

1 ***Interactive comment on “The impacts of Meltwater Pulse-***
2 ***1A in the South Atlantic Ocean deep circulation since the***
3 ***Last Glacial Maximum” by J. M. Marson et al.***

4 **Response Letter for Anonymous Referee #2**

5 We thank Referee #2 for the comments and suggestions, which we integrated into the
6 manuscript. The point-by-point responses follow below where the reviewer’s comments are in
7 italic with our response in regular Font.

8

9 **General comments**

10 *The hypothesis in the introduction is formulated imprecisely and is in fact not really at the*
11 *center of the discussed results. It is not so much about the timing of the onset of present-day*
12 *like conditions, but more about the differences between two simulations with different*
13 *freshwater input. Similar things have been done before (Roche et al., 2010 for the North*
14 *Atlantic; Menviel et al, QSR, 2011 for a transient simulation LGM-Pre-Industrial).*

15 The hypothesis was broadened (reproduced below).

16 It is our hypothesis that the present day circulation pattern of the South Atlantic Ocean was
17 established approximately at the onset of the Holocene (11 ka). Therefore we will investigate
18 the impacts of the freshwater discharges associated with H1 and MWP-1A, assuming
19 contributions from both hemispheres, on the structure of the NADW in South Atlantic Ocean.

20 We have included the recent reference of Menviel et al. (2011), as suggested by the reviewer.

21 The H1 changes in ocean circulation have been associated to atmospheric CO₂ changes
22 (Menviel et al. 2014). They discuss that an enhanced AABW could have been responsible for
23 30% of the atmospheric CO₂ increase.

24 *The transient simulation (TraCE-21K) was ‘constructed’ to match best the proxy data. In*
25 *particular the simulation was very carefully designed with regards to the timing and*
26 *amplitude and region of freshwater input into the ocean. This was done based on the excellent*
27 *expertise and careful analysis of proxy data sources where they compared the modeled*

1 *climate with proxy records. But once such a simulation was achieved to represent successfully*
2 *the proxy evidence, one has to be careful in the use of the model results to make new*
3 *inferences. I have the feeling that most of the discussion here is a circle-argument, in*
4 *particular after screening the details about the freshwater setup in Dr. He's Dissertation. I*
5 *suggest the authors use their gained insight to explain in some more depth how the freshwater*
6 *forcing in the Southern Ocean spreads in the oceans, and how it controls differences in ocean*
7 *and atmosphere, and as suggested in Stouffer et al. (2006) to explore in more depth if*
8 *'fingerprinting techniques' can help to constrain the meltwater contribution in the Southern*
9 *and in the North Atlantic Ocean using a network of proxies.*

10 The manuscript was substantially changed. The model initialization and details of the
11 freshwater flux were included in the data/methods section. We also discuss the uncertainties
12 inherent to analyzing a single experiment with no control run. We broadened our hypothesis
13 to include H1 as the event that set the stage for the impact of MWP-1A. We also revised this
14 to include the effect of both its southern and northern hemisphere fresh water contributions.

15 The main goal was to explain, the changes in the vertical characteristics of the South Atlantic
16 water mass structure (i.e. evolution of the T-S diagrams in Figure 5) from the transient
17 version of the NCAR-CCSM paleoclimate model starting at LGM and running to present-day
18 – based on salinity changes, in the light of several freshwater events into the North Atlantic
19 and one freshwater discharge event in the South Atlantic (associated with MWP-1A).

20 *Also I found the figures were not really giving support to the propositions in the result section*
21 *and conclusions. Perhaps, age tracers and oxygen concentrations are not available from this*
22 *run, but they would be very helpful to identify the ventilation of the deep and intermediate*
23 *ocean layers, marking of NADW, AAIW etc.*

24 We not only broadened our proposition (acknowledging the impact of the Northern
25 Hemisphere freshening events) but also included a few new figures such as the ocean and salt
26 and heat transport as a function of latitude, averaged for each of the key periods. We changed
27 Figure 5 that had snapshots of the vertical profile of salinity to average vertical profiles of
28 salinity for each of the periods considered. We also added a similar figure but with the
29 vertical profiles of salinity differences. We believe that through the salinity evolution and
30 differences we can tell the story of the evolution of the NADW in the NCAR-CCSM
31 paleoclimate transient experiment.

