010). However, as described in the results section, we verified that our Pa/Th signal is mainly driven by oceanic circulation changes and the importance of diffusive transport is therefore likely negligible here. This simple 2D Pa/Th model therefore appears adequate for comparison with our Pa/Th data." ***

P5; line 21 – 22: Boundary scavenging is weak in the Holocene Atlantic because of the short residence time of deep water in this basin (which results from a high overturning rate). This may not be the case for Heinrich Stadials and the expression of boundary scavenging at the margins during these events would depend on their duration. If the ocean stays in its Heinrich Stadial mode long enough (500 – 1000 years?) to start expressing boundary scavenging, the 2 D model will overestimate the Pa/Th in cores located in low productivity central basin regions and underestimate the Pa/Th in cores located at the margin. This needs to be kept in mind when interpreting the data

*** See below for answers concerning these concerns. ***

P5; line 35: As discussed above, if their duration is long enough, boundary scavenging should be expressed during Heinrich Stadials (if they are characterized by a very sluggish AMOC). If it is expressed during H4 but not during H2, this is an observation that needs discussion (was AMOC more sluggish during HS4? Was HS2 a briefer event? These questions should at least be raised). On the other hand, based on Fig. 3, it seems that boundary scavenging was also expressed during HS2 (as we would expect..)

*** Yes, we indeed have boundary scavenging during HS2, e.g. indicated by sedimentary Pa/Th ratios above the Pa/Th production ratio. However, we showed in a previous study that changes in sedimentary Pa/Th are mainly driven by oceanic circulation changes in core MD09-3257 (Burckel et al., 2015). On the contrary, HS4 Pa/Th values in core MD09-3257 appear to be mostly driven by vertical terrigenous fluxes (Burckel et al., 2015). We therefore chose to exclude these values (open squares in Fig. 3) and HS4 when discussing oceanic circulation. ***

Fig. 1: I suggest adding a panel showing long/lat of the cores to make it easier to visualize how boundary scavenging could affect Pa/Th in each core

*** We agree with your comment, but table S1 already lists the cores' positions and depths, along with the age models used. We therefore prefer to add a second panel to Figure 1 to show the position of all cores in the Atlantic Ocean. ***

Fig. 3 caption: I don't understand "average Pa/Th for each core is represented by the lines"

*** We mean "Replicates averaged Pa/Th signal". We modified the sentence: "In (a) the average Pa/Th for each core is represented by the lines and individual measurements by diamonds or squares (MD09-3257)." into "In (a) lines pass through average Pa/Th values in case of replicates, while diamonds and squares (MD09-3257) correspond to individual Pa/Th measurements". ***

P6; line 21: I would remove "indicating the absence of Pa export" Instead, Pa/Th > 0.093 indicates the influence of boundary scavenging in this margin core. We wouldthen expect that the 2D model underestimate the measured Pa/Th. Likewise, we would expect that Pa/Th measured in open ocean cores during that time would be lower than those generated by the model.

*** We would like to keep this sentence, as high Pa/Th signal at that time is reflecting reduced overturning rates. If we were to write "indicating boundary scavenging", we fear that the reader might think that sedimentary processes are overprinting the oceanic circulation information. Moreover, because reduced Atlantic basin width at the latitude of our Brazilian sites could result in an overestimation of simulated sedimentary Pa/Th (Lippold et al., 2011, see p.9, l.33 of the manuscript), the underestimation of sedimentary Pa/Th due to the absence of boundary scavenging in the 2D model might be partially or totally compensated on the North Brazilian margin. ***

P6; line 22: "Pa/Th variability associated with GS and GI is observed" Pa/Th for GI 10, 8 and HS2 (and 4; I am not sure why HS4 is not considered in the discussion; boundary scavenging is also apparent during HS2) are well documented. If the authors want to discuss AMOC variability between GS and GI, however, they need to add and discuss





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another time slice corresponding to a GS (same remark for p7; line 19)

*** Although there seems to be a difference between GI and GS oceanic circulation based on core MD09-3257 Pa/Th record we do not want to discuss variability between GS and GI because we lack a more comprehensive picture of the circulation during GS due to the absence of Pa/Th data in core MD09-3256Q during these periods. ***

Section 4.2.1 GI data fit well with the HS1 simulation (particularly is the latitude of deep water formation is adjusted). On the other hand, HS2 data do not fit well with HS1 simulation. This is confusing. If we accept the interpretation of the HS2 data, that would mean that the so-called HS1 simulation does not simulate circulation during Heinrich Stadials. Shouldn't then this simulation be called something else? (e.g. shallow, moderate overturning circulation scheme or such). What is the basis for taking the "HS1" streamfunction as representative of Heinrich Stadial circulation?

*** The names of the streamfunctions originate from the paper of Roche et al., 2014. The HS1 streamfunction is generated with a 0.16 Sv freshwater forcing in the Labrador Sea and allows for the presence of a shallow overturning cell, while a 0.35 Sv forcing results in the absence of deep-water formation in the high latitude North Atlantic (off-mode). However, we agree that calling one of the streamfunctions HS1 is confusing, especially when compared to the HS2 time slice. We therefore renamed this streamfunction "Shallow overturning streamfunction" in the entire manuscript. ***

P11; line 33: "Our data shows that the geometry of the AMOC changed at the onset of HS2" As illustrated on Fig. 7, the geometry did not change, only the rate of volume transport changed.

