The comments of the referee are indicated in black and the answers of the authors in blue.

Anonymous Referee #2
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Review of "variations of the Atlantic meridional overturning circulation in control and transient simulations of the last millennium" by D. Hofer, C. C. Raible and T. F. Stocker
This paper investigates the AMOC variability in control simulations and transient simulations of the last millennium. It makes use of an original method to detect variations of the AMOC and compare transition types and time scales under both conditions. Major result is the evidence of a specific transition which probability of occurrence is enhanced under historical forcing and which has important climatic consequences for the Scandinavian climate. The paper is generally well written and results are well presented. However, the modes of AMOC variability and the resulting climatic anomalies are not sufficiently related to existing literature both related to decadal and multidecadal variability of the AMOC and to results from proxies of the last millennium. This lack greatly reduces the reach of the paper and thus its general interest for the community. This is the major reason for me to advise major revisions for this manuscript before possible publications in Climate of the Past. I detail this points and others below.

1. Several studies have already focused on AMOC modes of variability. Here, the authors propose a novel approach based on transitions rather than modes of variability. In order to validate this method, and also in terms of scientific approach, the composites and transition types detected in 3.2 (Fig. 6) would need to compared to this literature. This literature may include e.g. Eden and Willebrand 2001, Mignot and Frankignoul 2005 Clim. Dyn., Danabasoglu 2008 J. Clim., (same model!), Frankcombe et al. 2010 (again!). More specifically, the high frequency composite looks like the interannual adjustement to atmospheric variability, namely the NAO. Types 2 and 3 resemble more to the decadal mode of variability of the AMOC generally found to be associated to deep convection (the 70yrs time scale of Frankcombe). This is consistent with the MLD analysis of section 3.4.1, but should be more clearly discussed somewhere in the paper. What is the link of type 2 and type 3 transitions with such mode of variability?

The discussion of the mechanisms for type 1 and 2 transitions has been added and the existing literature has been better included.

Changed (p. 1283 l. 19 – p.1284 l. 6): "For a better understanding of these changes, our results are compared with mechanisms that are responsible for the AMOC variations of Type 1 and 2. The high-frequency variability of the AMOC (Type 1) is mainly caused by changes in the atmospheric wind stress forcing (not shown). Similar to the mechanisms proposed by Eden and Willebrand (2000) for interannual variations, a sea level pressure pattern that corresponds to a positive North Atlantic Oscillation (NAO) tends to produce anomalous downwelling near 40°N and thus a positive AMOC index. In contrast to this, for the low-frequency variations of the AMOC (type 2 and 3) no significant impact of the NAO could be detected (not shown).

To analyse the mechanisms for the type 2 transitions we perform a lag-correlation analysis for the three simulations without Type 3 transitions using the low-pass filtered index time series. For these simulations, the AMOC index exhibits the highest correlation coefficients (significant at the 1 % level) with MIX_west lagging the mixing by 4 to 5 years, whereas for MIX_east no significant correlation is found. The changes in the mixing are caused by salinity changes rather than temperature (similar to the results of d'Orgeville and Peltier (2009) for the low-resolution CCSM3, but contradicting Danabasoglu (2008) for the high-resolution CCSM3). The two velocity indices are both positively correlated (significant at the 1% level) with the AMOC. V_100m simultaneously varies with the AMOC and V_1500m leads the AMOC by 3 to 4 years.

Comparing these results with the Type 3 transitions, we find that the changes in MIX_west and in the velocity indices are a general feature of any low-frequency AMOC variation, even though they are exceptionally strong for the Type 3 transitions. The main differences that separate the Type 3 transitions from the Type 2 variations are the coupling of the MLD in the eastern convection regions and the strong change of V_1500m which evolves opposite to the AMOC index. Thereby, the coupling of the MIX_east with the AMOC is likely connected to the changes in the gyre circulation. During the weak AMOC state, the Atlantic inflow into the GIN Seas exhibits an increased density in the top 200-300 m and a lower density below compared to the strong AMOC state (not shown).

In summary, the Type 3 transitions of the AMOC can be triggered by strong salinity anomalies in the deep water formation sites."

2.Most of the paper then focuses on type 3 transition. By eye in Fig. 6, it is not very far from the other two. What are the correlations among the patterns? Could the type 3 transition be found by any other statistical method? Why or why not?

In other words regarding the points above, the detection and distinction of transition types is original but not fully convincing in its present form. It is a bit presumptuous in my view to distinguish among different modes of variability solely based on a statistical detection of transition rates and without discussing physical mechanisms.

The ramp function regression method which is used in the study detects any change of the mean (which is then called transition). To distinguish between the different transition types the difference patterns of the AMOC are used. This point has been clarified in the manuscript. This includes also a clearer separation of the three types using the pattern correlation coefficients.