1 **Specific comments**

2 **Introduction**

3 ***Page 6376***

4 *Line 17: The last deglaciation started around 21,000 years ago, when orbital changes led to*
5 *increase in northern hemisphere summer insolation that prompted an initial melting that*
6 *started a chain of feedback processes that amplified the global deglaciation trends (Denton et*
7 *al. 2010, Clark et al. 2012). Need to acknowledge the alternative hypothesis that SH*
8 *insolation forcing may have played an active role, in particular to help to raise CO2 levels*
9 *and all-season global temperature increase [Stott et al, 2007, Timmermann et al. 2009,*
10 *Huybers and Denton, 2008].*

11 *At least it should be mentioned that CO2 is also important in the whole deglaciation (Kerr,*
12 *Science, 223, 1053-1054, 1984).*

13 As boundary conditions, TraCE-21K adopted transient orbital parameters, transient
14 concentrations of greenhouse gases (CO₂, CH₄ and N₂O) from Joos and Spahni (2008) and
15 coastlines and ice sheets volume variability following the ICE-5G reconstruction (Peltier,
16 2004), which also reflects the sea level variability. According to the ICE-5G reconstruction,
17 the continental ice sheets are modified approximately once per thousand year. The importance
18 of CO₂ for the deglaciation is mentioned in the text relative to the work of Menviel et al.
19 2014.

20 **Model description**

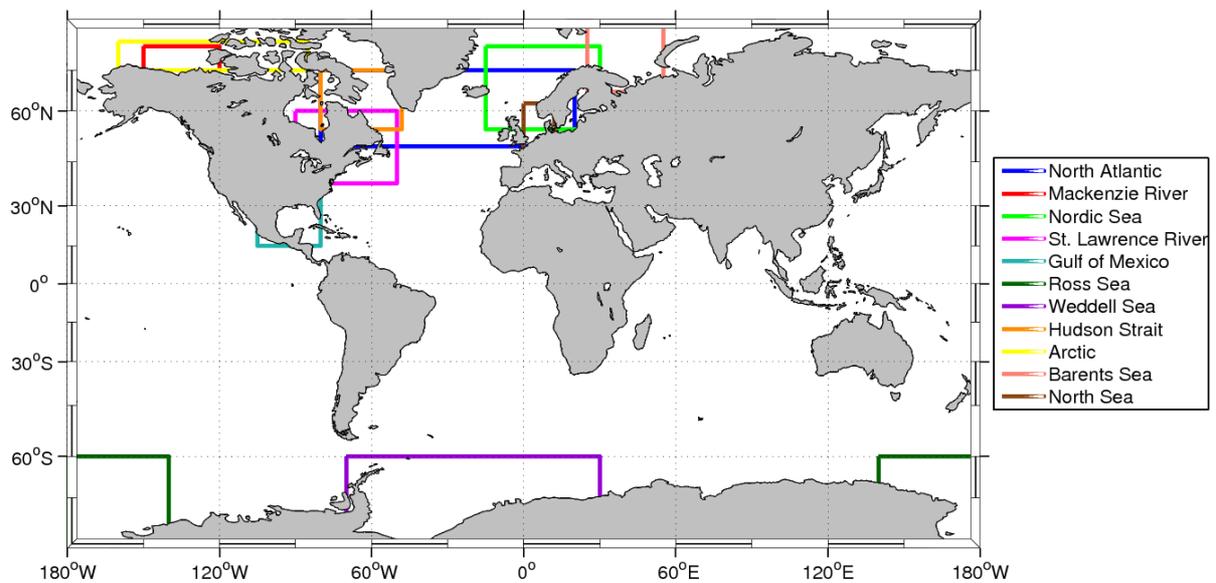
21 ***Page 6379***

22 *When was Bering Strait opening? This affects the salt export and overturning in the*
23 *simulations and should be discussed for the establishment of AMOC to present 3day values.*
24 *(Dr. He's dissertation has information on the timing; I think it is after the BA in the YD) (Hu*
25 *et al. 2012, PNAS, 109, 6417-6422, doi: 10.1073/pnas.1116014109)*

26 The Bering Strait (BS) was opened at 12.9 ka and could have contributed to further
27 weakening in AMOC. Mention of the Bering Strait was included.

1 *What is meant by several meltwater schemes: Meltwater input into NATl and SO were tried in*
2 *different proportions? What proxy data information was used to select from the various*
3 *forcing experiments? Was it based on reproducing MWP1a/YD sequences of climatic signals*
4 *in ocean and atmosphere?*

