

Response to Reviewer #1

Author's Response (AR): We would like to thank the reviewer #1 for his/her comments on our manuscript and the suggested corrections/improvements that he/she wrote. We answer below to each point raised by the reviewer.

This study presents the influence of oceanic geothermal heating (OGH) on the paleo ocean, specifically the LGM. This is not the first study to test the influence of geothermal heating on the global ocean, but its novel contribution is testing previously theorized salinity and temperature changes under a paleo climate in a well cited global coarse resolution (2degree) ocean/ice model. Overall, the paper is a useful contribution to the geothermal heating model literature and CPD readers. I suggest the paper requires minor revisions to be acceptable for publication.

Specific comments: INTRODUCTION: I think you need to make it clearer that this study differs from, for example, Adkins et al. (2005) because here you're actually testing the theories in a global ocean/ice model with realistic bathymetry. This will help strengthen the novel nature of the study.

AR: On line 57–59, we re-wrote the sentence into: “In the present study, we tested previously posed theories (e.g., Adkins, 2005) of the impact of the OGH on a glacial ocean state by using the forced LGM global configuration of Ballarotta (2013) setup with realistic bathymetry and atmospheric forcing.”

TERMINOLOGY: Often thermohaline circulation is used, but it is not specified where in the global ocean, or what part (upper lower, deep/bottom, etc.). Clarification is needed. Also, I suggest changing “effective” to “residual” or “total” when describing the combined Eulerian and eddy overturning circulation.

AR: When “thermohaline circulation” is used alone it means that we refer both to the upper and deep cells, otherwise we mention abyssal thermohaline circulation to refer to the deep cell. We have changed the term “effective” to “residual”. Note the term “effective” has been used in the paper of Emile-Geay and Madec (2009).

GRAMMAR: The grammar is fine, but a lack of indefinite/definite articles (e.g., “a”, “the”) in several places makes requires attention. I have noted a few instances below.

APPENDICES: There are two appendices, but they are not referred to explicitly in the

main body text. For example, specify “Appendix A”, “Appendix B”.

AR: We have referred in the main body text “Appendix A” line 166 in the section “Impact of the geothermal heat flux on the thermohaline circulation” and “Appendix B” on line 266 in the section “Discussion”.

On the subject of Appendix A, is it really necessary that you include a latitude depth analysis of the MOC? I find including both density and depth frameworks is confusing for the reader and makes it difficult to extract your key points for MOC changes. I suggest that you just add an extra sentence or two describing the MOC in latitude density space in the REF state so the reader has a basic idea of which overturning cells are which, and then state the results with OGH applied.

AR: We think this part is a crucial part of the manuscript. As we mentioned in the manuscript, most of the paleo climate analysis of the ocean circulation represent the ocean circulation or MOC in latitude depth coordinates. The paleo climate community might therefore not be familiar with the latitude-density framework. We decided to present the MOC in latitude-density coordinates because it is more representative of the ocean circulation, particularly for the Southern Ocean circulation. We also decided to present the MOC in latitude-depth coordinates in the appendix for the reader who is not familiar with the MOC in latitude-density coordinates and discuss why it is relevant to use this latest framework in our study.

Technical corrections:

Abstract

1. 6: “including or not INCLUDING geothermal heating”

AR: This has been corrected

Introduction

1. 5: “ocean dynamic” “ocean’s dynamics”

AR: This has been corrected

1. 8: “By applying A spatially constant...”

AR: This has been corrected

1. 12: Is the 5 Sv just for bottom water or for the global thermohaline circulation?

AR: The 5 Sv is for the bottom water. We add “abyssal thermohaline circulation” to be clearer.

1. 13-20: This whole paragraph needs re-writing. The first sentence is very long, break it into two. The second sentence is unclear. What do you mean by “supports the strong effect of the OGH on local scale”? And is the minimized impact on the GLOBAL thermohaline circulation?

AR: The paragraph has been re-written: “Sparse observations suggest that the high oceanic heat fluxes associated with spreading centres favour bottom water thermo-dynamical changes on regional scale and centennial time scale (Detrick et al., 1974; Joyce et al., 1986; Hautala et al., 2005; Björk and Winsor, 2006). A recent study based on laboratory experiment further explored the role of the OGH. The study supports the strong effect of the OGH on the regional scale but minimises its impact on the thermohaline circulation and the turbulent mixing (Zhou et al., 2014).”

1. 22: Replace “deep ocean is invoked for explaining the rapid...” with “deep ocean is responsible for the rapid ...”

AR: This has been corrected

1. 26. Insert a citation for this sentence “It is also postulated...CO2 storage”. p. 3600,

AR: Reference Adcroft et al (2001) has been added.

1.10: Replaced “We aimed at (1) evaluating...and (2) testing...” with “Here, we aim to (1) evaluate...and (2) test”.

AR: This has been corrected

p. 3602: 1. 3: “drifts” “drift”.

AR: This has been corrected

Results

1. 10 (and all other instances afterward): replace “drift” with “trend”, otherwise the reader would assume you are referring to the drift in the model itself, not the response associated with OGH.

AR: This has been corrected

1.12-13: Add a sentence explaining why there is colder water above warmer water in the Atlantic only.

AR: We modify the paragraph from line 137 to better emphasize this fact.

p. 3603, l. 2 and l. 11: “depthS”.

AR: This has been corrected

1. 12-14: Add a sentence explaining the reason behind these salt anomalies.

AR: We discuss the reason behind these salt anomalies and a possible mechanism in the Discussion section from line 227: “the warming of the abyssal waters contributes to freshening of the Southern Ocean surface waters via the advection of heat. The large formation of AABW contributes to fresher abyssal waters. Due to the closed freshwater budget and no restoring term in the sea surface salinity in the model, the Southern Ocean freshwater supply is counter-balanced by the densification of the surface waters becoming more saline in the North Atlantic and Pacific Ocean.”

