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Climate of the Past
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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 re-display here the reviewer's comments in italic, followed by our response in normal font, and quotation from the modified manuscript (see supplement) in quotation marks and bold font.

Junglaus et al. 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, and the Atlantic Water warming in Fram Strait in the 20th century. They suggest that the associated

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increase in ocean heat transfer to the Arctic can be traced back to changes in the ocean circulation in the sub-polar North Atlantic. The interplay between a weakening overturning circulation and a strengthening subpolar gyre as a consequence of 20th century global warming could act as a driving mechanism for the pronounced warming along the Atlantic Water path toward the Arctic. Generally, the data is very interesting. As the ocean circulation is among the dominant climate factors, the research papers of this kind discussing on basin-wide circulation variability are very important regarding to present-day climate change. The paper is definitely suitable for Climate of the Past and should be published. However, since I am not a modeler, I cannot take a stand on quality of modeling despite its key role in this paper.

We thank the reviewer for the positive over-all evaluation of the manuscript. Regarding the aspect of "quality of the model", we have included, in response to one of reviewer 2's criticism, a more thorough discussion of how the model results relate to observations. (see response to review 2, general comment 1).

In my point of view, the missing assessment of external factors (volcanic and solar forcing) and especially the interaction of Arctic sea ice –AMOC is the main weakness of the paper. I can understand that the authors want to keep the paper as compact as it stands now. However, the role of sea ice is not recommended to pass over due to its robust role in the ocean circulation system.

As we have stated in the manuscript, we want, in the present paper, discuss and analyze the dynamical changes that have led to the pronounced warming in the Atlantic Waters in Fram Strait and the unprecedented changes in the North Atlantic in the 20th century. We do that in the context of simulations that cover the entire last millennium to discriminate these changes from natural variability. In contrast to internally-generated variability and changes owing to volcanic and solar forcings, the 20th century changes have specific characteristics that are related to the anthropogenic forcing. We wish to concentrate on these effects. An investigation of the variability in the ocean-atmosphere circulation during the pre-industrial period is presently under way and has evolved in a PhD project. We understand the reviewer's point to give a more in-depth analysis of the mechanisms that lead to a modulation or a weakening of the AMOC. We are thankful for this hint because it helped us to further clarify the mechanisms involved. We agree and have published earlier (Jungclaus et al., 2005, see reference list) on the connection between Arctic sea-ice, fresh-water export from the Arctic via the East Greenland Current, convection in the Labrador Sea, and its influence on the AMOC. We have therefore extended our analyses to include an assessment of the factors modulating the AMOC strength in our present simulations. We find that, in the pre-industrial period, multi-decadal variations in LSW formation and AMOC are indeed related to fresh-water (and sea-ice) exports through Denmark Strait that are reflected in the surface salinity changes in the Labrador Sea (see the new figure 8). However, in the industrial period, under the anthropogenic forcing, the relation between freshening, cooling and weakened AMOC breaks down. Instead the decrease in surface density and stability in the convection region is characterized by warming that is accompanied by a slight freshening (caused, indeed by enhanced fresh-water export from the Arctic). We have included a new Figure 8a and an updated figure 8b that show the connection between AMOC, LSW formation, and the water mass properties in the Labrador Sea convection region. We have included an additional paragraph describing this figure:

"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 co-variability 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).”

Apart from that, I can find only some minor technical issues which should be taken into account before the manuscript could be published in Climate of the Past.

Minor comments: 2901, lines 21-25: I wonder why the ”great 1258” eruption is not *clearly discernible in model simulations though Tambora eruptions 1809/1815 can be seen in all models (see Fig. 2a)?*

We don't have a definite answer to that. The biggest volcanoes (1258, 1453, 1809-15) are clearly visible e.g., in simulated global mean temperature. We assume that internal variability is large relative to volcanic disruptions in the Arctic. Moreover, Zanchettin et al. (2013, modified reference!) have shown that initial conditions and the presence of a "double eruptions", like 1809/1815 might determine the actual response. We have (slightly) modified the manuscript:

"The resilience to volcanic forcing reflects the relatively small signal-to-noise ratio of Arctic summer temperatures, due to both strong internal variability of the Arctic regional climate (e.g. Beitsch et al., 2014) and seasonal character of local response mechanisms, which are most prominent in boreal winter (e.g., Zanchettin et al., 2012). Zanchettin et al. (2013) have also highlighted the role of background conditions (e.g. during the closely following 1809 and 1815 eruptions) for the actual response pattern in particular at high latitudes."

2901, line 22: 'see Fig. 5 in Junglaus et al'.

corrected

2909, l. 10: 'Miettinen'.

corrected

2909, l. 12: 'Reykjanes'.

corrected

2910, l. 8: 'Häkkinen'.

corrected

2918, Fig. 1 is small in its size and thus it is difficult to see different time series. 2918,

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Fig. 1: indicate the colours of different simulations. 2919, Fig. 2a: indicate the colours of different simulations.

We have renovated almost all figures for better clarity. We have splitted the former Figure 1 into two figures. Figure 1 is now showing pan-Arctic quantities, whereas Fig 2 reflects the more local variations near Svalbard. We have also included legends that allow identifying individual simulations.

2920, legend for Fig. 3: explain dotted lines

We have completely reworked the former Figure 3, which is now Figure 5 in the revised manuscript. We discriminate now the TOHTR, MOHTR, and GOHTR with solid, dotted, and dashed lines respectively and use colors to show individual simulations as well as the ensemble mean. In response to reviewer 2, we use now grey shading to indicate the 5-95

2903, Pavlov et al. 2011 is 2013 in references.

Thanks, Pavlov et al., 2013 is correct.

2904, Årthus et al., 2012 is 2013 in refs.

Arthun et al., 2012 is correct.

2915, Refs.: I could not find Müller et al. 2014 in the text.

Müller et al., 2014 was at 2910, line 5 in the original manuscript

2916, Refs.: Schauer et al. 2008 in the text?

Schauer et al., 2008 was at 2904, line 6 in the original manuscript

Please also note the supplement to this comment:
http://www.clim-past-discuss.net/10/C1776/2014/cpd-10-C1776-2014-supplement.pdf

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