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

Response Letter for Anonymous Referee #1

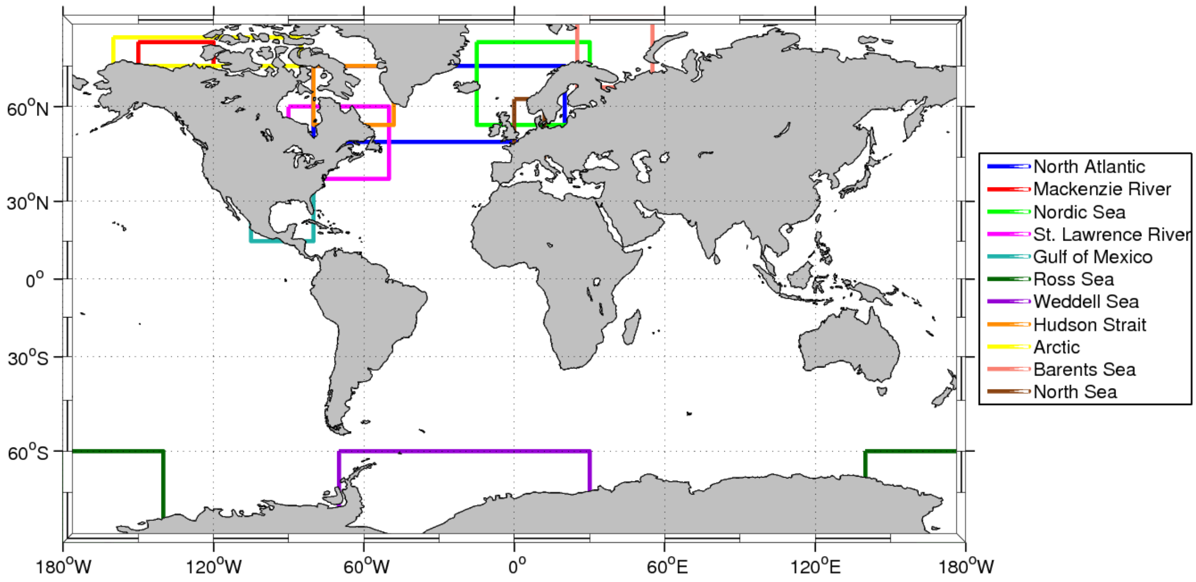
We thank Reviewer #1 for the very useful comments and suggestions. The manuscript underwent major revisions to reflect these comments/suggestions which we address point-by-point below. In our response, *reviewer's comment are copied in italic* with our answers right below.

General comments

Data and Methods

"This section needs to be rewritten. The experimental setup is not sufficiently described. The reader doesn't know the location where freshwater was injected. This, however, is important information as several previous studies have emphasized the sensitivity of deep water circulation to the geographical position of the meltwater source relative to deep water formation sites (e.g. Mikolajewicz, 1998)."

This section was totally re-written. The NCAR- CCSM, which is the model used in this study is described in more detail as is the run that provides the LGM initial conditions (from Otto-Bliesner et al., 2006). A thorough description of the meltwater scheme was also included in this section. The locations where the freshwater is injected in the transient model run are shown in Figure 1b below, which was included in the manuscript. The rates of meltwater flux applied to each region is in (m/kyr, 1m/kyr = 0.011 Sv). These are detailed in He (2011, his Table 4, Chap. 2). A simplified schematic of the rates is shown in Figure 1a.



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

"There are several meltwater pulses before MWP1A are discussed in the text (e.g. line 20, page 6382) with frequently repeated reference to the studies Liu et al (2009) and He et al. (2013). It should become clear how much of the results have already been discussed in these studies (and those parts should be moved to the introduction, see specific comments) and what is the contribution of the present work."

We have brought the discussion of H1 earlier in the text since we now argue that MWP-1A is not the sole responsible for the modern-structure and distribution of the South Atlantic NADW but a player in the ocean set-up established during the prolonged freshening of the North-Atlantic. The H1 pre-conditioned the ocean response to MPW-1A. In such, more references that discuss the strength and duration of the meltwater inflow (proxy and models) are introduced and discussed in the text. (e.g., Bond et al. 1992, 1997, 1999 ; Grousset et al., 2001; Rohling et al., 2003; McManus et al., 2004; Stanford et al., 2011; Roberts et al., 2014 and references therein).

Results and Discussion

"Marson et al. present an interesting evolution of the Atlantic deep water circulation since the LGM. The authors main conclusion is, that at the LGM a "very salty AABW" resulted in a first step in a "salinity barrier" (for example line 13, page 6384) at 13 kaBP in the north

Atlantic hindering surface waters sink to depth thus suppressing NADW. But it becomes not clear how this "salinity barrier" is established. From Fig. 5 one would guess the model was already initialized with such a barrier and with a deep Atlantic Ocean that was much saltier than today. Therefore, the reader must know in which way and under which assumptions the model was initialized and how it was spun up."

The data/methodology section was completely re-written to include all the relevant model details suggested (initialization, model details, meltwater scheme). The reviewer is correct; the salinity barrier is in the initialization fields (from the LGM conditions).

"Furthermore, the south deep Atlantic freshens between 19 and 14.1 kaBP (Fig. 5a-c) without any meltwater source in south (Fig.1). Is there model drift or is it internal variability?"

