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# *Interactive comment on* "AMOC-emulator M-AMOC1.0 for uncertainty assessment of future projections" *by* Pepijn Bakker and Andreas Schmittner

**Anonymous Referee #2**

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I think the use of emulators has great merits in particular for studying dynamics of large scale systems with substantial uncertainties such as the AMOC. In particular, as CMIP5 simulations miss out on potential important factors influencing future AMOC behaviour such as meltwater influx from Greenland. In this manuscript, Bakker & Schmittner present such an emulator based on previous work e.g. by Zickfeld et al. (2004).

Based on the results presented, however, I have no faith in the emulator to reproduce the AMOC behaviour in more complex models. If this cannot be improved substantially, I regret that cannot recommend a publication of this manuscript. Furthermore, the scientific novelty and relevance for the scientific community is not sufficiently demon-



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strated. The emulator approach is largely based on Zickfeld et al. (2004) and the importance of own additions (Bjerknes feedback) is not clearly shown. The emulator is then only applied to a single model somewhat contradicting the basic idea of emulator approaches of capturing a range of complex model output. If I'd be looking for an AMOC emulator, I'd like it to reproduce broadly the behaviour of state-of-the-art models.

In addition, the manuscript falls short to address the state of the literature relating to AMOC dynamics, conceptual models, and known short-comings of the Stommel-type model used.

I comment on this in further detail below.

## 1 General Comments

### 1.1 Introduction

The introduction does not sufficiently reflect the state of the literature on AMOC and in particularly not on conceptual models such as the Stommel-Model to study it.

Our understanding of AMOC dynamics has advanced considerably over the last years thanks to ongoing observations e.g. in the Rapid array (see Srokosz & Byrden, Science 2015). In addition a recent studies has suggest that the AMOC might already be in decline (Rahmstorf et al. 2015). While of course not directly relevant for the emulator itself, such observational findings need to be discussed in an approach that emulate AMOC behaviour over the next centuries. This should also include a discussion of atmospheric imprints on the AMOC e.g. such as atmospheric blocking events. It should also allow to assess the performance of GCMs in relation to the observational record.

Much more important though is the discussion in relation to the emulator approach

taken. Stommel type models have been used since quite some time and might be able to capture key dynamics of the AMOC (e.g. bistability). However, they at the same time have faced a lot of criticism and alternative models describing AMOC behaviour exist. This is in particular related to the relevance of Southern Ocean upwelling reflected in a conceptual model by Gnanadesikan (1999) related to changes in the pycnocline depth. A dynamic that is completely missing in the Stommel approach.

This has been explored further in conceptual models and attempts exist to unify pycnocline and freshwater-feedback dynamics. In this context, the authors should consider the work of Sijp et al. (2012) that they may find helpful.

Another question directly relating to the physical plausibility of the Stommel model relates to the relationship of circulation strength and meridional density gradient in a geostrophic ocean. The authors should consider work by Gregoy & Tailleux (2010) that present a kinetic energy approach essential providing a physical explanation for the (empirically supported) meridional density gradient outlining the relevance of the Western Boundary Current in modelling AMOC dynamics.

These comments should not be seen as undermining the Stommel model approach taken here, but they need to be addressed. In short, the authors should show motivate their approach in the light of the most recent literature.

### 1.2 The Emulator model

Here, the work dominantly builds on a previous model by Zickfeld et al. (2004) plus a representation of the Bjerknes feedback. It does however not become sufficiently clear, why this addition will represent a substantial advancement. The authors show the differences in Fig. 9 and describe that this will represent a negative feedback on the AMOC dynamics. But it's not clear, if Figure 9 shows two sets calibrated individually (with and without atmospheric feedback) or just from the optimal parameter set with





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this feedback switched on and off. Therefore, I cannot judge if the conclusion drawn by the authors on the importance of the effect are due to their specific parameter set or not.

It would add merit, if the authors could show that the model including the Bjerknes effect will in the end outperform the no-atmospheric feedback model in the fitting procedure. This would also justify, why there model is actually better than the one presented in Zickfeld (2004).

Furthermore, the model includes 5 atmospheric boxes. Why are 5 boxes needed and not 3 to resolve the meridional heat transport? I think that can be easily motivated and maybe I missed it. Maybe it's worth considering to restructure the approach by moving subsection 2.3 further up to discuss the setup of the atmospheric forcings.

In this context, the authors should also reflect on the limitations of the model to reproduce transient AMOC changes that relate to the assumption of well-mixed density within the boxes. This might be in particularly relevant in relation to the Greenland freshwater input. Clearly, this represents an over-simplification and may substantially limit the capabilities of this approach to emulate transient behaviour (I'll further comment on this below).

### 1.3 The tuning to complex model output

In the manuscript, the model is tuned to an EMIC model UVIC. I think that's generally no problem, but somehow contradicts the initial claims by the authors that this emulator could now be used to run larger ensembles. What is it exactly that the emulator provides that cannot be done with an EMIC?

In general terms, the strength of an emulator is it's capability to include projections from a range of different models. We have AMOC projections for several CMIP5 models, why is it not applied to those? In addition, there are the AMOC sensitivity studies by

Gregory et al. (2005) and Stouffer et al. (2006) that would provide enough runs to calibrate the model. Why isn't it applied to those runs?

In addition, the authors mention the AMOCMIP project. Can the emulator be applied to the AMOCMIP output? I checked the project homepage and understood that the AMOCMIP will explictly resolve different Greenland basins separately. Is that correct? If so, and following recent findings that it actually matters a lot for North Atlantic dynamics where the freshwater is actually applied, will this emulator be the best tool to reproduce these dynamics? Or should it maybe consist of a subpolar (Labrador Sea) and North Atlantic box? And/or should conceptual models of convection in marginal seas e.g. by Spall (2004) and Straneo (2009) be integrated?

### 1.4 Results

I've to admit I'm not impressed by the capabilities of the emulator in reproducing the model outcome. As apparent from Fig. 7, the emulator is systematically underestimating AMOC reduction for RCP4.5 and RCP8.5 no melt, while then over-estimating it for RCP8.5 plus GIS (maybe due to non-linearities kicking in here and timescale issues discussed above?). The authors discussion of this simply stating that "It is, however, to be expected that a box-model does not completely capture the behavior of the AMOC as simulated with a higher order climate model" is clearly insufficient. In particular, as there have been much simpler AMOC emulators around that actually perform much better (also and in particularly an AMOC recovery, e.g. Schleussner et al. 2014).

The apparent oscillations in the emulator arising from a "too direct response" of the emulator towards multi-decadal surface temperature oscillations also merits more discussion.

It is even worse for the predictions in Fig. 8. First of all, the figure is not well-labelled (no y-axis labeling, panels not clearly distinguishable, and what is given by the numbers

5,1,5?) and that there is no such thing as a top-middle panel for only two boxes.

For none of the panels, the model actually captures key features. It fails to capture the bumps in the top-left and bottom right, and for the two other panels, it gets it wrong completely. I cannot agree to the author's conclusions that "Overall, the predictive power of the AMOC-emulator is good for reasonable forcing scenarios when one considers the simplicity of the model."

### 1.5 Summary

Generally, I miss a section that reflects on the limitations and short-comings of the approach taken, given in particular the apparent limitations in reproducing the EMIC results. Furthermore, an outlook of where this can be applied and what it specific strengths are compared to other approaches should be included.

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