*** You are right, we modified "changed" into "likely changed". Based on our data we cannot determine the exact vertical extent of the southern sourced water mass on the Brazilian margin. We also modified Fig. 7 in order to picture the uncertainty on the vertical extent of the southern sourced water mass in the HS2 time slice. ***

S2 (Pa/Th uncertainties) I don't understand the meaning of "Hence, Pa/Th values associated with each time slice on core MD.. is invariant, despite dating uncertainties"

*** Because time slices are defined based on MD09-3257 Pa/Th signal, age uncertainties do not affect Pa/Th uncertainties associated with each time slice in this core. For all other cores, age uncertainties affect the Pa/Th uncertainties associated with each time slice. This has been clarified in the text. The new sentence reads: "Hence, Pa/Th values associated with the different time slices in core MD09-3257 are independent from the age model. For all other cores, dating uncertainties account for Pa/Th uncertainties associated with each time slice." ***

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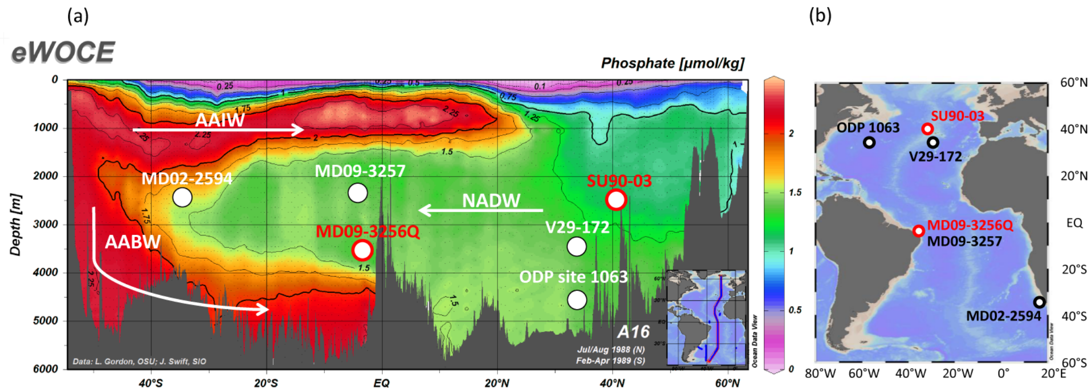


**Fig. 1.** Figure 1





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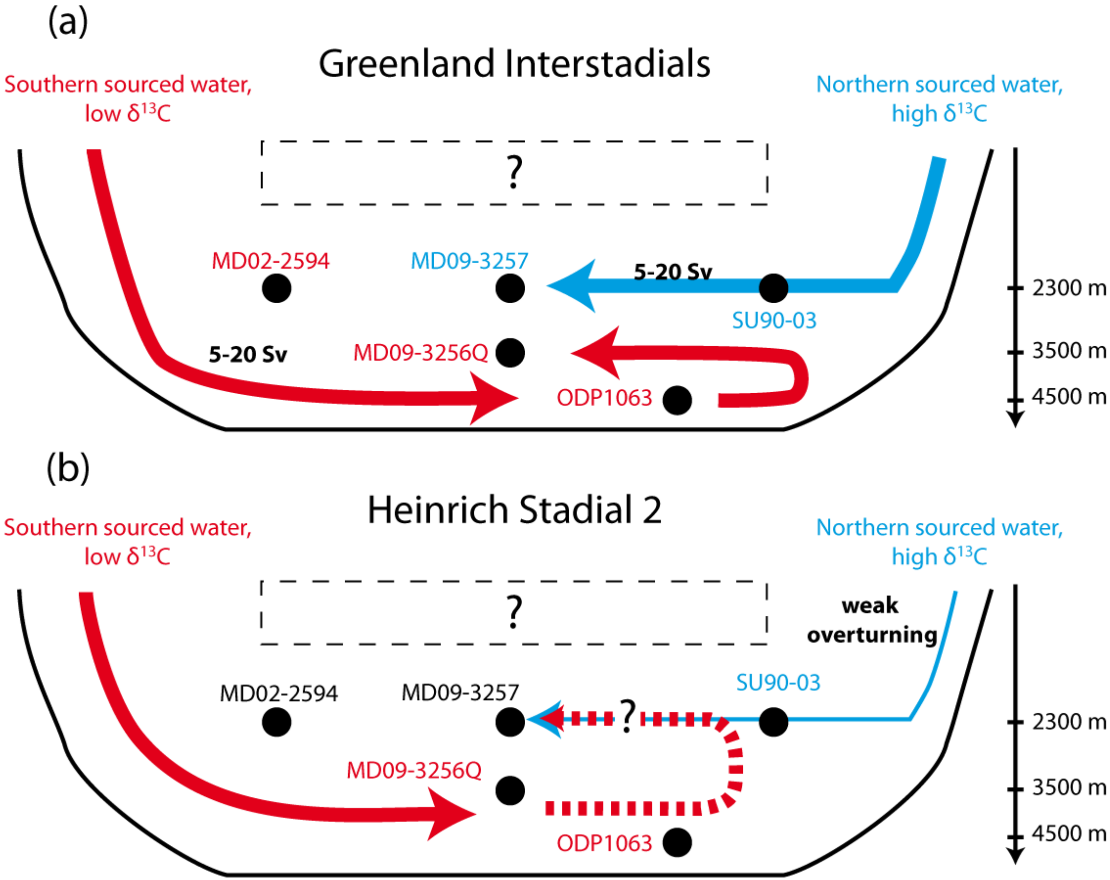


**Fig. 2.** Figure 7