Detailed response to Referee 2's comments

We are very grateful for the constructive and helpful comments we received from both reviewers. Accounting for them has been of great help to improve the manuscript.

Waelbroeck et al. have measured Ti/Ca and Pa/Th in a core taken on the margin of northern Brazil, which records rainfall on the nearby continental area and the strength of the Atlantic meridional overturning circulation at intermediate depths. Since the two measurements are done on the same core, they are able to determine the phase relationship between the two variables with minimum uncertainty, which gives them new insights into the response of the ITCZ to changes in the AMOC. They use wavelet analysis to determine phase lags at different frequencies and show that ITCZ movement lags changes in AMOC both at the D/O and HE frequency, but more so at the HE frequency. They attribute this difference to a positive feedback between the strength of the AMOC, seawater temperature and iceberg discharge, which they had first proposed in an earlier publication. The authors pay due attention to the possible impact of bioturbation on the phase relationship between Ti/Ca and Pa/Th, which they convincingly rule out, and to multiple caveats in the interpretation of Pa/Th in term of circulation changes. The paper is clearly written and provides important new findings. I recommend publication after considering the relatively minor comments below (note, however, that I am unable to provide knowledgeable comments on the technicalities of wavelet analysis).

While the authors have clearly established the lag between Ti/Ca and Pa/Th, their ultimate goal is to establish the lag in the response of the ITCZ to changes in AMOC. I think the authors should also discuss the extent to which there might be lags between processes and proxies. For instance, would a change in AMOC translate instantaneously into a change in Pa/Th in their core? I think this is unlikely. Pa/Th recorded in sediments is controlled by the ratio between lateral transport by circulation and vertical transport by scavenging of the Th and Pa produced in the water column. Even if seawater were flowing from the north Atlantic to the Brazilian margin through a pipe (i.e. changes in deep water formation would translate into an instantaneous change in lateral velocity in the pipe), there should still be a lag between sediment Pa/Th and changes in AMOC, depending on the response time of dissolved Th and Pa in the water column overlying the coring site. While the response time of Th is decadal, the full expression on circulation changes on Pa may take several centuries. In addition, the "pipe" is of course an unrealistic cartoon of the AMOC. In reality, I would expect an additional lag between lateral velocity at the coring site and changes in deep water formation, but at this point this is just intuitive and it is well beyond me to guess how long or how short this lag would be. Nonetheless, I think the authors could bring this up and indicate that the lag between Ti/Ca and Pa/Th should be taken as a minimum of the lag of the response of the ITCZ to changes in AMOC. There might also be a lag between Ti/Ca and the change in the seasonal latitudinal range of position of the ITCZ depending on the location of the region supplying lithogenics to the coring site. For instance, if the region is farther south from the southernmost zone of precipitation before the change in AMOC, it may take more time for the ITCZ to reach this region.

We thank Roger François for this important remark. We agree that we should explicitly mention the fact that a change in AMOC does not translate instantaneously into a change in Pa/Th.

To do so, we have added the following few sentences to the paragraph starting at line 25 on p. 13 "[…] our results indicate that rainfall increases in the region adjacent to MD09-3257 occurred several hundred years after the increase in sedimentary Pa/Th at our core site.":

"Furthermore, this lead of sedimentary Pa/Th over ln(Ti/Ca) should be taken as a minimum of the lead of AMOC over ln(Ti/Ca) because a change in AMOC does not translate instantaneously into a change in sedimentary Pa/Th. A delay between a change in AMOC and the resulting change in sedimentary Pa/Th is expected, which depends on the propagation time of the circulation change to the core site and on the response time of dissolved Th and Pa in the water column overlying the core site (i.e. 30-40 for ^{230}Th, 100-200 y for ^{231}Pa (François, 2007)). However, increases or decreases in sedimentary Pa/Th should be measurable before the dissolved Th and Pa have fully adjusted to the new circulation regime, especially at sites with high sedimentation rates as at our study site. We thus expect this additional delay to be less than 100 y and much smaller than the computed lead of MD09-3257 sedimentary Pa/Th over ln(Ti/Ca)."

