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Interactive comment on “On the glacial and inter-glacial thermohaline circulation and the associated transports of heat and freshwater” by M. Ballarotta et al.

Anonymous Referee #2

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Review of “On the glacial and inter-glacial thermohaline circulation and the associated transports of heat and freshwater

M. Ballarotta, S. Falahat, L. Brodeau, and K. Doos

Overall Comments:

Ballarotta and co-authors present an interesting analysis of the thermohaline circulation streamfunction computed using different coordinate systems as a framework to compare simulated glacial and modern ocean circulations. The most novel aspect of the analysis is the comparison of the thermohaline circulation in temperature-salinity coordinates, which helps to highlight differences in the global “Conveyor Belt” circu-

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lation associated with NADW formation. However, the message is muddled within a poorly written manuscript. The manuscript reads like a rough draft and would benefit from a grammar checking tool. The motivation and objectives of the analysis should be emphasized clearly from the start. State the motivation for using this novel approach for investigating glacial-interglacial thermohaline circulation differences. In addition, the conclusions should highlight the novel aspect that this analysis brings to the existing large body of work on this topic.

Specific comments:

Note: The word “streamfunction“ should be written as one word throughout the manuscript. There are numerous instances of subject/verb disagreement. In addition, the manuscript suffers from awkward sentence structure throughout.

Abstract: The overall objective and motivation for the study should be stated briefly here. p. 980, Line 2: verb agreement is wrong.

Line 9: Be quantitative about how much larger the poleward heat transport is in the LGM simulation.

Line 12: Awkward construction: “The LGM circulation is represented. . .”

1 Introduction: This section needs to be improved. Many statements are vague or awkwardly stated rendering the meaning unclear. The motivation for undertaking this analysis should be emphasized. The glacial climate state should be placed in a proper context here and emphasized as the focus of the present study. The main goal appears to be to compare the glacial thermohaline circulation to the modern state, yet no mention of the glacial simulation appears until the end of the last paragraph and nothing is stated about the underlying motivation for this comparison. State what is hypothesized about glacial thermohaline circulation from proxy reconstructions and how and why the glacial circulation differs from modern. How does this study differ from previous work or approaches and what makes this analysis novel? How does this particular analy-

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sis advance a new understanding of the response of the thermohaline circulation to glacial-interglacial climate change?

p. 981: Line 2: First sentence of introduction could be stronger. “large time- and spatial-scales ocean...” is awkward.

Line 7: “This AMOC is crucial because,” This phrase conveys no exact meaning in the sentence.

Line 13: “. . .might also change in a near future. . .” This thought seems to be incomplete. It should read “. . .in a near future under increased greenhouse gas forcing . . .” or something to that effect.

Line 22: “Originally illustrated . . .” As constructed, this sentence is awkward.

Line 24: “. . .the central role that plays the Southern Ocean. . .” is incorrect English construction. Consider “. . .the central role that the Southern Ocean plays . . .”

p. 982: Line 7: Subject/Verb agreement: “. . .when one consider . . .” Should be “considers”

Line 8: Subject/Verb agreement: “. . .Southern Ocean Cell...do not represent. . .” Should be “does not represent. . .” and also it should be “latitude-depth coordinates” in the same sentence instead of “latitude-depth coordinate.” In general, this error is found throughout the manuscript. It should be either, for example, “latitude-temperature coordinates” or “latitude-temperature coordinate system.”

Line 9: “. . .the “real” Southern Ocean overturning circulation. . . It should be explicitly stated here what is meant by “real.”

Line 12: “Recently . . .” This sentence has awkward construction. It can be improved by replacing the word “in” with “by.” Lines 14-18: Describing the novel approach of Doos et al. (2012): This is confusing. How does it both have the advantage of taking “into account the three-dimensional aspect” and the disadvantage of removing “the

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geographical coordinates?” Better elaboration of the advantages of the approach, and its relevance for this study is needed.

Line 19: Remove the word “the.”

Lines 19-20: “Since . . . ?” This statement is not a question. Is the study really focusing on how the “thermohaline structure” is different or is it focusing on how the thermohaline circulation is different? More precise word choice or usage would make for better clarity.

Line 21: “How the volume transports . . . are modified under glacial and interglacial conditions?” As written this does not read as a complete question. Perhaps, “How are the volume transports . . . modified . . . ?”