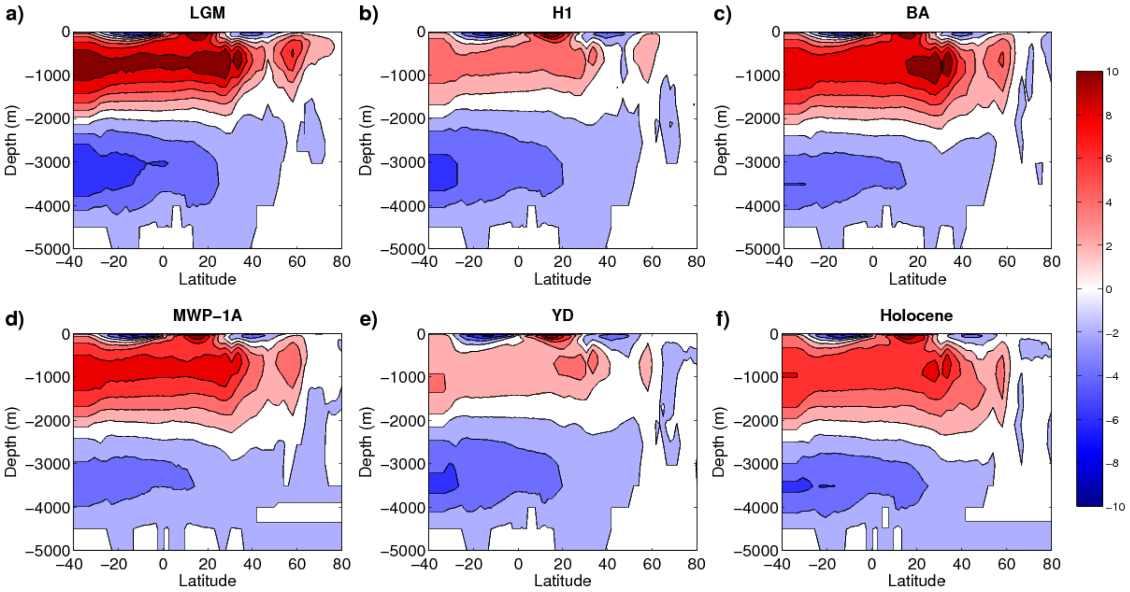
From 19ka there is a flux of fresh water inflow into the North Atlantic that ramps up to 17ka becoming quasi steady to the end of H1. This freshwater anomaly that initiates in the NH spreads out into the upper North Atlantic with accompanying freshening into the Southern Hemisphere where it mixes down, freshening the subsurface South Atlantic due to internal variability.

"In a second step the authors hypothesize that the MWP1A meltwater contribution from the southern hemisphere then made the deep North Atlantic more and more fresher over several thousand years thereby removing this "barrier" after 13 kaBP. However, after 13 kaBP the only significant FW contribution comes north (Fig. 1). Therefore, this hypothesis is not very convincingly supported by the provided model results (see also the specific comments below)."

We have adjusted our hypothesis of the impact of MWP-1A in the context of the H1 preconditioning of the deep ocean structure. In the model, The MWP-1A occurs between 14.35 and 13.85, when the Southern Ocean is very stable due to denser waters in the deep ocean and fresher in the upper layers (discussed by Mikolajewicz, 1998). The idea here is that at the time of the MWP-1A the strong stratification of the water column reduces AABW convection allowing the spreading of less dense waters into the deep ocean, which allowed the subsurface salinity barrier that was blocking the spreading of the NADW to the South Atlantic to be eroded. According to Broecker (1998) and Seidov and Maslin (2001), the AABW export is restored in the YD event.

"Quite often the authors infer changes in NADW formation and AMOC alone from the Atlantic heat transport time series in the South Atlantic 30 S – 0 (in Fig.2). The argumentation would be much more convincing if the authors would show corresponding time series for the heat transport in the (northern)North Atlantic (see also specific comments). In addition to that, if possible, the authors may consider also presenting an overturning function for specific time slices as quite often in the text changes in the AMOC are assumed to have occurred which are mostly inferred from salinity sections and heat/salt transports in the SH alone (e.g. page 6381, line 4-8)."

The reviewer is correct and we have added 2 new figures (see below) with time-slices of the overturning function averaged between 22 to 19ka (LGM), 19 to 14.67 ka; (H1), 14.67 to 14.35 (BA), 14.35 -13.85 MWP1A, 12.9 to 11.3 ka, (YD) and 11.3-0 (Holocene). They show the evolution of the AMOC (New Figure 4) and the Northward heat transport as a function of latitude (New Figure 2b)

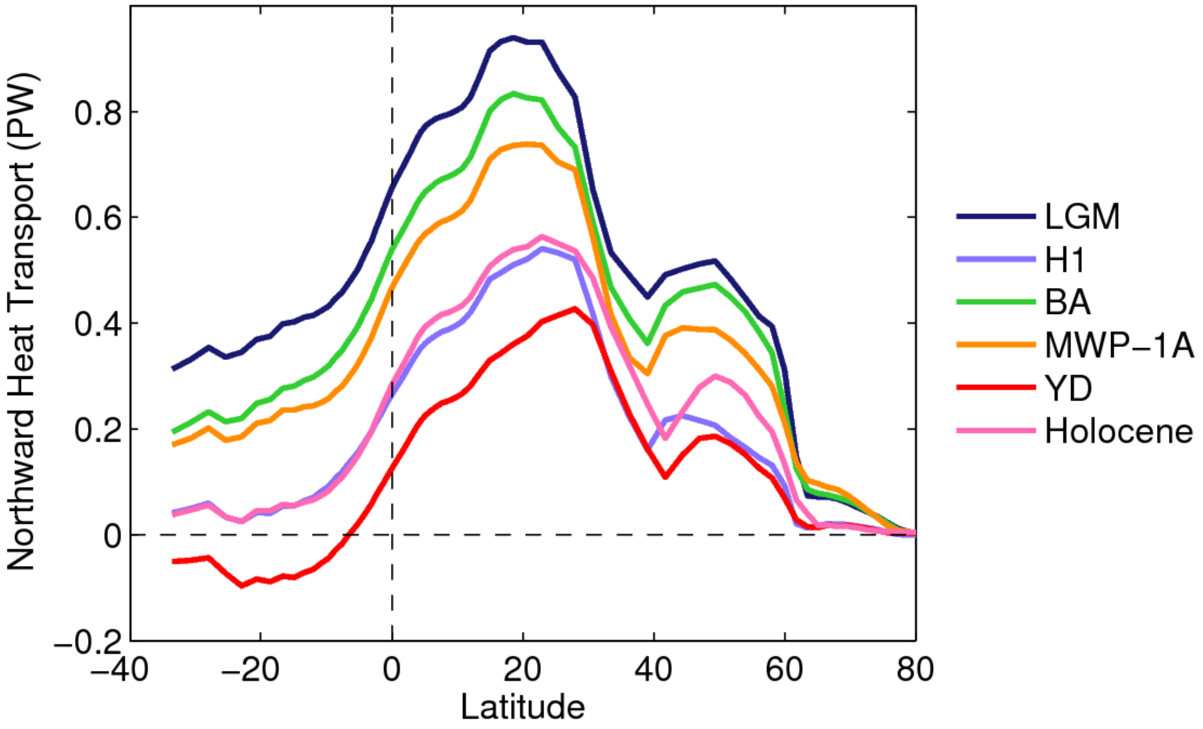


New Figure 4. Overturning function averaged for each period: (a) LGM – 22 to 19 ka; (b) H1 – 19 to 14.67 ka; (c) BA – 14.67 to 14.35 ka; (d) MWP-1A – 14.35 to 13.85 ka; (e) YD – 12.9 to 11.3 ka; (f) Holocene – 11.3 to 0 ka. The colors represent transport, in Sverdrups and negative values indicate transport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