1. 19: By stratification, you mean density gradient here, yes?

AR: Yes

1. 22: “circulation in the latitude-depth” “circulation in latitude-depth”.

AR: This has been corrected

1. 24: Why is the circulation better explained in a density framework, such as less work along required to move the water parcel along lines of constant density

surfaces? Add in a sentence/expand the present sentence, referencing papers by T. McDougall.

AR: We add the references T. McDougall (1987) and explain the reason of the better description of the MOC in latitude-density coordinates: Fluid parcels are essentially constrained to move along neutral density surface without doing work against gravitational force.

p. 3604, l. 2: insert “in” after “functions”.

AR: This has been corrected

l. 17: How much denser is the NADW? Quantify.

AR: We quantified it and added: “The MOC in latitude-density coordinates also shows that the NADW is $\sim 0.1 \text{ kg.m}^{-3}$ denser in GH than in REF.”

l. 21: “is ONLY slightly larger”.

AR: This has been corrected

l. 26: “reaches A maxima”.

AR: This has been corrected

l. 27: “Northern Hemisphere, AND southward”.

AR: This has been corrected

p. 3605, l. 8B12: You refer to Northern Hemisphere deep mixed layers, but in the previous sentence you refer to the Southern Ocean where similarly deep MLD exist also.

Section 3.4: This seems like a summary section...you might want to note this in the subsection title or first sentence.

AR: The subsection title is now: “Intermediate summary and Impact on the North Atlantic deep convection”

1. 20B22: The first sentence here says surfaces waters transported toward Antarctica freshen. The second sentence says AABW freshens. But there needs to be a sentence in between that says that high salinity shelf waters contribute to the formation of AABW. And note that this is NOT the only contribution to AABW formation (e.g., modified southward flowing warm and salty deep waters also contribute to AABW formation).

AR: This has been corrected

p. 3606, l. 1: “dynamicS”.

AR: This has been corrected

Discussion

General comment: I find the first paragraph difficult to understand. You are comparing your results to present day analyses (e.g. Hofman and Maqueda) and then saying that the difference in results is due to salinity restoring. What about all the other differences, like not including an interactive atmosphere (this is noted later, perhaps move it forward), or describing the individual models' mixing parameterisations and resolution, or timescale for simulations, or individual models' drifts, or the type of geothermal heating each of those studies uses, or the fact that they're analyzing different ocean climate states to your study....my point is that salinity restoring is unlikely the sole reason behind bottom water anomalies.

AR: We agree that it probably not the sole reason behind bottom water anomalies, and that other element might contribute, like including or not an interactive atmosphere, as we wrote in the manuscript, or the type of mixing parameterisations. However, salinity restoring is probably a dominant factor. It is important to mention that 1) all the studies about the impact of OGH during present-day ocean state have been done with ocean models of relatively similar resolution, 2) the type of geothermal heating can not be the main reason: Emile-Geay and Madec (2009) have shown that spatially variable OGH leads to a “modest increase in overturning (1.5Sv)” compared with the uniform OGH; and the averaged OGH value in our study is similar to the one used in Emile-Geay and Madec (2009).

The mixing parameterisations can also be an important factor. Therefore, we added a paragraph in the discussion from line 235 to better emphasize this fact.

1. 5: “simulationS”.

AR: This has been corrected

1. 18: remove “(reduced salinity)” as this is obvious.

AR: This has been corrected

1. 24 and 25: replace “value” with “anomaly”/”trend”.

AR: This has been corrected

1. 27: Replace “time scale, but...” with “time scale. However,...”

AR: This has been corrected

p. 3607, l. 1: “scaleS”.

AR: This has been corrected

p. 3608, l. 1: change to “Antarctic Bottom Water transports geothermally heated waters...”

AR: This has been corrected

1. 4B13: Here you should re-emphasise that this study is testing previously posed theories in a global ocean/ice model with realistic bathymetry...otherwise you imply that the study just proved an already well-formed theory (e.g. Adkins et al. work)...you need to stress this study is novel

AR: This has been added on line 275.

1. 14: Replace with “Our results are based on a forced (i.e.,)”

AR: This has been corrected

1. 16: “Sensitivity studIES”.

AR: This has been corrected

Appendix A: delete “A” at the start of the first paragraph.

AR: This has been corrected

Figures

Figure 1: The y-axis label on the bottom panel is too small to read. Perhaps use a word/single symbol label and expand to the equation in the caption. In the caption, change “drift” to “trend”.

AR: Figure 1 has been improved according to the referee recommendation

Figure 2: Fix salinity units in the third line of the caption. Also in the caption, why is 34S classed as the entrance to the South Atlantic, even in the INP panels? I suggest changing “South Atlantic” to “Southern Ocean” in this and other captions. Changed “dashed contours” to “hatched/striped regions”. Also, I can barely see those regions in your figure- might want to draw the reader’s attention to specific panels and depths.

AR: Figure 2 has been corrected. The 34°S is the meridional boundary of the mask we used for calculating the MOC in each basin

Figure 5: Make the zero contour bold.

Figure 5 and 8: Why haven’t you similarly added hatched/striped regions in Figure 5?

AR: In the manuscript, we discussed the fact that subtracting the streamfunction in latitude-density coordinates is meaningless because the OGH modifies the density structure of the ocean. As a result the significant differences of the streamfunction in latitude-density coordinates between the simulation with and without OGH might be a consequence of change in density structure and meridional transport, and therefore it is not obvious to display the region of significant difference. Note that in latitude-depth coordinates, the vertical coordinates (i.e, the depth) is not changing in time.