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Title: Persistent Climate Model Biases in the Atlantic Ocean's Freshwater Transport

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Point-by-point reply to reviewer #1

November 11, 2023

We thank the reviewer for their careful reading and for the useful comments on the manuscript.

In this paper the authors study biases in the AMOC stability metric Fov, by analyzing two CESM simulations with different resolutions, as well as a large number of CMIP6 simulations. The authors conclude that the biases that existed in CMIP3 and CMIP5 persist in CMIP6. Furthermore, they point to several biases in the freshwater budget as likely culprits for these biases in Fov.

This is a very thorough analysis, and I commend the authors for the work they have done. That said, the depth of the analysis has gone at the expense of the readability of the manuscript; I have to admit –with some embarrassment– that I have not been able to get past the first pages of the Results section, despite several attempts. In my mind, the information density is far too high to make this a comfortable read. To illustrate this point, page 4 alone refers to Fig. 1 (4 panels plus 7 insets), Fig. 2 (8 panels, each with two insets), and 5 figures in Supplemental. The total number of panels + insets covered on page 4 is 70. That is a lot of information to get one's head around in the space of 30 lines.

I hope that the authors will reconsider simplifying the paper and improve its readability. The paper can be slowed down significantly, simply by taking more time to develop the material. Not by adding more information, but by more carefully walking the reader through the argumentation following the key results. I understand that it is a challenging task, but the authors should make an effort to boil down the figures to those that are most critical to the storyline. Relegating more figures to Supplemental would be an option, but *it only works if they are indeed treated as being of secondary importance, with limited referencing in the main text to avoid distracting from the main storyline. Although the insets might be useful in some cases (after careful study, Fig. 2 started to make sense), in others they are definitely a distraction (Figs. 1, 3). The insets that are critical to the narrative deserve their own figure and should be described and referenced in the proper order.*

Author's reply:

Indeed, the information density is quite high, in particular on page 4, but there certainly is room to slow down the pace of the text and to simplify the figures.

Changes in manuscript:

We will rewrite and reduce the pace of the manuscript, in particular the result section. We will also strongly reduce the number of insets in the figures and only present the most relevant quantities in each panel. More specifically, we suggest the following changes to the figures in the manuscript:

- Figure 1 – Remove the P-E trends (insets panels a & b) and salinity trends (insets panels c & d). The P-E trend can be explained in the text and the freshening of the Indian Ocean is clearly depicted by the time series.
- Figure 2 – Remove all insets and only mention the relevant results in the text.
- Figure 3 – Remove the P-E trends (insets panels a & b) and replace the salinity trends (insets panels c & d) by only indicating the three different regions (Labrador, Irminger and Iceland basin).
- Figure A1 – Remove from manuscript and explain in text, the results will still be available through Zenodo.
- Figure A2 – Remove from manuscript and explain in text, the results will still be available through Zenodo.
- Figure A3 – Remove from manuscript and explain in text, the results will still be available through Zenodo.

- Figure A4 – Remove from manuscript and explain in text, the results will still be available through Zenodo.
- Figure A5 – Remove from manuscript and explain in text, the results will still be available through Zenodo.

The presented material is then less dense and is expected to improve readability as suggested by the reviewer.

It is possible that there is simply too much ground to cover for one paper, in which case the authors might consider splitting it up in two companion papers.

Author's reply:

We believe that splitting the story into two parts is not beneficial for our study. To understand the onset of the CESM biases we need to analyse the pre-industrial simulations and to realistically compare the biases against reanalysis we need to analyse the historical simulations as well. Our claim of persistent model biases can not be made by only analysing the CESM and a full CMIP6 comparison is essential. These analyses alone cover 8 out of the 9 main figures, the far majority of the manuscript. Apart from the present-day comparison, the projected freshwater transport trends under climate change (Figures 7 and 8) are also relevant to the manuscript given the importance of F_{ovS} as discussed in the manuscript. Substantially revising the text and figures, as suggested by the reviewer, is then sufficient to present the results in one manuscript.

Changes in manuscript:

We do not follow the suggestion to split the manuscript into two parts, we follow the aforementioned suggestions by reducing the information density of the manuscript.

Point-by-point reply to reviewer #2

November 11, 2023

We thank the reviewer for their careful reading and for the useful comments on the manuscript.

In this manuscript van Westen and Dijkstra take a detailed look into what is causing the model biases in Fov in the Atlantic at 34S. They investigate the bias by looking at the different water masses at 34S and how they change immediately after the model spins up. These responses are compared in both a high (0.1 degree) and low (1 degree) CESM model and later compared to CMIP6 models and changes in future projections. In the CESM models the surface fresh bias can be related to the impact the Indian Ocean has on the Atlantic Surface waters, while slightly deeper the North Atlantic Deep Water biases are related to issues with surface fluxes in the North Atlantic Subpolar gyre. The manuscript furthermore investigates Fov in CMIP6 models and how it changes in future climate projections.

Having begun the review of this manuscript after reviewer 1 posted their response I agree with them on the manuscript. The authors have approached the Fov bias issue from a from the perspective of different water masses, which is a very nice and informative way of investigating the model bias. Therefore, I believe this work is of interest to the community. They have also completed and presented a large amount of analysis. However, there is a large amount of information packed densely into one manuscript and it would benefit from streamlining it and/or splitting the manuscript. Similarly with the figures, some panels could be combined instead of having separate panels for the two models allowing a few of the insets to become their own panels, as opposed to small postage stamps.