The overturning function for the TraCE-21K results at LGM is intensified as shown in Figure 4a. The upper branch of the overturning is homogeneously strong in both hemispheres while the lower branch shows a vigorous Southern Hemisphere circulation, associated with the intensified dense AABW formation, occupying most of the deep Atlantic basin. During H1 (Fig. 4b), the intensified lower limb is still present with the maximum transport of 8-10Sv confined south of 25S. The upper limb changes significantly, becoming consistently weaker in both hemispheres. The maximum transports (~10Sv) at about 1000m at LGM are significantly reduced in H1 (max ~4Sv). During BA (Fig. 4c) and MPW1A (Fig. 4d), the deeper circulation of the lower limb weakens while the upper limb intensifies. In the BA there is an intensification of about 4-6Sv centered at 1000m between 20N-40N that is not seen in Fig. 4d. AABW picks up again during YD, which is responsible for the re-intensification of the lower limb of the meridional overturning (Fig. 4e) while the upper branch is weakened, except in the upper few hundred meters centered at 20N. The configuration of the Meridional Overturning for the Holocene is shown in Fig. 4f.

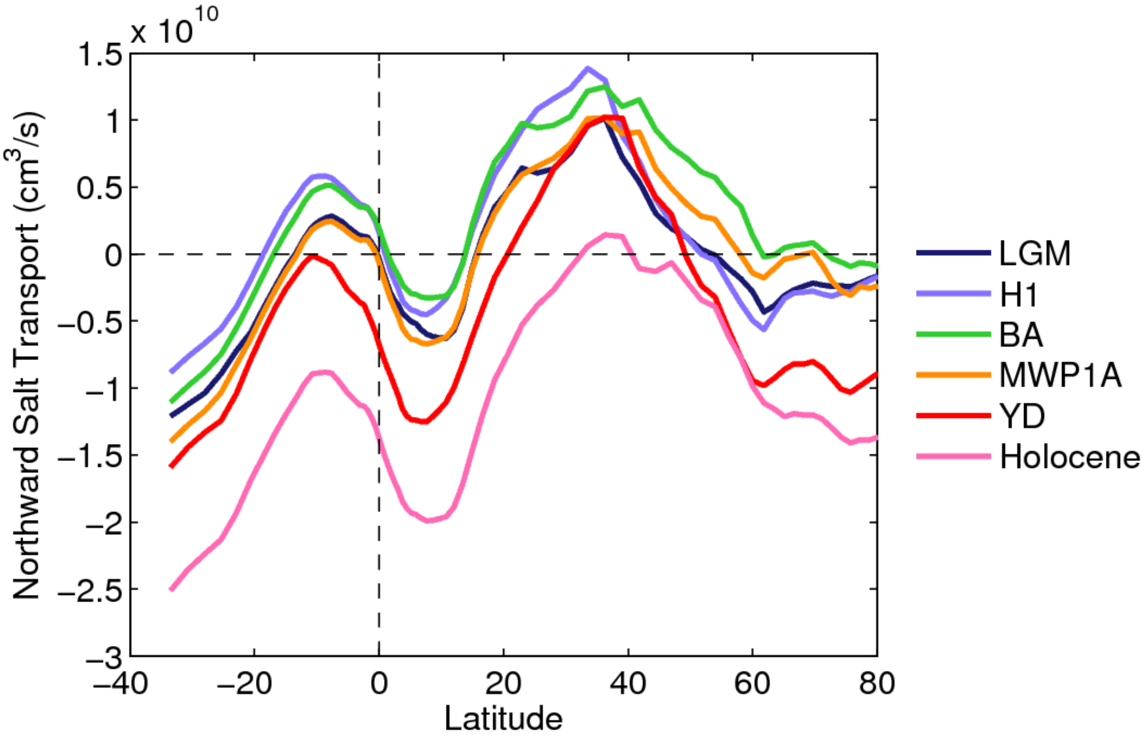
The northward ocean heat transport (NOHT) as a function of latitude for each of the key climatic periods in the simulation is shown in Figure 2b. NOHT has a maximum in the North Atlantic in the tropics, centered at 20N for the LGM and BA. This maximum shifts a few degrees north for the MWP1-A period. For the Holocene and YD the maximum northward transport is at about 30S reaching 35S at YD. The changes in magnitude of the transport between periods are non-linear and are related to the tropics, as discussed in Cheng, Bitz and Chiang (2007). The authors discuss the AMOC slowdown, related NOHT and the mechanisms for the high-latitude-tropical coupling through freshwater perturbation experiments.

In the South Atlantic, with exception at the YD, the NOHT is northward, largest at LGM, decreasing non-linearly at BA and MWP-1A, and very small for H1 and the Holocene.



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

We have also included another figure with the Northward Salt Transport (NOST) as a function of latitude. The NOST between the key climatic periods shows its maximum values between 30N-40N with a secondary maximum at 10S. In the North Atlantic the OST is southward for all periods from the Equator to about 20N after which, it becomes poleward reverting again to the equator at 60N. The strongest NOST is at H1, followed by BA, LGM and YD about 10^5 at 38N. At the Holocene with the exception of a small, albeit positive NOST at about 38N, all then OST transport is southward. In the South Atlantic there is northward transport at H1, BA and LGM while the NOST at YD and Holocene is southward.



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

“As there is only one experiment analyzed, without any sensitivity experiments or control integration (without the artificial MWP1A), the uncertainties/robustness of the model results should be discussed.”