3: Results

The beginning of the Results section might be a better place to discuss how well NEMO’s glacial and modern thermohaline circulations in latitude-depth space (Figure 4) compare to other models and proxy reconstructions. This would establish a firm context for the following analyses. This is given some discussion later in the Discussion section.

p. 984: Line 11: This sentence with “serving to understand” is awkwardly constructed. The meaning behind the usage is not clear.

Line 21: The description of the role and significance of the tropical cells could be clarified and elaborated. No mention of their being largely wind-driven is mentioned. The sentence ending in “in increasing their heat content” is confusing.

Line 23: Subject/verb agreement issue. Should be “. . . maximum . . . is similar . . .” Subject is “maximum volume transport.”

Line 24: “. . . tropical gyres . . .”

p. 985: Line 2: About the poleward heat transport in LGME being “slightly larger” than in PDE, because the tropical horizontal gyres are larger in LGME. First, be more

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quantitative here. How much larger? Second, the LGM horizontal gyre transports are twice as large but the maximum poleward heat transport is just “slightly larger.” Is the inference that most of the poleward heat transport is accomplished by the meridional overturning circulation in the tropics. This is referring to the poleward heat transport shown at the top of Fig. 6, but not referenced as such.

Line 3: by “reorganize” do the authors mean “redistribute?” It is not clear what is meant by the reorganization of salty water.

Line 4: Subject/verb agreement: “. . .water are found. . .”

Lines 6-8: Freshwater transports: Refer to Fig. 7 here where the meridional freshwater transport is shown at the top. From this figure the maximum northward freshwater transport at about 35S appears quite similar in both simulations. The cause of the stated difference is attributed to more melting sea ice in the PDE vs. the LGME case, but this effect is not shown in any figure.

Line 10: Usage: “. . .tropical cell is embedded into a meridional large cell . . .” is awkward.

Line 11-13: About the NADW cell in the N. Atlantic: The NADW cell in the LGME case is not just shallower, but very indistinct in latitude- depth space as compared to the cell in the PDE simulation (Figs. 4c and d). It appears to be a more distinct cell-like feature in the latitude-neutral density and temperature spaces, figs. 5 and 6.

Line 14: usage: “. . .associated to. . .” should be “. . .associated with. . .”

Line 14-15: Where the maximum AMOC streamfunction is located exactly is not clear from the figure, and not stated. It looks like the 13 Sv maximum could even be located close to 30S.

Lines 18-20: Unclear? It looks from fig. 4c, that saline water fills the entire deep Atlantic basin not just from 20 to 40N.

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Line 21: should be “higher latitudes. . .”

Pg. 986, Line 14: This line refers to isotherms in figs. 4 a) and b), but the temperature is shown contoured in figs. 4 g) and h).

Line 18-19: It’s unclear which figure is being referred to showing the isopycnal layers in LGME being shifted equatorward relative to PDE.

p. 987, Lines 1-5: The wording for “capturing a deep ocean stratification” is confusing.

Line 7: Usage: “associated to the AABW”

Line 13: Subject/verb agreement: “ The deep MOC . . .are also characterized by a circulation of . . ., which maintain. . .” It should be “is. . ., which maintains..”

Lines 18-23: Discussion of the deep clockwise cell below 4000m in the Pacific-Indian basin in the LGME case, also apparent in the Global basin in the latitude-depth coordinates. This is the depth range where AABW would be expected to flow in a counter clockwise circulation cell. It is stated that this cell appears to vanish in the other coordinate systems, however it appears to be an unusual feature of this simulation as compared to other model simulations of glacial climate (cf. Otto-Bliesner et al. 2007).

Section 3.2.1: Thermohaline streamfunction . . . in temperature and salinity coordinates
p. 988, Line 7: Awkward usage: “. . .reflects to the AABW. . .”

Line 8: Should “important” be “greater” ?

p. 989, Line 1: usage: “. . .in Conveyor Belt. . .”

Note, the definition of the Conveyor Belt circulation needs more elaboration in temperature-salinity coordinate space. Perhaps referring briefly to the nice schematics and discussion in Doos et al. (2012), such as their figs. 4 and 7, can help ground the reader here. This is the crux of the analysis and what makes the approach novel for the glacial-interglacial comparison. Also notating Figs. 8 and 9 with arrows and labels would be immensely helpful.

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Line 3: usage: insert “be” after “can” and use “follows”

p. 990, Line 3: Are these units a volume density rather than a Volume?