A few smaller points:

1. *The introduction seems short and could benefit from being expanded, discussion of the usefulness of Fov as an indicator would nice. See Yin and Stouffer 2007 and Mecking et al. 2016 for a discussion on using the divergence around the subtropical gyre. Also, the role of bias correction using flux adjustment (i.e. Liu et al. 2014, Liu et al. 2017, Jackson 2013). The paper Mignac et al. 2019 also worth mentioning.*

   Author's reply:

   Yes we agree, those studies are indeed relevant for the manuscript. The relevance of the F_{ovS} was already discussed in the manuscript (lines 292 – 305), but this can be mentioned in the introduction.

   Changes in manuscript:

   We will rewrite and extend the introduction of the manuscript. We will mention the relevant papers and discuss the usefulness of F_{ovS} as an indicator.

2. *line 80 – see Menary et al. 2020 figure S1 for a comparison between computing own AMOC and AMOC provided by CMIP6 models.*

   Author's reply:

   There are small deviations when using the AMOC streamfunction or the meridional velocities to determine the AMOC strength (in their paper at 35°N). The correlation coefficient between the two methods is very high ($r = 0.96$, Menary et al., 2020) and this provides (strong) confidence to use meridional velocities instead of the AMOC streamfunction. Ideally one would like to use the AMOC streamfunction, but not all CMIP6 model provide the AMOC streamfunction as standard output. To include as many CMIP6 models as possible (39 in total), we use meridional velocities to determine AMOC strength.

Changes in manuscript:

We will mention and discuss the study of Menary et al. (2020) here.

3. *What are the initial S&T conditions used in this study?*

Author's reply:

The ocean component was initialised with the January-mean climatological (from the World Ocean Atlas) for potential temperature and salinity and from rest (Chang et al., 2020).

Changes in manuscript:

We will clarify the initialisation of the ocean component (line 53).

4. *How are the freshwater transports computed in Fig.2 for the different water masses?*

Author's reply:

For each water mass we determine the vertical integral of the freshwater transport with depth between its vertical extent (e.g., see lower row in Figure 5). For example, the contribution of the Atlantic Surface Water (ASW, upper 500 m) is defined as:

$$F_{\mathrm{ovS}}(\mathrm{ASW}) = -\frac{1}{S_0}\int_{-500}^{0}\left[\int_{x_W}^{x_E} v^* \mathrm{d}x\right]\left[\langle S \rangle - S_0\right]\mathrm{d}z \tag{1}$$

where $S_0 = 35$ g kg^{-1} is a reference salinity. The v^* is defined as $v^* = v - \hat{v}$, where v is the meridional velocity and $\hat{v}$ the section spatially-averaged (i.e., full depth) meridional velocity. The quantity $\langle S \rangle$ indicates the zonally-averaged salinity.

Changes in manuscript:

We will clarify the water mass contributions in the section 2 (Methods).

5. *There isn't very much mention about Faz in the manuscript despite being defined. Interestingly, looking at the inset in Figure 1b it is clear that Faz also makes a quick adjustment. One thing that is very noticeable in Figure 5 d,e and f is that there is an azonal structure in ASW.*

   Author's reply:

   There is indeed room to elaborate on F_{azS} in the manuscript and compare its magnitude against reanalysis.

   Changes in manuscript:

   We will add two new panels to Figure 1 to display the F_{azS} time series (now shown as insets in Figures 1a,b) and add the reanalysis time series for comparison. We will change the text accordingly and discuss the F_{azS} results when applicable.

6. *In figure 5 and A6 it would be nice to see the plots as biases as opposed to absolute values.*

   Author's reply:

   This is a nice suggestion but we prefer absolute values over anomalies (w.r.t. reanalysis). The AAIW water mass is now clearly depicted in Figure 5 and its origin (Figure 6) is much harder to interpret when showing the figures as anomalies. Moreover, the reanalysis fields need to be interpolated onto each CESM/CMIP6 model grid and this procedure may give rise to small errors, in particular near the boundaries of the section.

Changes in manuscript:

No changes in the manuscript.

7. *There is no mention in the abstract about the future projection results.*

   Author's reply:

   It is indeed good to mention these results in the abstract.

   Changes in manuscript:

   We will change the text in the abstract accordingly.

I believe there are several nice results in this manuscript, and I would be happy to provide a more detailed review of this after the above mentioned comments have been considered.

References

- Yin, J. and Stouffer, R.J., 2007. Comparison of the stability of the Atlantic thermohaline circulation in two coupled atmosphere–ocean general circulation models. Journal of Climate, 20(17), pp.4293-4315.

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Editor comment (not posted online, 17 July 2023):

This manuscript is within Ocean Science aims and scope and thus the review and discussion process can begin. I note that it is common to use the following acronyms for the following Southern Ocean water masses: Antarctic Intermediate water (AAIW) and Antarctic Bottom Water (AABW).

Author's reply:

Yes, we agree with the editor and will change this to AAIW and AABW.

Changes in manuscript:

The acronyms will be changed accordingly in the text, figures and analysis software.