Concerning a possible lag between Ti/Ca and the change in the position of the ITCZ, we have specified in the submitted manuscript that our marine core records can only inform on rainfall changes over the catchment area of the rivers which directly deliver sediment to the study site, that is, over the adjacent continent. Rainfall changes in a region located north of this catchment area may occur before the rainfall changes recorded in our marine cores but we have no means to assess such a delay. We thus prefer not add anything on this subject to text.

While the authors have taken into account how changes in scavenging could obscure the interpretation of Pa/Th in terms of circulation, I think it would also be worth mentioning that interpreting changes in circulation from a single core can also be problematic. While it is correct that higher rate of AMOC should result in a lower sediment Pa/Th when averaged over an entire ocean basin, that may not be correct for any core. Depending on the proximity of the coring location to the site of deep water formation, decreasing the AMOC may actually decrease sediment Pa/Th (e.g. Luo et al., 2010; Fig. 14). I would suggest specifying that we would expect to see an increase in Pa/Th with decreasing rate of AMOC at the coring site of this study because it is sufficiently removed from the site of deep water formation.

Accordingly, I would change the wording on line 4-5 p5: "[*when average over an entire ocean basin*], high (low) flow rates therefore result in high (low) Pa export…"

We are aware that a change in AMOC can produce very different sedimentary Pa/Th signals depending on the location of the cores with respect to that of deep water formation, as demonstrated in Luo et al. (2010).

We have changed the wording on line 4-5 p. 5 as recommended, and modified

"High (low) flow rates therefore result in high (low) Pa export…"

into

"When averaged over an entire ocean basin, high (low) flow rates therefore result in high (low) Pa export…"

Also, we agree that deriving the state of AMOC from a single core location is prone to error. MD09-3257 is however located in an area where the measured Pa/Th vertical profile in core top sediments is consistent with a dominant role of the overturning circulation (Lippold et al., 2011), as explained p. 5, line 11-15 of the submitted manuscript.

Line 26, p7: shorter stadial may have lower increase in Pa/Th because they were too short to allow the full expression of the increase in Pa/Th (limited by the response time of Pa in the water column).

The Dansgaard-Oeschger (D-O) stadials discussed in the present paper have durations of about 1000 y, which is much longer than the response time of dissolved Pa in the water column (100-200 y for ^{231}Pa (François, 2007)). Therefore, the response time of dissolved Pa in the water column cannot be the reason for the lower increase in Pa/Th of D-O stadials with respect to Heinrich stadials. Rather, as explained p. 13, lines 27-31 and p. 14 lines 1-2 of the submitted manuscript, we suggest that a positive feedback involving iceberg discharges is only triggered in the case of Heinrich stadials. In contrast, AMOC slowdowns associated with D-O stadials would not trigger such a positive feedback loop and would hence remain limited.

Line 10, p8: (including Pa/Th values susceptible to be partially impacted by large particles flux [*or boundary scavenging resulting from slower AMOC*])

We have added "or boundary scavenging resulting from slower overturning circulation" to the parentheses p. 8, line 10, as recommended.

Line 24, p12: Why not use Th-normalized Ti instead of Ti/Ca to totally eliminate the effect of changes in carbonate dissolution/production?

This is an interesting suggestion. In our manuscript, we relied on the interpretation of the Ti/Ca signal given in former studies of the same area, but our $^{230}Th_{xs,0}$ measurements do indeed give us the opportunity to directly compute Th-normalized Ti flux in order to eliminate the effect of changes in carbonate dissolution and production on the Ti/Ca signal, if any.

We have computed core MD09-3257 Th-normalized Ti signal and compared it with the Ti/Ca and Ti signals in the following figure.

