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Climate of the Past Discussions

Interactive comment on "Mid-pliocene Atlantic meridional overturning circulation not unlike modern?" *by* Z.-S. Zhang et al.

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Dear Editors and Reviewers,

We very much appreciate the reviewers' comments and have taken all of them into account in the revised manuscript.

In the text below, we first address comments common to both reviewers, followed by replies to the reviewers' comments point-by-point.

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Comments common to both reviewers:

Both reviewers find that we place a lot of weight in the Hodell data set, and the second

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reviewer suggests to add d13C from other sites (for example the Caribbean and Ceara Rise).

Reply:

In this study, we only consider continuous d13C records published and freely available (as compiled by Hodell and Venz, 2006). Although we do not include continuous d13C series for the sites as suggested by the reviewer, we include an analysis of d13C records from Sites 999, 925 and 981/980 in the revised manuscript.

We received the d13C data of Site 999 from Gerald Haug. Unfortunately, we do not get d13C data covering the period ∼2-0 Ma from Sites 999 or 1000. From the available data, we do not observe a significant negative trend in d13C in the period 3.25 to 2 Ma (Figure A1b).

We digitalized the d13C data of Site 925 from the two papers written by Bickert et al. (1997) and Billups et al. (1997). From the available data, we do not observe a significant negative trend in d13C in the period 3 to 0 Ma (Figure A1c).

We also analyzed the d13C data of site 981/980 from Maureen Raymo's website (covering period 0-1.8Ma) and in the NOAA database (covering period 3.2-3.9Ma, Draut et al., 2003). These data does not show a significant trend in d13C over the period 3-0Ma (Figure A1a).

It should be noticed that 1) d13C gradient is a more reliable index to indicate AMOC than d13C evolutions at single site; 2) it is only reasonable to compare the large scale patterns and trend in the data and the models. Our point is that the largest changes occur in the Southern Ocean, and that the North Atlantic changes are much smaller (less significant). This is the first order pattern in both data and the simulation with the NorESM-L. Even the d13C serials from Site 999, Site 925 and Site 981/980 are added into Hodell data set, this first order pattern is not changed (Figure A1d).

In the revised version, we add the following sentence in the discussion section. "Even

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when considering changes in δ13C from others sites in the North Atlantic (Sites 999, 925, 981/982, Bickert et al.,1997; Billups et al., 1997; Haug and Tiedemann, 1998; Draut et al, 2003), the first order pattern of δ13C changes found by Hodell and Venz (2006) remains."

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Reviewer 1

First let me say that regardless of the semi agreement among some of these PlioMIP simulations, the conclusion that the Pliocene North Atlantic Ocean was not demonstrably different than the present day, flies in the face of a tremendous amount of proxy data. As someone with a fair bit of experience in the North Atlantic, I can tell you that the faunas, benthic and planktic, show marked changes as does the chemistry of the bottom waters. I realize this isn't much of a comment for an author to be able to respond to, but at the least I would go back and reword things a bit.

Reply:

We appreciate this comment and would like to clarify that we do not claim that the mid-Pliocene North Atlantic was similar to today. We only conclude that the mid-Pliocene Atlantic Meridional Overturning Circulation (AMOC) is similar to today's situation, not much stronger as suggested by earlier proxy studies.

In the revised version, we emphasize that the changes in the strength of the AMOC and in the properties and vertical structure of the Atlantic ocean should be distinguished:

"However, it should be stressed that these findings do not imply that the structure of mid-Pliocene Atlantic ocean circulation is equivalent to the pre-industrial/late Quaternary. The mid-Pliocene Atlantic ocean circulation is clearly different to pre-industrial/late Quaternary, for example, the mid-Pliocene North Atlantic surface is much warmer than pre-industrial/late Quaternary (Dowsett et al., 2009). However, these changes should not be simply attributed to a stronger AMOC. A more likely candi-

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date for the reconstructed North Atlantic surface warming is increased radiative surface forcing, which is dominated by increased atmospheric CO2 levels, solar insolation (Haywood et al., 2013b), and the reduced size of the Greenland ice sheet (Lunt et al., 2012)."

You cite Lawrence et al., Naafs et al. and several of the PRISM papers (Dowsett et al.) as reconstructions. I'd be very careful. Those first two references are technically reconstructions but you are looking at individual sites, in high resolution, over several million years. The PRISM reconstruction is basically a time slice (or slab). Comparing the three of them is somewhat mixing apples and oranges. Lawrence et al. barely gets back to the interval of time the authors were attempting to simulate. The PRISM reconstruction is an average of interglacials (for want of a better word) over 240,000 years.

Reply:

The sentence "The PRISM3 SST reconstructions are comparable to other independent reconstructions such as Naafs et al. (2012) and Lawrence et al. (2010)." is deleted.

