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Interactive comment on "Enhanced 20th century heat transfer to the Arctic simulated in the context of climate variations over the last millennium" *by* J. H. Jungclaus et al.

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We thank the reviewer for his/her insightful comments, which have helped us to clarify our arguments and to improve the manuscript. We display here the reviewer's comment in italic, our response in regular font, and quotation from the modified manuscript in quotation marks and bold font.

This study assesses the results of coupled climate simulations covering the last millennium and reaching into the 20th century. The mechanisms responsible for temperature variability in the pan-Arctic region during the last millennium are assessed. In the preindustrial time period, the simulated temperature variations in the region are found

to correlate closely with ocean heat transport variations. For the postindustrial period, previous paleoceanographic reconstruction studies have indicated a dramatic warming in Atlantic Water (AW) as compared to the preindustrial period, leading to anomalous enhanced ocean heat transport into the Arctic. This has previously been suggested to be a key element in the Arctic response to anthropogenic warming, adding to the local warming and sea-ice temperature feedback. This study proposes a mechanism by which this could take place: anthropogenic warming results in a weakening of the deep water formation and the Atlantic meridional overturning circulation (AMOC), which leads to a strengthening of the subpolar gyre (SPG). Assessing quantitatively the factors contributing to regional climate changes is undoubtedly of importance. The results are very interesting and contribute to our understanding of Arctic climate change in a paleoclimatic perspective, highlighting the importance of ocean circulation changes in the Arctic amplification of global warming. Although the focus of the manuscript is the 20th-century, the discussion is framed in the context of the last millennium and thus the manuscript is well suited for Climate of the Past. The paleoclimatic focus and the paper itself would both gain if preindustrial simulated variations were discussed in depth in this same manuscript, but I can understand that the authors reserve this for a future manuscript, as they mention.

We thank the reviewer for the positive evaluation of our manuscript. A more thorough study of the mechanisms leading to the pre-industrial variations in the North Atlantic/Arctic ocean-atmosphere system has evolved into a promising PhD thesis. We would stress indeed that we see a specific value in the present study in the fact that it put the recent changes in times of anthropogenic changes into context with internally-generated and naturally-forced variations.

General comment 1: The authors claim that the mechanism they describe explains the enhanced 20th century warming. However, to be totally convincing they would need to illustrate it using 20th century oceanographic observations. It is clear that for the previous period there will be no observations available, and this is where their simulations *are most valid. But without current observations what they show is just a plausible mechanism as inferred from their climate model. As the authors say, 'the model results have to be confronted with observations and reconstructions to assess in how far they reproduce the real climate evolution, both in direct comparison'. This applies also to the mechanisms. Thus, I suggest including an assessment on observational changes in ocean heat transport in the 20th century, assessing whether it is taking place and whether it responds to the same mechanism as described here. If this is not possible, it should be explained clearly why, and some of the conclusions should be rephrased.*

We agree and have conducted a more thorough literature survey to find long-term observations that could serve to support or question the mechanism described in our study. However, most continuous observations (e.g. from weather ships) are only available for a few decades and are mostly characterized by strong multidecadal fluctuations (see, for example weather ship Mike (Osterhus and Gammelsroed, 1999, in the new reference list). Moreover, quantities like heat transport need sophisticated equipment for measuring both temperature and transport, and there are no long-term observations. Compilations of observational data are available in the form of (partly gridded) data sets, like HadISST. We have included in our discussion now a paragraph including an assessment of these data sets and some additional references to high-resolution reconstructions of SSTs for the last few centuries (Hall et al., 2010; Cunningham et al., 2013 see new reference list). A very robust finding appears to be the relative cooling of, at least, part of the subpolar basin that is clearly visible, for example in HadISST. We also quote a compilation of 20th century surface temperature and salinity data (Reverdin etv al., 2010), which do not support our mechanism, and have added this to our discussion on model uncertainty:

"Obtaining a comprehensive view from long-term direct observations of temperature, salinity, or transports remains challenging. There exist only a few long-term time series. Many continuous records, such as those from weather ships (e.g. Østerhus and Gammelsrød, 1999) cover the last decades and are char-

acterized by multi-decadal variability. The temperature measurements over the 20th century near Svalbard by Pavlov et al. (2013) and one of the longest time-series available at all, the Kola section in the Barents Sea (Skagseth et al., 2008) support the pronounced warming in the Atlantic Water branch in the industrial period. Polyakov et al. (2004) synthesized various observational data sets to conclude that the intermediate Atlantic Water layer in the Arctic shows a continuous warming trend that is superposed by multi-decal variability. Combining proxy data and observations, Cunningham et al. (2013) compiled a synthesis of SST changes in the north-eastern North Atlantic and the Nordic Seas during the last millennium. For the 20th century (their Figure 1a), they report that most of the records reflecting the Atlantic Water branch along Scotland and Norway indicate a warming, while other records from the sub-polar North Atlantic indicate neutral or cooling conditions. High-resolution proxies from the Iceland Basin (Hall et al., 2010) over the last 230 years indicate cooling of SSTs in the central sub-polar gyre region, which would be consistent with our findings. The available SST gridded data sets HadISST (Rayner et al., 2006) and ERSSTv3 (Smith and Reynolds, 2004) as well as the Simple Ocean Data Assimilation (SODA) reanalysis (Carton and Giese, 2008) are all characterized by a cooling trend in the sub-polar gyre region (Drijfhout et al., 2012; Kim and An, 2012). Polyakov et al. (2010) have used historical data from the North Atlantic Ocean and decomposed the changes between the 1920s and present into non-linear trend and multi-decadal variability patterns. The large-scale nonlinear trend pattern resembles the 20th century SST trend in the HadISST and is characterized by cooling over the sub-polar gyre (see their figure 5) and warming in the subtropical North Atlantic and on the northwestern European Shelf, again compatible with our results for the 20th century simulations. On the other hand, the 20th century compilation of temperature and salinity data from the subpolar gyre region by Reverdin (2010) compares less well with our study: the central SPG at about 60N is characterized by slightly positive temperature and negative density trends. Uncertainties

in early observations and reconstructions preclude a definite answer to what degree the findings reported here can be verified by observations. While the dynamical mechanisms proposed here to explain the enhanced heat transfer to the Arctic appear largely compatible with observed features in the North Atlantic, they may depend on the particular model system."

General comments 2: Another point I think should be addressed is the statement that the AMOC reduction is the trigger of the SPG increase. Is an AMOC decrease really necessary to strengthen the SPG, or are the AMOC decrease and the strengthening of the SPG both a response to reduced deep water formation and local cooling? A reduction of the AMOC under anthropogenic warming at most only attenuates the warming. Cooling is rather only found locally, in response to reduced deep water formation. I think it would be more exact to frame their results in this way.

Although we cannot definitely say if the AMOC weakening is the initial trigger of the SPG increase, or if changes in the baroclinic structure influence the SPG strengthening we would state the following with confidence: 1. Reduced deep water formation would not accelerate the SPG per se. On the contrary, as has been shown in many previous studies (e.g. Eden and Willebrand, 2001; Häkkinen and Rhines, 2009) stronger cooling by surface fluxes in the Labrador Sea (for example during NAO+ situation) leads to the characteristic doming of the isopycnals in the Lab Sea and to an enhanced SPG strength. In our study, we find reduced deep water formation in the 20th century mainly related to warmer conditions in the Lab Sea (see the new figure 8a) and, as a consequence, a slightly reduced magnitude of the barotropic stream function (new Figure 4b. 2. We show that the combination of reduced MOHTR in subtropical and subpolar latitudes and the increase in GOHTR leads to a changes in the TOHTR that are associated with advective cooling or warming (derived from the divergence of the lateral heat transports). We hope that the newly drawn Figure 5 (previously Figure 3) helps to clarify better the relation between the components of the heat transports and the induced warming/cooling. Moreover, the atmosphere-ocean

heat fluxes are positive over the cool region in the subpolar North Atlantic (new Figure 5b). Thus the atmosphere warms the colder ocean and acts to damp the temperature changes. 3. Also in observations (e.g. HadISST, see, for example Kim and An, 2012, or Drijfhout et al 2012) the so-called "warming hole" does not occur localized in the deep water formation region in the Labrador Sea.