The reviewer is correct and we have added the following paragraph to the text:

We analyze a single transient run where no control simulation (or other companion sensitivity experiments) was available at the time to access uncertainties and robustness of the results with respect only to MWP-1A. Furthermore, there are other intrinsic uncertainty sources such as the prescribed meltwater flux in TraCE-21K that is obtained (indirectly) from sea-level records. The timing, magnitude and location of the meltwater flux, associated with global sea level change, have significant uncertainty as well.

In this respect, interpretation of the results have to be taken with caution considering that the lack of a control run does not allow us to single out cause and effect relationships relative to individual events, nonetheless the transient nature of the simulation permits the formulation of a broad picture of how the deep Atlantic evolved. Changes start from the intense freshening of the Atlantic during H1 and the trigger of the SH source of freshwater associated with MWP-1A leading to the modern-day structure of the NADW.

Specific comments

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Author's affiliations should be set in the right order.

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Line 13: remove "... associated with the North Atlantic Deep Water..." was removed

Line 23: include reference for "..20m of sea level rise in less than 500yrs - The references for the 20m of sea level rise in less than 500yrs were included in the manuscript: Weaver et al., 2003; Peltier and Fairbanks, 2006; Hanebuth et al., 2009.

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Line 11: be more specific: which proxy evidence do you refer here?

We refer to the sea level records discussed in Deschamps et al. (2012), based on corals drilled offshore from Tahiti during Integrated Ocean Drilling Project Expedition 310.

14ff: This needs further explanation: Do you mean the LIS contributed 37% or do you mean 37% of the original LIS are not enough for a 20m sea level increase?

This number is based on Carlson et al. (2012). They discuss that the largest abrupt rise in sea level (10–20 m of sea-level rise) could have been coincident with the timing of MWP-1A, which triggered the North Atlantic warming, and possibly a significant contribution from the Laurentide Ice Sheet (LIS). They indicate that the maximum MWP-1A rates of global mean sea-level rise represent an increase in the rate of sea-level rise by 1.6–1.8 cm yr^{-1}, of which the decrease in LIS surface mass-balance (or its equivalent sea-level rise) can account for 37 ± 13%.

Line 22: There are numerous meltwater modeling studies that showed the NADW decrease in response to freshwater input (e.g. Manabe, S. and R. J. Stouffer, 1997, 2000, Rind et al., 2001 etc.). Why not referencing them? There are also studies that emphasize the sensitivity of NADW formation to the routing of these meltwater discharges.

The reviewer is correct and the suggested references that showed the NADW decrease in response to freshwater input were added to the text:

It is believed that freshwater inflow into the North Atlantic had a significant role in past climate changes considering that the response of the thermohaline circulation involved considerable reorganization (e.g., Broecker, 1990; Rahmstorf, 2002; Alley et al., 2003). There are numerous meltwater modeling studies that showed the NADW decrease in response to freshwater input: Rind et al. (2001), in study with the GISS model, discuss the impact of freshwater inflow relative to the weakening of the either from glacial melting (e.g., Broecker et al., 1985), or from ice sheet instabilities. Their results show a rather linear response of the NADW decrease relative to the amount of input of freshwater. Rind et al. (2001) also point out that other studies discuss changes in the NADW associated with the millennial-scale cooling events (Curry et al., 1999; Zahn et al., 1997; Manabe and Stouffer, 1997, Charles et al., 1996). However, the influence of salinity, which was not considered in these earlier papers, becomes important since it is what causes the non-linearity of the system (Stommel, 1961).

Line 23: Was the input of deep water to the world ocean constant during the geological past or at least to during the last glacial? Please include a reference for this or provide a physical mechanism, which would keep the deep-water input constant.

Changes in the deep ocean have profound impact on the earth's climate. The idea of an alternating meridional overturning circulation between hemispheres feeding the deep, dense currents that drive the overturning circulation is not new. It is driven by the NADW (in the northern hemisphere) and by the dense AABW in the Southern Hemisphere. This is extensively discussed in Broecker (1998), Seidov and Maslin (2001), Seidov, Barron and Haupt (2001), Ganopolski and Rahmstorf (2001) and others. The argument is that the strength of the circulation is out-of-phase with respect to the Northern and Southern hemispheres. That is a weakening of the NADW in the north allows more formation of AABW in the south, displacing the NADW to shallower depths and vice-versa. Seidov et al. (2001) discuss evidence the overturning circulation is significantly reduced with the weakening of the NADW during NH meltwater episodes (e.g., Manabe and Stouffer, 1988, 1995; Rahmstorf, 1995a; Rosell-Melé et al., 1997; Zahn et al., 1997).

Line 26: remove "water" following AABW(water). Usually, AABW is less salty. Remove "extremely salty" which is confusing here. I browsed through the referenced Marchito et al. and Curry and Oppo papers and found no evince for an "extremely salty" AABW.

The text was modified according to the reviewer.

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Line 10: Please explain more detailed why you want to investigate MWP1A (which occurred at 14 kaBP) when you hypothesize that the onset of modern deep water circulation was at 11 kaBP.

Our hypothesis was expanded to include the other freshwater events. It is our hypothesis that the present day circulation pattern of the South Atlantic Ocean was established approximately at the onset of the Holocene (11 ka). Therefore we will investigate the impacts of the freshwater discharge associated with H1 and MWP-1A, assuming contributions from both Hemispheres, on the structure of the NADW in South Atlantic Ocean. The idea here is to show that at the time of the MWP-1A the strong stratification of the water column reduces AABW dense water formation at the surface because of the freshening caused by the freshwater discharge allowing the spreading of the lighter class water into the deep ocean which allowed the subsurface salinity barrier that was blocking the spreading of the NADW to the South Atlantic to be eroded.

What are the reasons to assume 75% meltwater contribution of the AIS and please tell the reader at which location the meltwater was injected.

A detailed description of the meltwater flux scheme and location was included in the methods and data section. The reasons to assume that the inflow from the Southern Hemisphere was three times that of the Northern Hemisphere was based on the proxy records of sea level discussed in McManus et al. (2004); Stanford et al., (2006); Praetorius et al., (2008). If the inflow of freshwater from the north was greater than 5m, it would not agree with the proxy records. Considering (i.e. Weaver et al., 2003) that there was an increase in sea level of 20m in 500 years during this period, the choice of (5m) originating from the North Atlantic and 15m from the Southern Hemisphere (Weddell and Ross seas) was adopted.