5 The meltwater discharge is added to the ocean model as a freshwater flux on the ocean
6 surface. To get the unit freshwater flux, it is divided by the total area to be added onto each
7 grid point of the ocean model. The meltwater scheme (summarized in Figure 1) and their
8 locations (shown in New Figure 1b below) for this simulation are described in Liu et al.
9 (2009) and He (2011) as follows. From 19 ka to 18.4ka, the first meltwater pulse was imposed
10 at the rate of 3 m/kyr (1m/kyr = 0.0115 Sv; 1 m/kyr refers to 1 meter of equivalent global sea
11 level rise per thousand year) over the North Atlantic. From 18.4 ka to 17.5 ka, this freshwater
12 input was increased linearly from 0 to 5 m/kyr in the Gulf of Mexico and from 3 to 5 m/kyr in
13 the North Atlantic. From 17.5 ka to 17.0 ka, the meltwater inflow remained at 5 m/kyr in the
14 Gulf of Mexico and linearly increased from 5 to 15 m/kyr in the North Atlantic. The
15 meltwater flux in the Gulf of Mexico was shut off immediately after 17.0 ka, while the
16 meltwater flux in the North Atlantic remained at 15 m/kyr until 14.67 ka when it was abruptly
17 shut off. The meltwater discharge applied to simulate MWP-1A lasted for 500 year in both
18 hemispheres. The rate of meltwater discharge in the Southern Hemisphere was three times of
19 that in the Northern Hemisphere, such that 5 meters (i.e. Carlson, 2009) of sea level rise came
20 from the north and 15m from the south. From 13.8 ka to 13.1 ka the meltwater flux is
21 10m/kyr. From 12.9 to 11.3 it is 20m/kyr. For the Holocene there is a constant freshwater
22 inflow from 9ka to 8ka of 10m/kyr and half of that from about 8.5kyr to 6.9kyr. The values
23 chosen were estimates from sea-level rise from data records presented in Clark et al. (2002)
24 and Peltier (2004). Geological indicators of ice sheet retreat and meltwater discharge were
25 obtained from Licciardi et al. (1999), Clark et al. (2001, 2002), Clark and Mix (2002),
26 Carlson (2009).



1

2 **New Figure 1b.** Regions where meltwater was injected in TraCE-21K simulation (adapted
 3 from He, 2011).

4

5 *Was any weight given on the Holocene climate, too? This is worth noting, because the main*
 6 *hypothesis and conclusion in the end are focusing on the Holocene circulation onset (p.6378*
 7 *l. 10-13). In other words the results from freshwater experiments not shown here, do they all*
 8 *end up in a state with low Overturning in the Holocene?*

9 Yes – in the sequence of changes shown in the vertical sections of salinity, the Holocene
 10 presents the distribution of the modern day ocean as can be seen in the South Atlantic T-S
 11 structure for the Holocene.

12 **Page 6379**

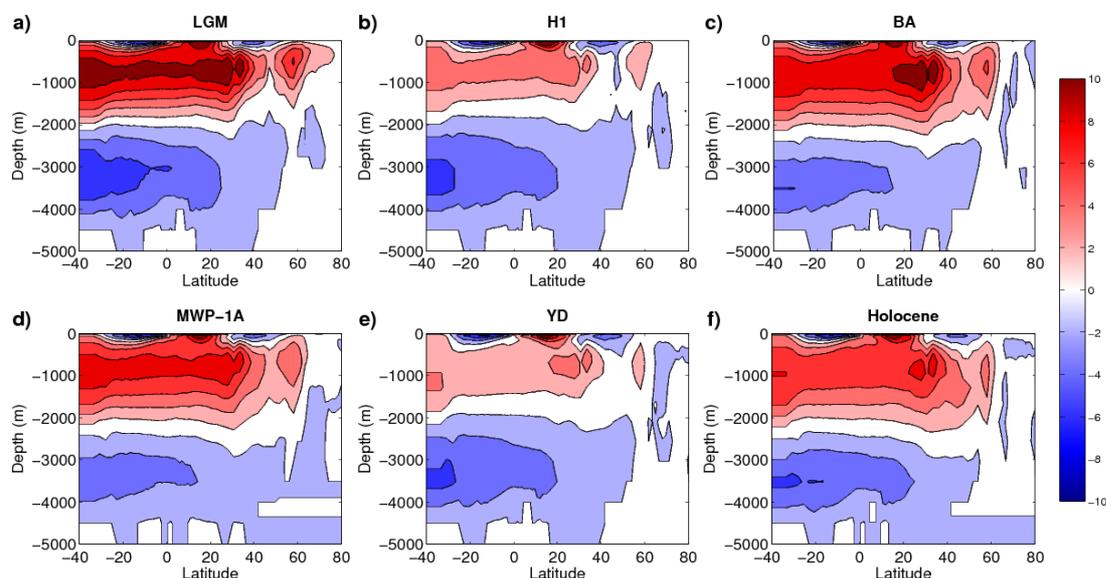
13 *Equation: Integral has upper and lower bounds. Please add them.*

14
$$Qt = \int_{5000m}^0 \int_{70W}^{20E} c_p \rho \theta v dx dz$$

15 **Results**

16 *I would prefer to start with the 'typical' depiction of the 2-d structure of the overturning*
 17 *circulation and then go into the description of the representative grid box average etc.*

1 A figure was included with the AMOC relative the time averages of the key periods: LGM:
2 22 to 19ka; H1: 19 to 14.67 ka; BA: 14.67 to 14.35; MWP-1A: 14.35 to 13.85; YD: 12.9 to
3 11.3 ka; Holocene: 11.3 to 0 ka.