Lines 13-16: To help delineate the Conveyor Belt cell discussed here and shown on figs. 10 and 11, consider delineating the clockwise circulation streamlines with dashed contours. This is one of the important points stated in the abstract and conclusion and thus could use more elaboration.

Line 19: Consider swapping figures 12 and 13 to maintain the same order as the last few pairs where LGME plots came before PDE plots.

Line 26: Also, the volume of AABW in LGME is very large, as stated in line 4, which would have the effect of increasing the turnover time.

4: Discussions (Discussion)

p 991: Line 4: Usage: “large-scales oceanic circulation. . .”

Line 6: Consider adding for clarity, “. . .diagnostic used for comparison is based . . .”

Lines 7-9: This sentence is unclear and lacking in precise meaning.

Line 10: Very vague.

Lines 20-21: This sentence is extremely unclear.

P 992: Line 5: Usage: “preventing density gradient to maintain. . .” should be “preventing density gradients from maintaining. . .”

Lines 10-12: discussing the appearance of a weaker Deacon cell in latitude-density and latitude-temperature coordinates being due to large eddy-induced velocities. More elaboration is necessary here regarding the cancellation due to eddy-induced transport.

Line 14: Subject/verb agreement

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Line 16: Add “a” before “better”

Line 20: Should be “coordinate” here.

Lines 21-23: Unclear wording. Is it meant that characterizing the three-dimensional structure is essential for understanding the Southern Ocean circulation?

Line 24: Subject/verb agreement

Line 27: the word “paleo-climate” is not hyphenated.

P. 993: Lines 7-9: Concerning LGME AABW: Note that AABW in LGME, in latitude-depth coordinates does not appear as a bottom water outside of the Southern Ocean, due to the presence of the counter circulating abyssal clockwise cell that appears in this simulation. Also, AABW, the deep counter-clockwise circulation with origins in the Southern Ocean is very weak in both of these simulations. This glacial simulation, thus, differs dramatically from most other glacial simulations (cf. Otto-Bliesner et al. 2007).

Line 14: Consider starting with “ Reconstructions of glacial circulation using paleo-proxy data also suggest . . .” It is unclear what is meant by “various geometries.”

5 Conclusions

This section needs to be tightened and vague concepts, such as “structure of the ocean” given better clarity.

p. 994: Line 20: comparing the size of the maximum heat transport in the tropics. How much larger is the transport in the LGME case? It would be useful to report these differences more quantitatively such as in %increase. On p 985 the LGM transport is described as only “slightly larger,” whereas here this distinction is lost. Perhaps add these to Table 1, if the differences are discussed in the conclusions.

Line 22: Usage error: “coordinates framework”

Line 26: Usage error: should be “weak meridional density gradient”

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Line 27: Consider starting a new paragraph with “The circulations in . . .”

p. 995: Line 3-6: awkward construction and verb disagreements.

Note: This final part of the conclusion section, describing what is learned from the application of the new approach of projecting the glacial thermohaline circulation in a thermohaline (temperature-salinity) coordinate system is this study’s novel contribution to the literature. Consider improving the clarity of the presentation and discussion. Include statement concerning how this study advances our understanding of the response of the thermohaline circulation to glacial-interglacial climate change.

Appendix:

p. 996: Line 4: Usage errors and awkward construction.

Equation A2-A4: Shouldn’t the order of integration be reversed? Two-dimensional streamfunction is defined after zonal integration. Check the descriptions of the methodology of computing the different streamfunctions against Doos et al. (2012) and Zika et al (2012).

p. 1000: Equation A8: dot product is needed between vector quantities. Are time averages taken before or after the dot product and spatial integrations as in Doos et al. (2012)? Tracers considered to be in steady state?

Additional comments on the figures:

The individual panels in figures with 4 or more panels in the vertical appear to be too small to see some of the described details. Also, consider making the contour and axis labels larger for better visibility.

Fig. 4: Panels a) – h) need defining in the figure caption. The figure caption describes only salinity as the color contoured field, which is only in panels a)-f). The description for g) and h) is missing, which appears to be the Global Ocean streamfunction plotted over temperature.

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Fig. 7: Specify which panel corresponds to which basin.

Figs. 10 and 11: Volumetric census. Explain the edge effects in these figures. Check the units of the stated contour interval, $107 \text{ m}^{-3}(\text{oC PSU})^{-1}$ as compared to the label on the label bar.

Figs. 12 and 13: Consider swapping the order of the figures to correspond to the order of the earlier figure pairs.

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