Therefore we keep to the description of the mechanism as we outlined it in the first submission. We have substantiated the connection between AMOC, deep water formation, LSW, and Labrador Sea surface characteristics by providing the new figure 8a and the corresponding text in the manuscript:

"To further elucidate the origin of the circulation changes we identify first the reason for the weakening of the AMOC in the subtropical and subpolar North Atlantic. A key ingredient modulating the AMOC here is the strength of deep water formation in the Labrador Sea (Latif et al., (2006), Lohmann et al., 2014). To quantify the latter we calculate the thickness of the Labrador Sea Water (LSW) in the region (Lohmann et al., 2014). Normalizing the anomalies, we see a clear covariability with the AMOC at 30N and 1500m depth when AMOC lags by roughly 8-10 years. Next, we establish a link between LSW thickness and surface properties by correlating LSW thickness with the surface density field (not shown), which reveals the central Labrador Sea as convection hot-spot. The evolution of surface density, temperature and salinity in the so-identified region reveals, as expected, that enhanced LSW formation comes together with positive density anomalies at the surface, which reduce the static stability and induce convection. Also shown in Figure 8a are the corresponding temperature and salinity time series. Following the evolution through the last three centuries indicate pronounced multi-decadal variability and pronounced differences between the industrial period and the centuries before. The multidecadal variability is characterized by co-varying temperature and salinity, where apparently, density is

determined by the salinity changes (e.g., fresher and lighter conditions lead to less dense surface waters, which is not compensated by colder temperatures). The variations in the regional fresh-water budget is mainly caused by modulations of the sea-ice and fresh water supply from higher latitudes (Jungclaus et al., 2005). During the 20th century, however, this relation breaks down as somewhat fresher conditions (also caused by increasing sea-ice and fresh-water export through Denmark Strait, not shown) go along with a general warming, partly caused by direct radiative forcing, partly be redistribution of heat by an enhanced Irminger Current. As a result, AMOC weakens at latitudes downstream from the LSW formation region. The temporal evolution of the vertical density structure in the Labrador Sea indicates then generally less dense conditions in the upper 2000m. Interestingly, the deepest layers are characterized by relatively colder temperatures and higher densities that are caused by the enhanced overturning in the Nordic Seas and associated changes in the strength and density of the Denmark Strait overflow. Changes in the vertical density structure are important for the east-west density gradient driving the AMOC (Lozier et al., 2010), but also affect the baroclinic structure of the gyre directly (Drijfhout and Hazeleger, 2006)."

Other minor comments to consider are the following: - Abstract: I find misleading the statement in the abstract saying 'Here we present results from Earth system model simulations over the last millennium that reproduce and explain reconstructed integrated quantities such as pan-Arctic temperature evolution during the pre-industrial millennium'. Besides the very low frequency variability, climate variations in the preindustrial period are not really reproduced or explained. I assume this is part of a companion paper, as the authors say.

Point taken: since we do not discuss the pre-industrial evolution in detail, we have removed the respective statement.

Page 2899, line 10: correct 'Intercomparision' Corrected

- Page 2905: why do the authors say 'a weaker overturning component is compensated by a stronger gyre'? Despite the weaker overturning the MOHT does increase, at least at high northern latitudes. This figure is however very confusing, see below.

We admit that we haven't made the point clear enough and the old figure 3 was, indeed, hard to understand (partly it appeared pretty small in the printable version). Firstly, we have moved the old figure 5 (the 20th trends in AMOC and barotropic stream function) to appear earlier in the manuscript as figure 4.. The AMOC figure clearly shows the reduction in subtropical and subpolar latitudes, while there is an enhancement north of 60N. Second, we have modified the old Figure 3 (now Figure 5): In figure 5a, one can now more clearly see the strong reduction of MOHTR (now the dotted lines), but, between 40 and 55N, this is partly compensated by GOHTR (the dashed lines). The resulting TOHTR exceeds the range of natural variability mainly outside this region, but its variation with latitude is quite pronounced, which indicate divergence or convergence of the heat transport.

- Page 2901, section 3: related to my comment above, the discussion of the preindustrial last millennium is limited to the comparison of the broad, low frequency variations in the reconstructed and simulated Arctic surface air temperature, sea-ice and Atlantic water temperatures. This discussion could be deepened. For example, even though figure 1b shows the simulations and reconstructions agree within the uncertainties of the latter, the simulations a priori seem to show a larger degree of agreement with each other than as compared to the reconstructions. These similarities could be a matter of chance or be related to the external forcing, but in the latter case they should also be reflected in the reconstructions, unless internal variability is strongly underestimated by the model. I understand in the case of 1c it can be partly a consequence of limited temporal resolution of the proxies.