4
5 **New Figure 4.** Overturning function averaged for each period: (a) LGM – 22 to 19 ka; (b)
6 H1 – 19 to 14.67 ka; (c) BA – 14.67 to 14.35 ka; (d) MWP-1A – 14.35 to 13.85 ka; (e) YD –
7 12.9 to 11.3 ka; (f) Holocene – 11.3 to 0 ka. The colors represent transport, in Sverdrups

8 **Page 6380**

9 *Line 2-3: "In contrast with the other oceans, [...]" Well there are only two other oceans: The*
10 *Pacific, and the Indian Ocean. The Indian Ocean has no polar Northern Hemisphere*
11 *extension and is not really comparable to the situation in the Atlantic. Leaves one other*
12 *ocean, the Pacific.*

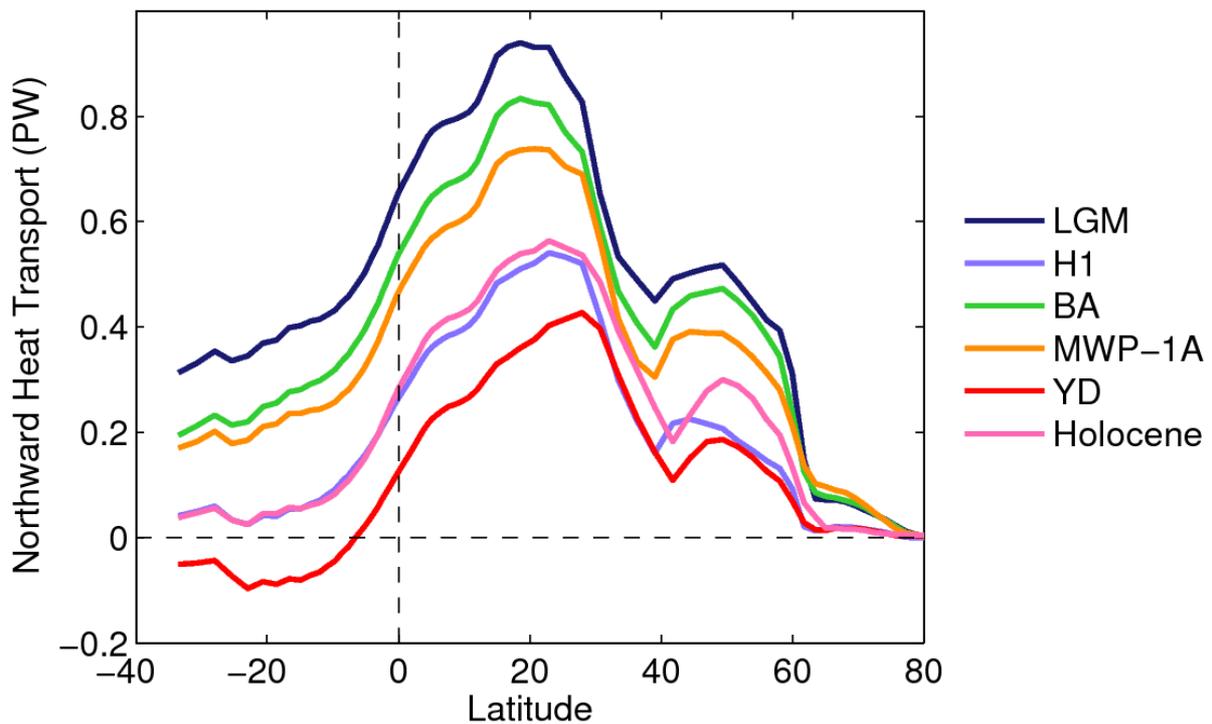
13 The reviewer is correct and the sentence was re-written to include just the Pacific Ocean.