Line 21: "It should be noted ...". This sentence is misplaced here. If you aim to validate your model you should choose those parameters you are discussing in the results (for example AMOC strength or heat transport where several values from the models can be derived from literature).

The sentence was removed.

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Line 3: Please describe the "meltwater schemes" and the sensitivity experiments in a more comprehensive way. The PhD thesis of He (2011) is not available. Which proxy data were chosen for selecting the specific meltwater schemes? Without this information it is difficult to assess the plausibility of the experimental setup.

A detailed description of the meltwater flux scheme and location was included in the methods and data section.

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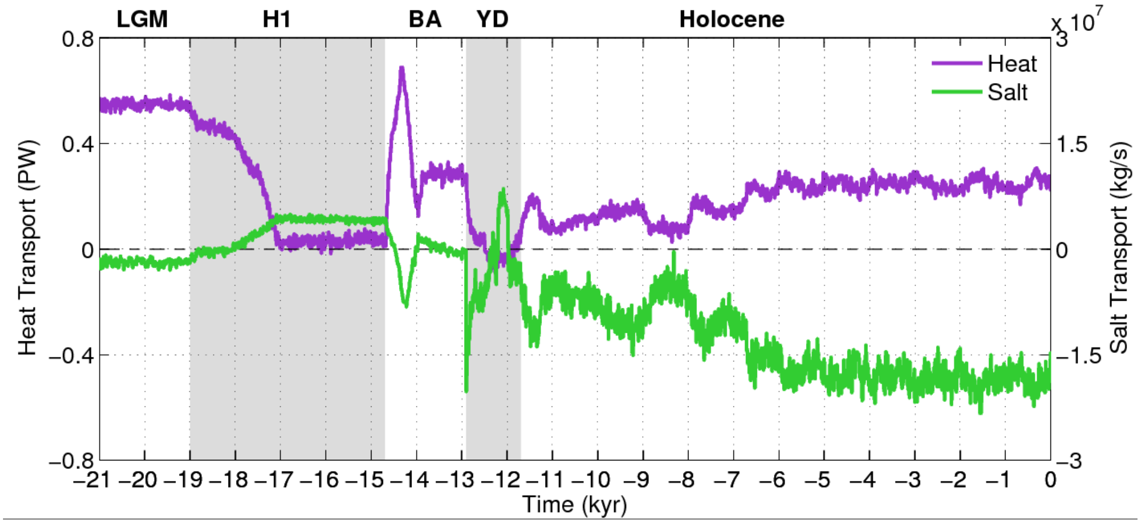
Line 9: As CP addresses to a broad and interdisciplinary readership it may be better to show not only anomalies in heat/salt transport.

New Figure 2 now shows the absolute values of the heat and salt transport



It is also not clear from the figures why a strong northward heat transport at 0 – 30S results necessarily in "warm northern Hemisphere" since this is subject to several other processes. May a time series for heat transport in the northern Hemisphere would be better. Or is there an explanation in the Liu et al. (2009) study?

The meridional heat transport in the South Atlantic is directed northward (with the exception of the YD). In order to clarify the changes in heat transport between the north Atlantic and South Atlantic we have included a new figure (Figure 2b, above) , which shows the northern ocean heat transport, by latitude averaged for each key climatic period (LGM, H1, B1, MWP1A, YD and Holocene). It is clear that the changes are sensitive to the freshwater pulses and the magnitude of the transport is highly nonlinear.

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Lines 20ff: be more specific here. What are the physical mechanisms in you model that force the strong relationship between heat and salt transport? Which water masses play a significant role for this relation? It is also not surprising that with your freshwater perturbation the correlation is getting weaker as a reorganization of deep water structure can be expected.

The freshwater flux and freshwater transport play an important role in inhibiting heat release from the ocean and determining sinking regions. The freshwater inflow has a stabilizing effect on the water column and impacts sea ice formation which changes (weakens) fundamentally the formation of the deep water masses such as the AABW and NADW that are driving the overturning circulation. In other words, there is a negative correlation between the heat and salt transport. The dense AABW transports salt northward near the ocean floor while the saltier NADW transports salt southward at the deep levels. Depending on the location of the freshwater flux, the transport of salt (and heat) will increase or decrease. For example, the MWP-1A that discharged the equivalent of 15m/kyr of freshwater into the Southern ocean where the AABW is formed would cause the NADW to transport salt southward more intensely. According to Seidov and Maslin (2001), for example, a stronger NADW is associated with increased northward heat transport, more salt transported to the south, leading to an inverse correlation. The same is true for AABW (more AABW, more heat towards south and more salt towards north).

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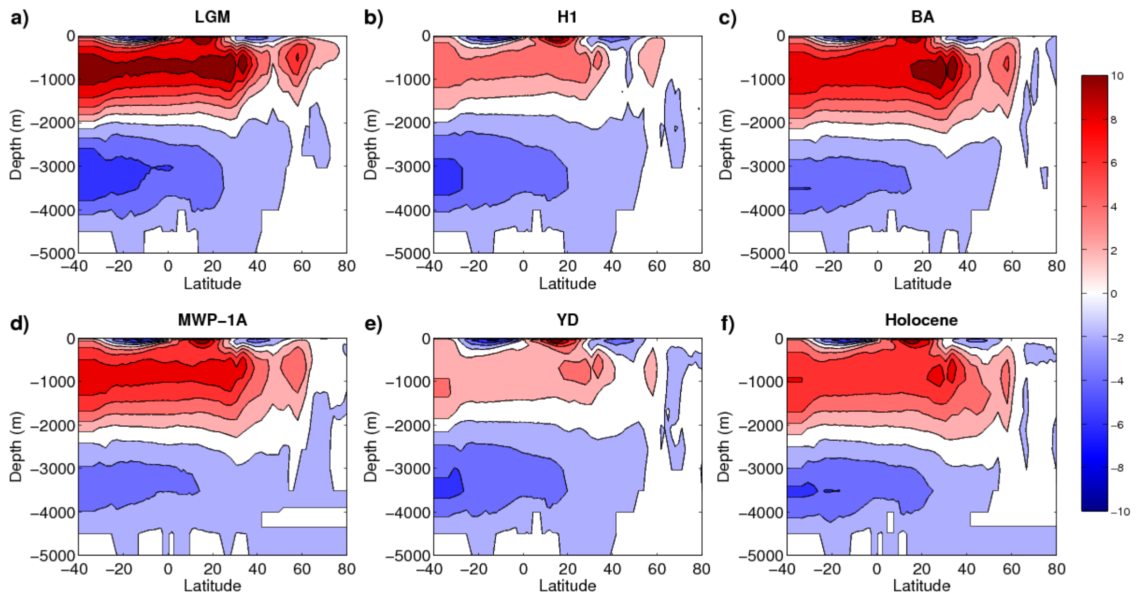
Line 6: Is there any indication that the AMOC is stronger at 21k in your model? It should be possible calculate the AMOC from your model output in a similar way as equation 1.