The conclusion has two troubling points. (1) the Pliocene was not unlike the modern. Back to my first statement above. Take a look at the actual data and you would find it difficult to support such a statement (your simulations not withstanding). You place a lot of weight in the Hodell data set...

Reply:

Please see the reply at the beginning of this response. Even changes of δ13C from others sites (Sites 999, 925, 981/982) in the North Atlantic are also considered, the first order pattern of δ13C showed by Hodell and Venz (2006) is not changed. The PlioMIP simulation and the δ13C gradient do not support that mid-Pliocene AMOC is much different to pre-industrial/late Quaternary.

(2) You do mention this in your discussion but from a readers standpoint, you seem to

neglect at least two of the simulations that are contrary to your conclusion. I'm not sure how you can do this? If we are to learn from these fantastic model experiments, I think we need a much more in-depth discussion of why two, maybe three? of the simulations do not show what you are concluding. What is different about those models? There must be other applications of all 8 models that would lend insight into why things are coming out the way they do.

Reply:

The earlier strong AMOC theory suggests that the much stronger AMOC increased northward ocean heat transport thus caused the large warming at the Atlantic surface in the mid-Pliocene. However, no model in the PlioMIP supports this theory. Even in the simulations with MRI-CGCM2.3, GISS-ModelE2-R and COSMOS there is a significant increase in the AMOC maximum for the Pliocene, the ocean heat transport increase is minor (3%, 4 % and 6%). The Atlantic surface warming simulated in the PlioMIP is clearly not caused by the stronger AMOC and increased northward ocean heat transport. Therefore, we conclude that changes in mid-Pliocene AMOC (compared to the present/late Quaternary) do not play a decisive role in explaining the reconstructed warm surface temperatures in the high latitude North Atlantic, as has been suggested by earlier studies.

In the revised version, we add the sentence "Earlier studies suggest that a significant increase in northward ocean heat transport, caused by a strengthening of the AMOC, is required in order to explain the surface warming of the high-latitude North Atlantic in the mid-Pliocene. However, the PlioMIP simulations presented here do not support this theory."

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Reviewer 2

The comparison with proxy records is mainly based on the Hodell and Venz paper with short mentioning of Raymo et al. and Ravelo and Andreasen. I would add the records which were generated in the Caribbean (Sites 999 and 1000), Ceara Rise (Site 925) (and possibly NW-Africa (Site 659)) which show high-resolution reconstructions of benthic d13C (Haug and Tiedemann, 1998; Haug et al., 2001; Steph et al., 2010). These studies do not work with the d13C gradient over the Atlantic but rather look at the end-members of the southern and northern water masses, resp., as well as the interplay between upper- and lower-NADW. These studies do suggest a stronger AMOC too. Besides, the distinction between upper and lower NADW would be an interesting comparison with the data results suggesting the depth change in the overturning cell.

Reply:

Please see the reply to common question, at the beginning of this response. Even changes of δ13C from others sites (Sites 999, 925, 981/982) in the North Atlantic are also considered, the first order pattern of δ13C showed by Hodell and Venz (2006) is not changed. δ13C from these site does not indicate the changes in NADW depth sufficiently, though the PlioMIP simulations show the AMOC cell become shallow.

What are the errors associated with these experiments? Coming from a non-modeling background I wonder what the real impact is of a, for example, 4% change in the heat transport, especially when the results between different models seem to vary up to 100%. Is this the reason to suggest that no significant change in comparison with today occurred? Such variations in modeling experiments are definitely too small to reconstruct with proxy studies and might, as such, be overlooked in downcore records.

Reply:

Supposing the total heat flux received by the Atlantic surface does not changed, when northward ocean heat transport is increased in the Atlantic, the total South Atlantic will be cooled down, and the total North Atlantic will be warmed up. However, the increased heat will redistribute from surface to deep in the North Atlantic. Although the increased heat causes warming at the surface North Atlantic, it does not mean the surface warming in the North Atlantic has a simply linear relationship to the increased northward ocean heat, since there are other factors (eg. vertical mixing) influenced the redistribution of increased heat in the North Atlantic. Therefore, the control of the AMOC on transport of heat to high latitudes, and thereby high latitude ocean surface temperature (as suggested by the earlier strong mid-Pliocene AMOC theory) is questionable.

Although the PlioMIP simulations vary between the models, none of them shows remarkable increases in the northward ocean heat transport. Even in the simulations with MRI-CGCM2.3, GISS-ModelE2-R and COSMOS, where there is a significant increase in the AMOC maximum for the Pliocene, the ocean heat transport increase is minor (3%, 4 % and 6%) and the simulated warming at the surface of the North Atlantic is weaker than the PRISM reconstructions. Thus, none of the PlioMIP models supports the conclusion that the mid-Pliocene surface warming in the North Atlantic is mainly caused by a significant increase in northward ocean heat transport, as suggested by earlier studies.

