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Climate of the Past
Discussions
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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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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.

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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

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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). 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.

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.

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.

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 geom-

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etry 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).

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..

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

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.

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

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.

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

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horizontal grid spacing. In the model used by Luo et al., the inherent mixing is about 800ms−2, 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).

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

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..)

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

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

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 would

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then 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.

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

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?

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.

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”

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