A new figure (New Figure 4) with the overturning function, averaged for each climatic period was included and one can observed the intensified LGM.



New Figure 4. Overturning function averaged for each period: (a) LGM – 22 to 19 ka; (b) 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 – 12.9 to 11.3 ka; (f) Holocene – 11.3 to 0 ka. The colors represent transport, in Sverdrups.

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Line 3ff: How was the model initialized and spun up for the LGM? Usually models are tuned present day climatologies. Did you then remove a water volume corresponding to a 120 m sea level equivalent? And how long was then the model spinup afterwards?

The CCSM Transient run was initialized with the results of the LGM simulation with the CCSM described by Otto-Bliesner et al. (2006). This CCSM3 LGM simulation has concentrations of atmospheric greenhouse gases based on ice core measurements (Fluckiger et al., 1999; Dallenbach et al., 2000; Indermühle et al., 2000) and are tabulated in Otto-Bliesner et al. 2006 (their Table 1) as are the atmospheric aerosols. The concentrations of atmospheric carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are decreased relative to the Pre-Industrial values, resulting in a total decrease in radiative forcing of the troposphere of 2.76 W m^2. The majority of this change (2.22 W m^2) results from a decrease in the amount of CO_2. Continental ice sheet extent and topography in the LGM CCSM3 simulation are from the ICE-5G reconstruction (Peltier, 2004). The coastlines are also taken from the ICE-5G reconstruction and correspond to a lowering of sea level of ~120 m. The orbital parameters of 21kyr ago (Berger, 1978) are used to determine the total solar flux. As discussed in Clauzet et al. (2007) and Otto-Bliesner et al. (2006), the LGM ocean is initialized by applying anomalies of the ocean three-dimensional potential temperature and salinity fields derived from a LGM run with the Climate System Model version 1.4 (CSM1.4, Shin et al. 2003). This approach allows a shorter spinup phase by starting with a previous LGM simulation that reached quasi-equilibrium. The LGM simulation is run for 1800 years before initializing the TraCE-21K simulation. The initial fields present a colder and saltier deep ocean compared to the present day thermohaline structure.

We have included this description in the data/methods section

Line 8: It is difficult to follow the line of arguments here. How can sea ice formation be intensified by lower CO_2 concentration? And resulting from increased sea ice formation the glacial ocean was much more stratified? Please be more specific here and provide a physically plausible chain of arguments.

This was stricken from the text: freshwater stabilizes the ocean (lower density layers on top of the higher density layers) while sea-ice formation, through brine rejection and convective overturning de-stabilizes the water column.

The authors here provide a survey of evidenced processes from other studies like changes in sea ice formation, deep convection in the north, stratification etc. that agree with a reduced northern heat transport as observed in Fig. 2. But which of these important aforementioned processes can you really see in your model? Are these processes eventually described in Liu et al (2009, line 17) or He et al 2011?. Then this paragraph should be moved to the intro to avoid the impression of reworking published material.

This is paragraph was moved to the introduction.

Line 17: Do you see the opposing NH – SH in air temperature changes also in you model experiment as Liu et al. did? Or do you reinterpret the Liu et al results?

Considering it is the same model, same simulation. The out-of-phase air temperatures are also in the model results; however we did not look at the air temperatures specifically.

Line 20ff: Again the author take an explanation from the Liu et al (2009) paper to explain a peak in heat transport anomaly shown in Fig 2. Do you see this "overshooting" in AMOC also in your experiment or do you analyze the same result as Liu et al. (2009)?

We do reproduce the same results. The overturning function averaged between 14.67 to 14.35 ka in Figure 4(c) is intensified.

Can you estimate how robust are the changes in North Atlantic circulation with respect to the geographical location of the H1 FW injection? If not, this uncertainty should be discussed somewhere in the text.

No, we cannot estimate the changes in the North Atlantic circulation with respect to the individual geographical location of the H1 freshwater injection. This is added to the discussion:

The FW inflow during H1 comes from North Atlantic between 50N and 70N and the Gulf of Mexico (Figure 1b). The overturning circulation in the Atlantic in H1 weakens associated with the decrease formation of the deep-water masses (NADW in the north). This response and associated impact on the global climate are not simply controlled by the rate and strength of the meltwater inflow into the ocean. The location of meltwater injections may be more important, with NADW formation being particularly sensitive to surface freshening in the Arctic/Nordic (Stanford et al, 2011). Since in this simulation we cannot separate the impact from the different geographical locations of the H1 sources of the MWF, the response of he ocean circulation cannot be related to the individual source location.

The BA period is mostly recognized in Northern Hemisphere proxy data sets. Fig. 2, however, shows only the heat transport anomaly between 30 S and 0. When you assume that a change in the oceanic heat transport contributed much to BA warm period, then it would be more appropriate when you show the oceanic heat transport anomaly for the NH (perhaps 0 – 40 N, 30 N – 60 N). Or you should explain why the 30 S – 0 heat transport as shown in Fig. 2 is more indicative for the NH climate.