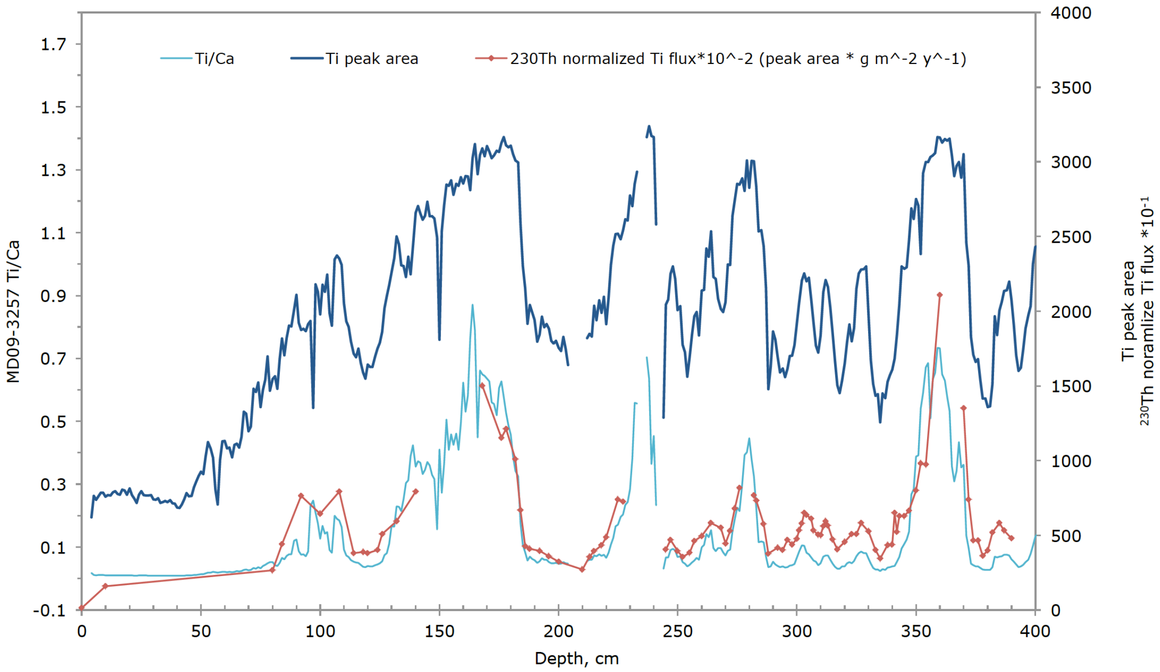

Figure 1. Comparison of core MD09-3257 Th-normalized Ti, Ti/Ca and Ti signals.

We see that the Th-normalized Ti signal is indeed very similar to Ti/Ca, thereby confirming that the Ti/Ca signal is not biased by changes in carbonate dissolution or production.

However, MD09-3257 Th-normalized Ti signal is measured at much lower resolution then MD09-3257 Ti/Ca, and suffers from gaps over the Heinrich stadials. Therefore, the use of MD09-3257 Ti/Ca instead of the Th-normalized Ti signal remains the best option for the present study.

Line 8; p13: Briefly describe what the "independent approach" is.

We have modified the sentence

"This lead is comparable to the relative phase previously estimated between MD09-3257 Pa/Th and Ti/Ca at the onset of HS4 (690 ± 180 y) and HS2 (1420 ± 250 y) respectively, using a completely independent approach (Burckel et al., 2015)."

into

"This lead is comparable to the relative phase previously estimated between MD09-3257 Pa/Th and Ti/Ca at the onset of HS4 (690 ± 180 y) and HS2 (1420 ± 250 y) respectively, based on the identification of the transition in the Pa/Th and Ti/Ca signals at the beginning of these two stadials (Burckel et al., 2015)."

Cited references

François, R.: Chapter Sixteen Paleoflux and Paleocirculation from Sediment 230 Th and 231 Pa/230 Th, Developments in Marine Geology, 1, 681-716, 2007.

Lippold, J., Gherardi, J.-M., and Luo, Y.: Testing the 231Pa/230Th paleocirculation proxy: A data versus 2D model comparison, Geophys. Res. Lett., 38, doi:10.1029/2011GL049282, 2011.

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