14 **Page 6380**

15 *Line 10-13: This statement is way too much simplified: (a) it does not match the anomalies*
16 *during LGM (Fig.2 which would be a 'warm NH' relative to the Holocene. The problem is*
17 *that the authors assume that the total NH temp (anomalies) are explained by the ocean heat*
18 *transport in the overturning in the Atlantic. The atmospheric fluxes must be included of*
19 *course (see for example the recent paper of Donohoe et al., J. Clim, Vol 26, 3597-3618,*
20 *2013). (on p. 6381 l.4-8 the authors describe and try to explain the LGM exception, so I*

1 *assume they want to stress the H1-BA-YD time, i.e. the statement works for millennial-scale*
2 *variability, not orbital-scale variability)*

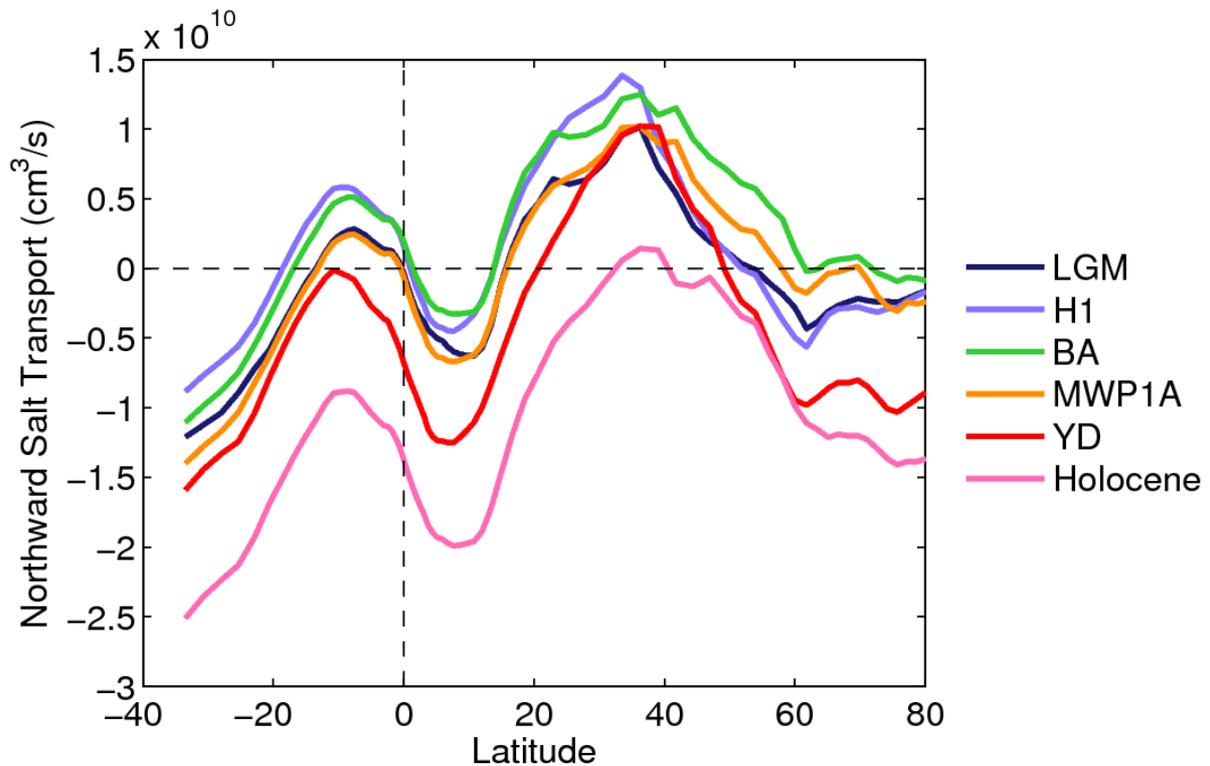
3 The text was re-written. We now use the absolute values of the heat transport so the
4 discussion is not about a deviation from the mean. We have also added a new figure (see
5 below) with time-slices of the northward ocean heat transport as a function of latitude
6 averaged between 22 to 19ka (LGM), 19 to 14.67 ka; (H1), 14.67 to 14.35 (BA), 14.35 -13.85
7 MWP-1A, 12.9 to 11.3 ka, (YD) and 11.3-0 (Holocene)



8
9 **New Figure 2b.** Northward ocean heat transport (NOHT) for the key climate periods: LGM
10 (dark blue curve) 22 ka -19 ka; H1 (lilac curve) 19 ka -14.67 ka; BA (green curve) 14.67ka -
11 14.35 ka; MWP-1A (orange curve) 14.35ka - 13.85 ka; YD (red curve) 12.9 ka -11.3 ka; (f)
12 Holocene (pink) 11.3 ka - 0 ka.

13
14 We have also included another figure with the northward salt transport (NOST) as a function
15 of latitude. The NOST between the key climatic periods shows its maximum values between
16 30N-40N with a secondary maximum at 10S. In the North Atlantic the OST is southward for
17 all periods from the Equator to about 20N, after which it becomes poleward reverting again to
18 the equator at 60N. The strongest NOST is at H1, followed by BA, LGM and YD at 38N. At

1 the Holocene with the exception of a small, albeit positive NOST at about 38N, all then OST
 2 transport is southward. In the South Atlantic there is northward transport at H1, BA and
 3 LGM while the NOST at YD and Holocene is southward.