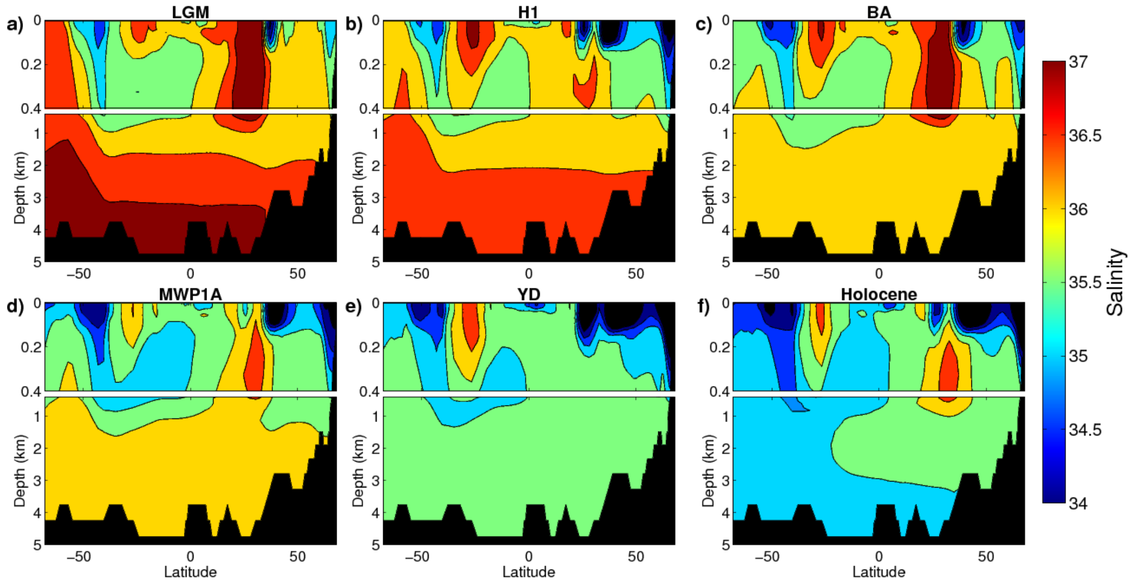
The thought was to look at the contribution of the South Atlantic based on the idea of heat piracy (Seidov et al., 2001) when there is an out of phase relationship between hemispheres. In other words, when there is warming of the North Atlantic, for example, the South Atlantic becomes cooler because its heat is being transported northward.

Line 25 – 28: From Fig. 1 it is obvious that there is also a significant meltwater contribution from the NH contemporaneously. How can you be sure that the salinity anomaly arises only from the southern FW source?

The reviewer is correct, we cannot isolate the response in terms of SH sources. What we can speculate is that, considering that the magnitude of the Southern Hemisphere contribution of MWP-1A was 3 times sharper than from the NH, it would have had a greater impact on the structure of the NADW.

How many years were averaged for the plots in Fig.5? According to Fig. 1 the meltwater discharge associated with the YD starts at already at 13 kaBP. Do you average across this event? Then you should consider how much of the change between Figs 5c and 5d is according to YD meltwater in the NH?

The plots on Fig. 5 were time slices, not means. This was changed and the <u>new</u> Figure 5 (below) now depicts the averages; LGM: mean between 22 to 19ka; H1: mean between 19 to 14.67 ka; BA: mean between 14.67 to 14.35; MWP-1A: mean between 14.35 to 13.85; YD: mean between 12.9 to 11.3 ka; Holocene: mean between 11.3 to 0 ka.



New Figure 5. TraCE-21K salinity meridional sections across the Atlantic Ocean (25° W) at (a) LGM – 22 to 19 ka; (b) 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 – 12.9 to 11.3 ka; (f) Holocene – 11.3 to 0 ka.

Line 28ff: From the salinity profiles alone it is difficult to deduce the presence/absence of NADW formation. It seems there is no strong NADW formation as long as you have a strong freshwater source in the NH, which is the case from 17 kaBP to around 11 kaBP. After that, a modern-like salinity pattern can be recognized in Fig. 5. f-g. May be this could be one of the main conclusions of paper (rather than that the southern meltwater sources are important)?

The reviewer is correct – this was added to the conclusion of the paper. The freshwater pulse during H1, although weaker, was sustained for a long time. This freshening of the North Atlantic is what maintained the water column structure shown in Figure 5 T-S diagram before MWP-1A. We can argue that no strong NADW formation will occur as long as you have a strong freshwater source in the NH. The NH continuous freshening of H1 sets the stage and the strong and sharp, predominantly SH origin MWP-1A triggers the evolution of the modern-like salinity pattern can be recognized in Fig. 5. f-g

Page 6382 line 29 – Page 6383 line 1

The YD (or H0) meltwater injection starts already at 13 kaBP (according to Fig. 1). Shouldn't this meltwater discharge suppress the NADW formation rather than building up a precursor of modern NADW?

This paragraph was re-written. The H0 FW discharge suppresses the NADW, but does not interfere with the high salinity pocket at the subsurface. It is the northward transport of freshwater triggered by MWP-1A that allows the pocked to be eroded by mixing associated with the spreading of the NADW into the South Atlantic.

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Line 8 – 10: I agree that the termination of the YD meltwater input leads to the establishment of NADW formation after 11.7, which in turn forces an increased northward heat transport in the NH. But doesn't this contradict your main conclusion that MWPA1 in the SH was crucial to the setup of modern NADW (stated in the abstract, last sentence)?

The reviewer is correct – the MWP-1A alone was not responsible for the present-day NADW. The freshening of H1 did set the stage (ocean structure) for the exchanges of heat and salty that took place after MWP-1A, eroding the salinity barrier between the upper and lower ocean column and allowing the salty NADW to be transported into the SH resulting in the T/S structure we see in Figure 4 (red curve). Stanford et al. (2006) discuss that the AMOC (e.g., NADW) recovery is coincident with the Bølling warming (McManus et al., 2004; Stanford et al., 2006). The authors suggest that in fact the AMOC "switch on" and the Bølling warming were intrinsically linked.

Line 10 – 12: be more specific. Which salinity barrier do you mean? Earlier (line 1 page 8363), you stated that the upper layer temperature was too high for the water to sink at 13 kaBP (Fig. 1d, so it was rather a temperature barrier?).