Added (p. 1277 l. 11): "The prolonged periods of strong and weak overturning that have been estimated by eye in Fig. 4 are indeed separated by transitions. However, the applied method identifies many additional transitions."

Added (p. 1278 l. 28): "The low values of the pattern correlation coefficients with Type 1 (0.62) and Type 2 (0.45-0.54) highlight the different structure of the Type 3 pattern."

4.I find it difficult to really realize which are the transition of type 3 on the different time series. In this respect, Fig. 8 is very instructive and the AMOC behavior in this figure should perhaps be discussed much earlier, at the beginning of section 3.4.

We think it is better to start the discussion of the Type 3 transitions with the mean changes in the ocean. The changes that have been made to the manuscript due to the comments of the referees should make the definition of the Type 3 transition clear before section 3.4.

Concerning Fig. 9, the text states that "the temperature response due to the AMOC transitions can be recognized" (p. 1285 l. 11). This is not clear to me at all. Can you find a way to indicate the specific transitions you are talking about on this figure? And perhaps reproduce again the AMOC? At least, please avoid that the legend masks some parts of the time series!

The statement on p. 1285 l. 11 has been removed as it went too far. Also Fig. 9 has been changed, so that the legend does no longer mask the time series. The inclusion of the transitions or the AMOC time series has been refused, as the figure would have been too overloaded.

Changed (p. 1285 l. 10-13): “ Nevertheless, the periods of a weak overturning generally coincide with high Scandinavian temperature, e.g., 1650 to 1800 A.D. in TRa4.”

5. The conclusions and abstract are sometimes going a bit too far: (i) The statistics given at the end of section 3.2 highlight their rarity, even the transient simulation (5 occurrence over 3000 years). This point should be better pointed out in the abstract and conclusions.

The rarity of the transition events is now pointed out both in the abstract and in the summary.

Changed (p. 1268 l. 4-7): “In the transient simulations the AMOC exhibits enhanced low-frequency variability that is mainly caused by infrequent transitions between two semi-stable circulation states which amount to a 10 percent change of the maximum overturning.”

Changed (p. 1287 l. 12-14): “As these rare transitions occur significantly more frequently (at the 5 % level) in the transient simulations, we conclude that the transient forcing induces and supports such variations.”

(ii) p. 1287 l. 4: the “realistic climate evolution” was never checked in this study, nor did you explicitly refer to a study showing this.

The sentence has been reformulated:
“The simulated NH temperature evolution is consistent with reconstructions for most of the last millennium and the simulations exhibit a realistic overturning strength.”

(iii) p. 1287 l. 7-8: the effect of aerosol forcing (or non-forcing) on the AMOC variability was not checked...
please rephrase these points.

The sentence has been removed.

Specific points
p.1269 l. 11: “Furthermore”: no clear link with the previous sentence. Please rephrase.

The paragraph has been rephrased.

Changed (p. 1269 l. 6-12): “In this study, we investigate and characterize the differences in the AMOC between several control simulations and an ensemble of transient simulations with time-varying forcing in a comprehensive atmosphere-ocean general circulation model (AOGCM). In addition, the atmospheric response to the low-frequency variations of the AMOC is investigated. The transient simulations cover up to the last millennium, so that the focus is set more on natural variations of the external forcing than on the anthropogenic impact.

p.1269 l.11: “existing”: omit

done

p.1269 l.15-20: I would advise to refer to this recent paper :North Atlantic Multidecadal Climate Variability: An Investigation of Dominant Time Scales and Processes, by Frankcombe et al. Journal of Climate, Vol 23, pp. 3626-3638 doi: 10.1175/2010JCLI3471.1

The study of Frankcombe et al. (2010) does not primarily focus on AMOC oscillation. However, it strengthens the case for one mechanism that causes oscillations in the North Atlantic basin that involves the AMOC. Thus, the study is included at the end of the paragraph, where the mechanisms are discussed:

Changed (p. 1269 l. 23-24): “Others suggest an internal ocean mode that is excited by atmospheric noise (e.g., Frankcombe et al., 2010) or a coupled ocean-atmosphere mode involving the North Atlantic Oscillation (e.g., Timmermann et al., 1998; Danabasoglu, 2008).”

p.1275 l. 4: I would advise to refer to this recent paper: Servonnat et al. 2010 Influence of solar variability, CO2 and orbital forcing between 1000 and 1850 AD in the IPSLCM4 model, Clim. Past, 6, 445-460, 2010 (I recognize that both these papers were hardly published at the time of submission)

The study of Servonnat et al. (2010) points out the mismatch between the time of the simulated and the reconstructed NH warm period at the beginning of the millennium. Therefore, it makes sense to include the reference in this paragraph:

Changed (p. 1275 l. 3-5): “The 11th century in the TRb1 simulation is 0.2 to 0.3 K colder than suggested by the reconstructions (similar to the results of other simulations, e.g., Servonnat et al. (2010)).”

p. 1275-1276: “anomalies from the long term mean”: what do you mean exactly? If it is just anomalies from the average over the full simulation length, the drift that was problematic a few lines before should remain here...? Please explain. The argument is probably simply that the study focuses on multidecadal (and not longer) variability.