4
 5 **New Figure 6.** Northward ocean salt transport (NOST) for the key climate periods: LGM
 6 (black blue curve) 22 ka -19 ka; H1 (lilac curve) 19 ka -14.67 ka; BA (green curve) 14.67ka
 7 - 14.35 ka; MWP-1A (orange curve) 14.35ka - 13.85 ka; YD (red curve) 12.9 ka -11.3 ka; (f)
 8 Holocene (pink) 11.3 ka - 0 ka.

9
 10 **Page 6381**

11 *The description of the water masses: two deep water masses can be distinguished in a T-S*
 12 *phase space by the end members and mixing of them would be along a line between them.*
 13 *Now looking at Figure 4b one could argue, that due to the much more salt release into the*
 14 *AABW during brine rejection in the sea ice formation process the LGM AABW has been*
 15 *extremely salty. And if AAIW did not change that much in temperature and only more or less*
 16 *in the same way as the global average salinity decreased, one could at any point in time*
 17 *define the mixing line of these two water masses. The NADW may have experience some*

1 *changes in temp and salinity 'physically independent' from AABW and AAIW formation*
2 *processes, such that is was lying always between AAIW and AABW in terms of temperature,*
3 *and shifted in salinity at a rate between the AAIW rate of change and AABW rate of change.*
4 *At a certain point in time the connecting mixing line AAIWAABW could line up with the*
5 *NADW. Now does that mean that the NADW water mass not formed or formed at a lower rate*
6 *or replaced in its depth range by the AAIW-AABW mixing? Additional tracers (age tracers,*
7 *Epsilon Nd., d18O,d13C) would could help to more firmly support the water mass formation,*
8 *spread and mixing.*

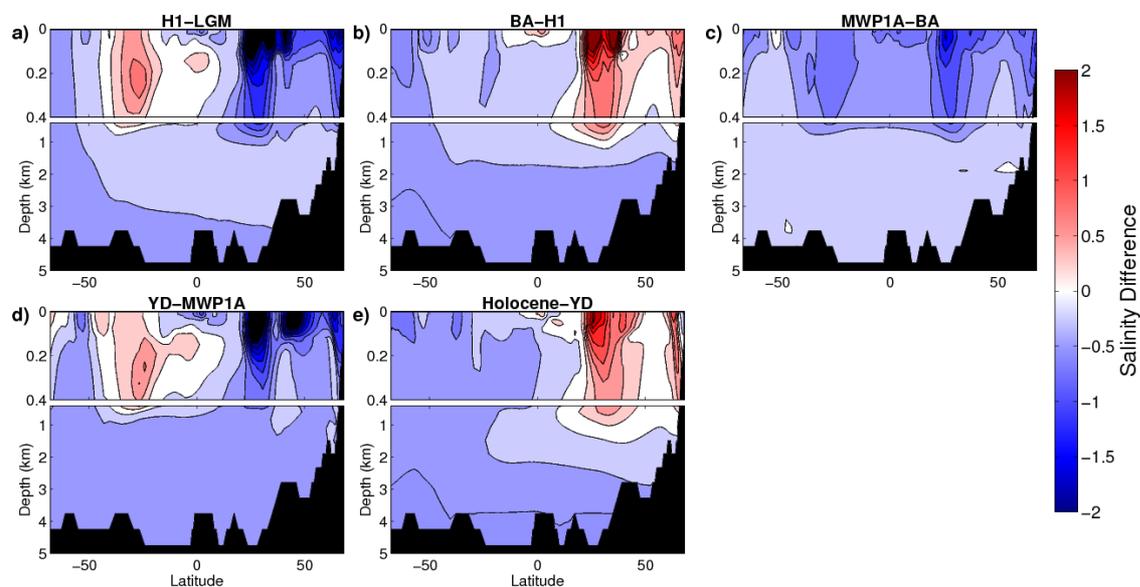
9 We decided to use salinity as a water mass tracer in the absence of stable isotopes or nutrients
10 from the model. To decipher the freshwater sources in the Atlantic, salinity is very useful (it
11 would be best together with oxygen-18, but that is not possible yet with the CCSM).