From the salinity vertical profiles, starting at the LGM (new Figure 6), there is a region between 30N-45N extending from the surface to about 1000m of high salinities (maximum of 37) – this salinity pocket is seen at the subsurface in H1, recovers to the surface at BA, is considerably reduced during MPW1-A disappearing at YD.

After 13 kaBP there almost only a strong northern FW source in your experimental setup. It's not plausible how the erosion of the salinity barrier might come from the south. From 13kaBP to 11 kaBP the entire Atlantic freshens more and more with only very minor FW contribution *from the south but much more FW from the north (Fig.1). Also the south Atlantic further freshens profoundly after stopping the FW contribution from MWPA1. How is this possible?*

We agree, the NH freshening was important to establish ocean conditions (i.e. fresher NA, saltier deep ocean throughout, the salinity barrier in the NA). We believe, however, the MPW-1A was the trigger – further freshening consolidates the ocean conditions (deeper, saltier NADW).

Line 22ff: Yes, these conclusions appear reasonably. But as far as I understand the establishment of NADW formation is mostly sensitive with the presence/absence of a NH FW source. Maybe you overestimate role of the southern meltwater sources.

Yes – We underestimated the role of the NH freshening, in particularly the long and continuous inflow during H1. This can be thought of (as in Seidov et al., 2001) of the relative (and out-of-phase) role of the AABW in the SH and NADW in the Northern Hemisphere. The intensification of one implies in the weakening of the other as a function of the freshwater inflow. In other words, the Southern Hemisphere ocean response to MPW-1A is a weakened AABW, which leads to the increase of the NADW production. This sequence converts a cold trend to warm trend and can reverse the cooling in the north, despite the H1 freshening (e.g. Seidov et al, 2001).

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Line 13ff: From the plots in Fig. 5 I would guess you already initialized the model with a "salinity barrier". Otherwise you should explain when exactly this barrier was established, which processes were responsible for it and how it advanced to the north.

The salinity barrier was indeed already there in the initial conditions, when the stratification was stronger than the observed on the present day. This was included in the text.

Page 6384 line 24 – Page 6385 line 2

This sentence appears a bit misplaced in the context and in the conclusions at all.

The sentence was removed

<u>Technical comments</u>

Fig. 2 caption: "...positive values... indicate a northward transport...". According to the Y-label you show here anomalies. Do you mean a northward transport (less southward transport respectively) relative to the mean transport?

We have changed anomalies to absolute values in this figure, which clarifies this issue.

Fig. 5: The color bar is not readable: How many years have been averaged for the individual slices?

A new Figure was drafted.

For clarification, we also included a figure of salinity vertical profile differences (below). The Atlantic basin is considerably fresher at H1 when compared to the LGM (Figure 7a), the largest differences are in the North Atlantic in the upper 1000m with maximum values in the upper 200m. The subtropical South Atlantic in the upper 800-900m is saltier in H1 compared to LGM. This is because the prolonged freshening was entirely in the North Atlantic with the residual LGM saltiness remaining in the southern subtropics upper ~ 800-900m. Figure 7b shows the salinity differences between H1 and BA when the NADW recovers, which is seen by the positive salinity difference in most of the North Atlantic in the upper 1000m, reaching the equator in the surface layers. The impact of MWP-1A with respect to BA is observed in Figure 7c with a basin-wide freshening. The salinity differences between the YD event with MWP1-A (Figure 7d) show a similar distribution to Figure 7a, except the deeper ocean is significantly fresher. The upper 500m display a saltier South Atlantic and a fresher North Atlantic, indicating a stronger AABW and weaker NADW. This structure finally evolves into the opposite with and intensified NADW that is able to spread into the Southern Hemisphere as seen today.

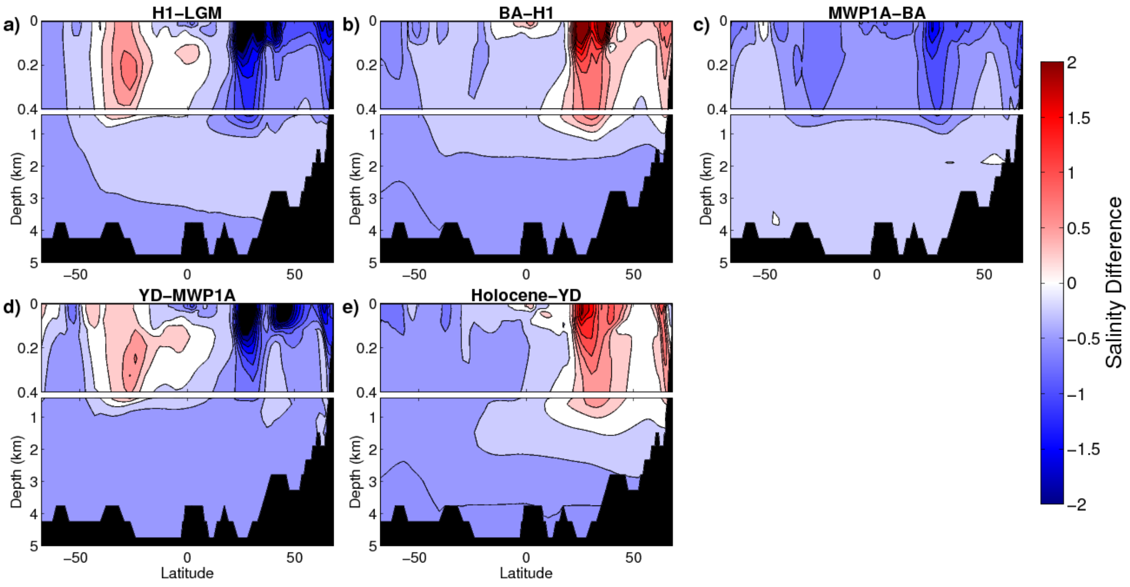

Figure 7. TraCE-21K salinity differences between a) H1 (19ka -14.67ka) and LGM (22ka – 19ka); b) BA, (14.67ka -14.35 ka) and H1 (19ka -14.67ka); c) MWP-1A (14.35ka -13.85 ka) and BA, (14.67ka -14.35ka); d) YD (12.9ka - 11.3 ka) and MWP-1A, (14.35ka -13.85ka) d) Holocene (11.3ka - 0 ka) and YD (12.9ka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

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