In the revised version, we revise the paragraph in the discussion section.

"Although there is a significant model spread, none of models simulate a significant increase in northward ocean heat transport (Figure 3b). Earlier studies suggest that a significant increase in northward ocean heat transport, caused by a strengthening of the AMOC, is required in order to explain the surface warming of the high-latitude North Atlantic in the mid-Pliocene. However, the PlioMIP simulations presented here do not support this theory. Even in the models (MRI_CGCM2.3 and GISS-ModelE2-R), which show a large increase in AMOC maximum, the heat transport does not increase significantly (3% and 4%). Therefore, based on the PlioMIP model results, changes in the AMOC or Atlantic ocean heat transport does not play a dominant role in setting the pattern of North Atlantic SST during the mPWP."

Title: “not unlike modern?” feels a bit awkward. I suggest changing this into something like “similar to the modern situation”.

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Reply:

We agree with the reviewer that phrasing the title as a question is not optimal and have therefore edited by removing the questions mark and thereby making the title a statement of the main conclusion of the paper.

Page 1304, Lines 4-7: How is the warming in the North Atlantic explained then?

Reply:

A more likely candidate for the reconstructed North Atlantic surface warming is increased radiative surface forcing, which is dominated by increased atmospheric CO2 levels, solar insolation (Haywood et al., 2013b), and the reduced size of the Greenland ice sheet (Lunt et al., 2012). Please see page 1305 line 25 to page 1306 line 2 in the discussion paper.

Page 1305, Line 20: add "the" before AMOC.

Reply: The sentence is rewritten.

Page 1306, Line 5: add "modern" before NADW. Line 25: add "and" before in the.

Reply: Done

Page 1308, Line 3: add "the" before other.

Reply: Done

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References

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2. Billups, K., A. C. Ravelo, and J. C. Zachos (1997), Early Pliocene deep-water circu-

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3. Draut, A.E., M.E. Raymo, J.F. McManus, and D.W. Oppo. 2003. Climate stability during the Pliocene warm period. Paleoceanography 18(4):1078.

4. Haug, G. H., and R. Tiedemann (1998), Effect of the formation of the Isthmus of Panama on Atlantic Ocean thermohaline circulation, Nature, 393, 673–676, doi:10.1038/31447.

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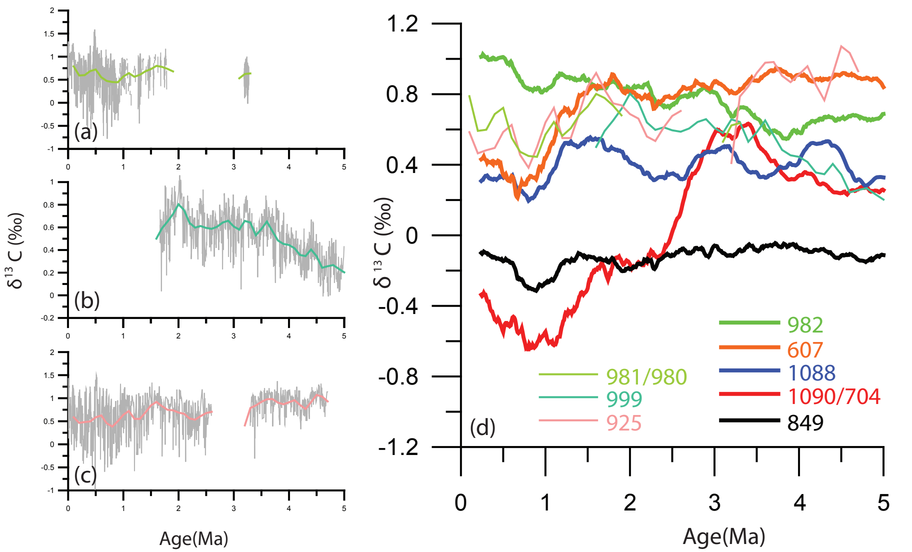

Figure A1. Smoothed d13C from Sites 980/981, 999 and 925 with comparison to the d13C compilation by Hodell and Venz(2006). (a) d13C from Sites 980/981, the grey line shows original data from Maureen Raymo's website (http://www.moraymo.us/climate_archives.php#natl) and Draut et al. (2003), and the bold green line shows running averages of 0.2Ma windows (the trend). (b) d13C from Sites 999, the grey line shows original data from Haug and Tiedemann (1998); and the bold aqua green line shows the smoothed trend. (c) Digitized d13C from Site 925(grey, Bickert et al. 1997; Billups et al. 1997), and smoothed trend (magenta). (d) Smoothed d13 of Sites 980/981, 999 and 925 plotted against the d13C compilation by Hodell and Venz (2006).

Fig. 1.