As guessed, the “anomalies from the long term mean” means “anomalies from the average over the full simulation length”. The paragraph has been reformulated to make things clearer.

Changed (p. 1275 l. 27-p. 1276 l. 5): “For the other control simulations the equilibrium mean AMOC strength cannot be reasonably determined as the simulations do not reach a sufficiently equilibrated state due to the drift (section 2). The best estimate, namely the mean AMOC index of the last 100 years in the simulations prior to the detrending process, is 15.9 Sv and 14.9 Sv in CTRL1500 and in CTRL1000, respectively. The exact equilibrium values are not important in this study as the analysis focuses on the variability of the AMOC. For the analysis in the control simulations, anomalies from the average over the full simulation length are used after detrending. For the transient simulations the anomalies are calculated with respect to the mean value of the corresponding control simulation.”

The description of Fig. 4 is not very convincing if you do not specify the “prolonged periods of strong or weak overturning” you are thinking of in the transient simulations. In Tra1, Tra2, Tra3, Trb1, I rather see a long term drift.

The periods are now indicated in the text.

Changed (p. 1276 l. 25-27): “In contrast to this, the AMOC index in the other transient simulations exhibits prolonged periods of strong or weak overturning - most visible in TRa2 to TRa4 with generally high AMOC-index values from 1500-~1720 (TRa2), 1500-~1680 (TRa3), 1500-~1620 and ~1830-2000 (TRa4) and low values from ~1750-2000 (TRa2), ~1700-2000 (TRa3) and ~1650-~1810 (TRa4) - leading to the increased low-frequency variability (Table 2).”

p.1277 l1-6: the protocol is not perfectly clear to me: what does it mean to look for a level lasting at least 20yrs when a running mean window of 51 to 201 yrs has been applied?

The ramp can only be placed in the middle of the running window (for a 51 yrs running window this are the middle 11 years).

Changed (p. 1277 l. 4-6): “ Thus, we consider only ramps (i.e., transitions), where the two levels are separated by more than one Stdd of the AMOC index in the control simulations (1.09 Sv) and where each level extends to a period of at least 20 years (i.e., the ramp can not be in the first and last 20 years of the running window).”

p.1280 l. 18-20: Here again, the protocol is not fully clear to me: during “the strong AMOC periods”, the AMOC mean value can still be different, isn’t it?

The protocol has been clarified.

Changed (p. 1280 l. 18-20): “To determine the significance of the differences the mean for all simulations is adjusted so that the mean value during the strong AMOC period is the same, the strong AMOC periods (and similarly the weak AMOC periods) are concatenated and the two-sided Student's t test at 5 % level is applied at every grid point for the resulting two time series.”

p.1280 l.22-23: “clockwise / anticlockwise” is not physical vocabulary and depend on your own convention. Please use “anticyclonic” and “cyclonic” instead.

done

p. 1282 l.9 “the deep” replace by “depth” or “the deep ocean”.

done

p.1290 l. 4 reference to Brocker 2000 and Denton and Brocker 2008 does not need to be repeated here.

done

The comparison to available paleoproxies is limited to the last few lines of the manuscript. Of course, I recognize that it is difficult to find estimations of the AMOC or oceanic data variations over this period with decadal resolution, is it possible to try to detect such transitions in atmospheric reconstructions, or available SST reconstructions such as Sicre et al. 2008?

A paragraph discussion two SST reconstructions has been included.

Added (p.1282 l. 14): “The oceanic changes - especially SST changes - that go along with a Type 3 transition should also be present in marine proxy reconstructions of the last millennium. To investigate this, two SST reconstructions from the Norwegian Coast (Kristensen et al., 2004; core P1-003MC) and from the North of Iceland (Sicre et al., 2008) with high temporal resolutions of several years to a few decades are used. The record from Kristensen et al. (2004) exhibits multidecadal variations, but no prolonged periods with different mean SSTs are found since 1400 A.D.. In the longer reconstruction of Sicre et al. (2008), however, the period from ~980 to ~1350 A.D. is roughly 1 K warmer than before and after this time, and the transitions from low to high SST (and vice versa) occur within a few decades. Thus, even though the investigated proxy data are not sufficient to provide clear evidences for the occurrence of SST changes that corresponds to an AMOC transition, the record of Sicre et al. (2008) demonstrates that strong and persistent changes of regional SSTs have happened in the past.”