Detailed response to the reviewer of the manuscript

"Mechanismfor potential strengthening of Atlantic overturning prior to collapse"

by D.Ehlert and A. Levermann

Referee #1 (A Cimatoribus)

The article presents results from a simple analytical model of the AMOC, building on the classical Gnanadesikan pycnocline model, and discussing in particular a mechanism for the strengthening of the overturning rate before a collapse of the AMOC. Overall, I think that the paper is clear, concise and presents interesting results. How- ever, before publication, I think that a few points should be considered in more detail. My main comments are in fact linked to our recent papers "Meridional overturning circulation: stability and ocean feedbacks in a box model" on Climate Dynamics (2014) and "Reconciling the north-south density difference scaling for the Meridional Overturning Circulation strength with geostrophy", under review in Ocean Science Discussions. It should be clear, however, that this does not imply that the authors should follow our approach.

Response: We would like to thank the reviewer for taking the time to review our paper and this very positive assessment. His comments have significantly improved our manuscript and we are confident that we were able to address all issues.

- The authors follow Marotzke (1997) considering the pole-tropics density differ- ence as the one controlling the overturning rate. In the papers mentioned above, we suggest that the definition of the density difference may be essential for re- producing some results of numerical models. How essential is the definition of for obtaining the results shown in the present paper?

  Response: This is a very important issue. The main point of the paper was to introduce an additional density difference which controls the Southern Ocean eddy transport. This is motivated by the "double-crossing" of the Atlantic by the AMOC (once in the South and once in the North). Since this open-ocean circulation in the upper layer has to be balanced geostrophically it needs to correspond to a density difference. These density steps can be seen in observations and models alike. While there is some freedom in where exactly to locate the density difference in the real ocean, it is important for our model to apply a meridional density difference both in the northern and southern Atlantic.

- From lines 7-10 on pag. 38 I understand that mN can have negative values, a result which is not discussed in much detail. This amounts to an enhanced upwelling in the high latitudes of the north Atlantic. Is this the case and, if so, how can this be physically justified?

  Response: We do not consider negative values of mN in itself, which would be an interesting addition, but would require the discussion of an entirely different circulation state which would in our opinion be out of the scope of this study. What we rather discuss is the possibility of the discriminant to become negative which defines our critical values and is discussed in the text.

- pag. 38, line 18: pycnocline depth increases with increasing freshwater forcing in fig. 4a. Furthermore, do the negative values of FN in the figure mean that freshwater is transported from the high to the low latitudes? Surface fluxes tend to transport freshwater from the low to the high latitudes in the real world, so how should be FN interpreted?
  Response: Positive F_N refers to freshwater flux by atmospheric dynamics from low to high latitudes. It dilutes salinity in the northern box and increases salinity in the low latitudes. Thus negative FN would mean decreased salinity in lower latitudes and increased salinity in higher latitudes. This behavior might not be applicable with surface transports. Thank you for the comment. We have added an explanation to this end. However, the threshold behavior and the increase in overturning prior to the threshold occurs for positive freshwater fluxes, thus a

freshwater flux from lower to higher latitudes. In any case the main result of the paper is not affected by this the behaviour in the case of negative freshwater flux.

- pag. 41, Freshwater-induced MOC strengthening: a strengthening of the AMOC under increasing freshwater forcing is shown in Fig. 5 of Cimatoribus et al. 2014, but the definition of the forcing freshwater is different therein. Is there a link between these two results, in particular concerning the mechanism causing it?

  Response: We are very sorry that we have not mentioned your work. This was merely due to the fact that we had submitted the paper a few years ago and in the mean time working contracts and places had changed. We simply missed your paper and are sorry about that. Now we have added a note on the fact that this has been seen previously. Thanks for pointing us in this direction.

- pag. 43, lines 1-4: Could this mechanism be interpreted as a change in the baroclinic modal structure (i.e. in the depth of the first baroclinic mode)? In the real ocean, gradients tend to decrease with depth; could this change the results?
  Response: As shown in an earlier study (Fürst & Levermann, Clim. Dyn.) we find that the vertical density structure as represented by the pycnocline is rather stiff in comparison to the meridional density differences. Compared to the Stommel model the Gnanadesikan models with meridional density differences tend to show a more stable meridional circulation. Changes in the circulation when they occur are then however associated with meridional density differences. We thus believe that this will not be easily measured in the vertical but rather in the meridional density differences of the real ocean (or even in the sea-level pattern.)

Minor comments:

- pag. 33, lines 15-17: "The four meridional tracer transport processes..." could this sentence be rephrased more clearly?
  Response: Rephrased sentence which hopefully clarifies its content that the tracer transport processes control on the one hand the horizontal and vertical density structure and they control the strength of the overturning on the other hand.

- pag. 35, lines 16-...: Since the use of this parameterisation for the eddy flow is one of the main new elements in the model, I would suggest that a more detailed motivation for the parametrisation is given, even if it has already been discussed in Levermann and Fu rst 2010.
  Response: Thank you for the suggestion. A more detailed description of the experiments and results in regard to the eddy return flow in Levermann and Fu rst 2010 has been included here. However, in our opinion going into further detail would unnecessarily expand the article, as the interested reader can find the an extended and very detailed description in the Levermann and Fürst 2010 article.

- pag. 36, eq. 6a: it seems to me that the equation should read ... SU(mN + mE)... instead of ... SU(mN +mW).... Even if at the steady state they are equal, I think that the equation would be more easily understandable this way.
  Response: Thank you for the detailed reading, the typo has been corrected.

- pag. 37, lines 8-11: as far as I understand all the results presented refer to steady states of the system. I think that the last sentence of this paragraph could be misunderstood as saying that time-dependent states are considered.
  Response: We agree with the suggestion. The sentence has been rephrased and includes now that we only refer to steady states.

- pag. 37, line 21: "provide" instead of "provided"
  Response: Thank you for the detailed reading, the typo has been corrected

- pag. 41 line 7: Can this result be obtained more rigorously by taking the limit mE 0?
  Response: In this part of the paper the goal was to find a value of F_N,krit that is variable independent. Using m_E lead to including the pycnocline depth D into

the formula, therefore we used the southern meridional density difference instead. However, if there is a more straight forward way to derive F_N,krit in the wind driven case we would be happy to include in into the manuscript.

- pag. 41, lines 21-22: please rewrite the sentence.
  Response: The goal of this sentence was to summarize the main finding, that the overturning creases prior to reaching a threshold under freshwater forcing. We rephrased that sentence, so that the content should be clearer now.

- pag. 42, line 21: “strong” should read “strongly”
  Response: Thank you for the detailed reading, we corrected the mistake.
- pag. 42, line 25: missing “depth” at the end of the line.
  Response: Thank you for the detailed reading, we corrected the mistake.
- pag. 44, line 23: the two papers cited mostly deal with numerical models. Comparisons with observations are found, to my knowledge, in the works of Talley and Bryden.

  Response: We included citation from Bryden 2011 (Journal of Marine Research) into the manuscript here. Thank you for the very helpful comment.

- Fig. 2: I could not find where Figure 2 is discussed in the text.
  Response: Thank you for pointing this out. We included the missing reference in the first part of section 3. There, possible solution of the pycnocline are discussed.