12 I would like to comment that the paleoclimate version of the NCAR-CCSM3 was used to
13 analyze changes in the water formation rates in the Atlantic for time slices (LGM, MH and
14 Pre-industrial). During the LGM, the production of North Atlantic Deep Water (NADW) is in
15 fact significantly weakened (Wainer et al. 2012). The NADW is replaced in large extent by
16 Antarctic Intermediate Water (AAIW), Glacial North Atlantic Intermediate Water (GNAIW)
17 and also by an intensified of Antarctic Bottom Water (AABW), with the latter being a
18 response to the enhanced salinity and ice formation around Antarctica. Most of the LGM
19 intermediate/mode water is formed at $27.4 < \sigma_{\theta} < 29.0 \text{ kg/m}^3$ while for the Mid Holocene and
20 Pre Industrial (1870) most of the subduction transport occurs at $26.5 < \sigma_{\theta} < 27.4 \text{ kg/m}^3$. The
21 simulated LGM Southern Hemisphere winds are more intense by 0.2-0.4 dyne/cm².
22 Consequently, increased Ekman transport drives the production of intermediate water (low
23 salinity) at a larger rate and at higher densities when compared to the other climatic periods.

24 *However, Fig. 5 gives a better dynamical perspective, but this follows after this paragraph*
25 *and that's why it is probably better to start with the 2-d structure of the overturning and*
26 *water masses before showing Fig. 3, in my opinion. In addition, snap shots of the mixed layer*
27 *depth, convective regions, sea ice formation or concentration could help to support the*
28 *described changes in NADW*

29 A new figure with the salinity differences (below) was added to the text as a companion to
30 Figure 5, averaged for the same key climatic periods. The Atlantic basin is considerably
31 fresher at H1 when compared to the LGM (Figure 7a). The largest differences are in the North

1 Atlantic in the upper 1000m with maximum values in the upper 200m. The subtropical South
 2 Atlantic in the upper 800-900m is saltier in H1 compared to LGM. This is because the
 3 prolonged freshening was entirely in the North Atlantic with the residual LGM saltiness
 4 remaining in the southern subtropics upper ~ 800-900m. Figure 7b shows the salinity
 5 differences between H1 and BA when the NADW recovers, which is seen by the positive
 6 salinity difference in most of the North Atlantic in the upper 1000m, reaching the equator in
 7 the surface layers. The impact of MWP-1A with respect to BA is observed in Figure 7c with a
 8 basin-wide freshening. The salinity differences between the YD event and MWP-1A (Figure
 9 7d) show a similar distribution to Figure 7a, except that the deeper ocean is significantly
 10 fresher. The upper 500m display a saltier South Atlantic and a fresh North Atlantic, indicating
 11 a stronger AABW and weaker NADW. This structure finally evolves into the opposite with
 12 and intensified NADW that is able to spread into the Southern Hemisphere as seen today.



13
 14 **Figure 7.** TraCE-21K salinity differences between a) H1 (19ka -14.67ka) and LGM (22ka –
 15 19ka); b) BA, (14.67ka -14.35 ka) and H1 (19ka -14.67ka); c) MWP-1A (14.35ka -13.85 ka)
 16 and BA, (14.67ka -14.35ka); d) YD (12.9ka - 11.3 ka) and MWP-1A, (14.35ka -13.85ka) d)
 17 Holocene (11.3ka - 0 ka) and YD (12.9ka - 11.3 ka).

18
 19 **Page 6382**

20 *Line 4-5: rewrite this sentence ("does not only impact in reducing the entire water")*

1 (?) and "along the Atlantic" (?))

2 The description of Figure 5 (new Figure 6) was re-written.

3 *Line 12-13: Denton may not be the best reference for the attribution of the H1 event to the*
4 *first meltwater input into the N Atlantic. I am not aware of this new idea that the 19ka*
5 *freshwater forcing directly caused H1. Please be specific as to the causes of the early sea-*
6 *level rise (i.e. meltwater input and implications for AMOC). Clearly in the simulation the H1*
7 *event is forced by the later freshwater input.*

8 Removed from the text, which was re-written. We cite Stanford et al. (2011) that, from proxy
9 data, also see a weakening of NADW formation at H1.

10 *Line 25-28. Stouffer et al describe and illustrate the surface spread of the salinity anomaly,*
11 *but details of the vertical advection/mixing processes that eventually mix the anomalies into*
12 *all depths must be explained here more clearly, since the stratification is a stabilizing*
13 *anomaly.*

14 The text was modified and the discussions in line 25-28 (together with the reference from
15 Stouffer et al. 2007) were stricken from it.

16 **Page 6383**

17 *Line 22: This is an example where the statement is correct but the information it conveys is*
18 *misleading: "The TraCE-21 model results are consistent with the idea of a weaker NADW*
19 *during YD [...]" Because the model simulation was 'designed' to be consistent with this YD*
20 *reduced AMOC / NADW. So, it should be put not into the results section but the model*
21 *description.*

22 The discussion was changed with the re-write of the text with the model description in much
23 more details.

24

25 **Conclusions**

26 **Page 6384**

1 *Line 6-16: The summary should follow the temporal order from LGM to PD. Confusings*
2 *otherwise.*

3 *Line 17-19: This conclusion goes too far! In his dissertation Dr. He describes clearly that*
4 *Holocene AMOC levels are sensitive to freshwater forcing following during YD and*
5 *Holocene. Your statement suggests a delayed effect of more than 4000 years are more*
6 *important (is that what 'much' means suggests?) than the direct forcing control*

7 The conclusion section was re-written and it reflects the importance of the NH freshening as
8 well as the southern contribution of MPW-1A.