We have modified the respective paragraph regarding the variability in the sea-ice reconstruction and simulations (Figure 1b) and modified our conclusion regarding the role of internal variability:

“Notwithstanding questions regarding uncertainties in the reconstructions, it is difficult to relate the event to known volcanic or solar forcing variations (e.g. the minimum around 1700 appears at the time of the Maunder minimum in solar variations). The anomalies in the 15th to 17th century exceed the 2-sigma range of control experiment variability significantly. We have detected events of similar magnitude in unforced control simulations, but they appear only very rarely (once in a 1000 yr simulation). It is therefore possible that the model underestimates internal variability of the sea-ice extent.”

-Page 2907, line 18: the sentence in the discussion stating the SPG intensification is caused by 'the weakening of the AMOC and the associated reduced heat supply' is misleading. As explained above, the SPG I understand is spun up because of local cooling due to reduced deep water formation, not because of reduced heat transport by the overturning. The AMOC does decrease, but as the authors say this does not imply reduced heat transport by the overturning. Also, is an AMOC decrease really necessary to strengthen the SPG or are the AMOC decrease and the strengthening of the SPG both a response to reduced deep water formation and local cooling? (see also the comment below).

See response to “General comment 2”. We have shown that that the SPG does not strengthen as a response of cooling by surface forcing, while we have clearly demonstrated that the AMOC weakening in subtropical and subpolar latitude is related to deep water formation in the Labrador Sea. What we cannot rule out, however, is that the changing density structure in the western part of the North Atlantic has a direct effect on the gyre circulation, as has been pointed out by Drijfhout and Hazeleger (2006). Therefore we have modified the first lines of the “Discussion” section:

“Our analysis has demonstrated that the increasing heat transports to higher latitudes are mainly caused by changes in the gyre and overturning circulation

in the subpolar North Atlantic. These changes are caused by a reduction in deep water formation in the Labrador Sea, which leads to reduced overturning circulation in subtropical and subpolar latitudes. In addition, changes in the vertical structure of water masses at the western boundary can modify the baroclinic gyre circulation (Drijfhout and Hazeleger, 2006). The associated changes in MOHTR and GOHTR lead to enhanced TOHTR towards higher latitudes and heat transport divergence (cooling) in the subpolar region. The colder and denser SPG then spins up baroclinically, which further increases the GOHTR (dashed lines in Figure 5a), which, in turn, extracts even more heat from the SPG center and further increases the horizontal density gradient.”

- Page 2909, lines 8-21: the authors give arguments supporting a similar mechanism might operate during the late Holocene. They end up saying that the preindustrial millennium will be assessed separately. However, as suggested in my major comment above, they could attempt to identify this mechanism in present-day observations or explain why this is not feasible.

See response to “General comment 1”

- Page 2011, line 16: again, is an AMOC decrease really necessary to strengthen the SPG or are the AMOC decrease and the strengthening of the SPG both a response to reduced deep water formation and local cooling?

See response to “General comment 2”, and the comment to page 2907, ln18.

- Figure 1: please state which of the three simulations corresponds to each colour. Also, in panels b and c, it is difficult to distinguish the thin from the thick lines. The same goes for figure 2b. I would strongly suggest using shading for the confidence

intervals.

We have redone most of the figures for better clarity. We have split Figure 1 into two and discriminate now between the pan-Arctic changes in summer temperatures and sea ice (new Figure 1) and the more local time series from Fram Strait (now Figure 2), which is also quite essential for the manuscript. We have also included labels to discriminate between individual simulations. Using now dashed lines for the confidence interval for reconstructed sea ice seems to work well.

- Figure 3a is confusing: I understand there are three colors, black for the total, red for the gyre and blue for the overturning component, I assume for the ensemble as fig 2b. If so the ensemble should be explicitly mentioned. What are the dotted lines? As before, there are too many lines, I would strongly suggest using shading for the confidence intervals.

We agree and apologize that we did not pay attention to the bad visibility of the figure in the printable manuscript. We thank for the suggestion using shading. We have therefore completely modified this figure (that is now Figure 5). We use shading in the background for the confidence interval. We use now colors for individual simulations and labels to identify them. We discriminate between the components MOHTR and GOHTR using dashed and dotted lines, respectively, whereas TOHTR is given now by solid lines. It is now much clearer what is outside/inside the range of internal variability.

Please also note the supplement to this comment:
http://www.clim-past-discuss.net/10/C1782/2014/cpd-10-C1782-2014-supplement.pdf

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