9 **Pages 6384-6385**

10 *That part of text in a conclusion? I have hard times to 'transfer' deglaciation processes and*
11 *AMOC of millennial time scale into time periods, where glacial cycles were absent or*
12 *completely different than in the last 1,000,000 years. Not needed.*

13 The sentences were removed.

14 *Last paragraph: Repeated content. What's the point? Not always do we need a connection to*
15 *the future climate change debate. Understanding past climate is enough of a scientific*
16 *challenge. If you want keep it, it must be written in a more convincing way that the BA period*
17 *analyzed here gives more information than Stouffer et al. (2006) could have 'extracted' from*
18 *their study, for example.*

19 The paragraph was removed.

20

21 **References**

22 Carlson, A. E.: Geochemical constraints on the Laurentide Ice Sheet contribution to meltwater
23 pulse 1A, Quaternary Science Reviews, 28, 1625–1630, 2009.

24 Clark, P. U. and Mix, A. C.: Ice sheets and sea level of the Last Glacial Maximum,
25 Quaternary Science Reviews, 21, 1–7, 2002.

1 Clark, P. U., Marshall, S. J., Clarke, G. K., Hostetler, S. W., Licciardi, J. M., and Teller, J. T.:
2 Freshwater forcing of abrupt climate change during the last glaciation, *Science*, 293, 283–287,
3 2001.

4 Clark, P. U., Mitrovica, J., Milne, G., and Tamisiea, M.: Sea-level fingerprinting as a direct
5 test for the source of global meltwater pulse IA, *Science*, 295, 2438–2441, 2002.

6 He, F.: Simulating transient climate evolution of the last deglaciation with CCSM3, Ph.D.
7 thesis, University of Wisconsin, Madison, WI 53706, 2011.

8 Joos, F. and Spahni, R.: Rates of change in natural and anthropogenic radiative forcing over
9 the past 20,000 years, *Proceedings of the National Academy of Sciences*, 105, 1425–1430,
10 2008.

11 Licciardi, J. M., Teller, J. T., and Clark, P. U.: Freshwater routing by the Laurentide Ice Sheet
12 during the last deglaciation, Wiley Online Library, 1999.

13 Liu, Z., Otto-Bliesner, B., He, F., Brady, E., Tomas, R., Clark, P., Carlson, A., Lynch-
14 Stieglitz, J., Curry, W., Brook, E., Erickson, D., Jacob, R. and Kutzbach, J., and Cheng, J.:
15 Transient simulation of last deglaciation with a new mechanism for Bølling-Allerød warming,
16 *Science*, 325, 310–314, 2009.

17 Menviel, L., M. H. England, K. J. Meissner, A. Mouchet, and J. Yu: Atlantic-Pacific seesaw
18 and its role in outgassing CO₂ during Heinrich events, *Paleoceanography*, 29, 2014.

19 Menviel, L., A. Timmermann, O. Elison Timm, A. Mouchet, Deconstructing the Last Glacial
20 termination: the role of millennial and orbital-scale forcings, *Quaternary Science Reviews*, 30
21 (9–10), 1155-1172, 2011.

22 Peltier, W.: Global glacial isostasy and the surface of the ice-age Earth: The ICE-5G (VM2)
23 model and GRACE, *Annu. Rev. Earth Planet. Sci.*, 32, 111–149, 2004.

24 Stanford, D., Rohling, E. J., Bacon, S., Roberts, A.P., Grousset, F.E., and Bolshaw, M.: A
25 new concept for the paleoceanographic evolution of Heinrich event 1 in the North Atlantic,
26 *Quaternary Science Reviews*, 30 (9–10), 1047-1066, 2011.

27 Stouffer, R. J., Seidov, D., and Haupt, B. J.: Climate response to external sources of
28 freshwater: North Atlantic versus the Southern Ocean. *Journal of Climate*, 20(3), 2007.

- 1 Wainer, I., M. Goes, L. N. Murphy, and E. Brady: Changes in the Water Mass Formation
- 2 Rates in the Global Ocean for the Last Glacial Maximum, Mid-Holocene and Pre-Industrial
- 3 Climates, *Paleoceanography*, 27, PA3101, 2012.