

# “Sensitivity of deep ocean biases to horizontal resolution in prototype CMIP6 simulations with AWI-CM1.0” by Thomas Rackow et al.

## #Referee 2

Rackow et al. are describing a hierarchy of climate model using the AWI-CM. They present the capability of the ocean model on unstructured mesh for climate application. The focus is on the benefit of using local refinement in eddy active region to decrease the deep temperature bias. In addition to that, they discuss why the high resolution decrease the bias. This leads to a discussion on the initialisation strategy of the model configuration in case no eddy parametrisation is activated.

I recommend a major revision

### 1 Major Comments:

- At the end of the paper, I am still wondering if this paper is a paper analysing possible sources of deep bias in climate model using a hierarchy of climate model with various ocean resolution or if this paper is a description on possibility open by unstructured mesh ocean model for climate application with an overview of the improvement generated by the local refinement. In the first case, the paper is maybe not adapted for GMD. In the second case, the analysis is only focused on the deep bias and nothing else. So it is not enough to convince me it is worthwhile to use this capability in a climate model for decade to century. There is no evaluation of other basic climate index as sea ice, ACC, AMOC, meridional heat transport ...
- Discussion about the contribution of Gibraltar need to be strengthen (more detailed on the geometrical issue, overflow representation and water masses properties at the Gibraltar sill)
- In your 5 experiments, one of them do not have the same atmospheric model. The vertical profile suggest the atmospheric model resolution could also lead to strong bias reduction. For clarity, you should focus only on those having the same atmospheric model.
- As you mentioned a link between the deep layer and the surface via the mixed layer, you should discuss in more details what could affect the mixed layer depth intensity and location (path of the North Atlantic current, surface fresh water flux, heat flux, restratification process via eddy activity ...). About the overall idea of the initialisation strategy, I found it interesting. As it is included in the result section, I think you have to try it and show result on the initial bias in the HR case. You mentioned the GM eddy parametrisation is the key in LR to avoid ‘overshoot’ of the bias because it is fully active from the start in LR. Why not run in parallel to your idea on 3d T/S restoring during the spin up of the eddy fields (something like GM fully active from the start with a decreasing intensity over a specific time scale).

In Minor comments, I went through the manuscript from the beginning. Some comments are related to the one mentioned above.

## 2 Minor Comments:

### Abstract

- P1L6: 'we find that two major sources at the surface are responsible for the deep bias in the deep Atlantic': Please briefly mention these 2 mechanisms.

### Introduction

- P1L21: You mentioned a major bias is present in CMIP5. Could you add references to it in addition to your illustrations?
- P2L2: You should reformulate "..., as well as climate change (...) that is, errors are larger ..." It is not easy to understand.
- P3L3: This is the first time in the main text you are using AWI-CM acronym, I think you should define it here.
- P3L11 and elsewhere: Be careful when using 'eddy resolving' term. I am not convinced you are, even in the location reddish in your figure 2. You should specify where you are eddy resolving or permitting. In introduction, I can suggest something like '... a strong case to aim for a high resolution (X km or higher) in eddy active region ...'

### Model configuration

- P3L18: just mention the acronym here as you explain it before (see comments above).
- About GM details, I am sure that how to define the location where you activate GM and how to make the transition from 'off' to 'fully active' trigger a lot of discussion in your group. My question is: should it be dependant of the Rossby Radius instead of prescribed resolution threshold (25km and 50km)? At 25 km a lot of eddy active region are still not eddy resolving. Could you explain more why you choose these numbers (25 and 50), what are the sensitivity of your ocean model to these numbers?
- You should specify also in your model configuration
  - o Your input data for the bathymetry
  - o Your vertical coordinate system and number of vertical level and resolution range
  - o If you are using some icebergs representation, how do you represent iceberg (iceberg model or prescribed pattern, melt set in surface or spread between surface and iceberg draft depth) and how you compute its calving rate.
- P4L1 : try to avoid pages with figures, tables and with only a few lines of text at the bottom. It is really easy to miss these lines.
- About the XR resolution, you should just mention it in the conclusion as perspective and remove reference to it. In the main text, I found it not useful, as you do not show and discuss any result from this configuration.

### Results

- P6L30: The figure 3 do not represent a drift. So please reformulate.
- About the S profile there is some differences which seems not related to resolution:
  - o Surface salinity error are from -0.2 to 0.2 without clear resolution dependence. So as it is a couple run, if you change your atmospheric resolution (REF vs LR) or you oceanic resolution (LR, MR, MRO and HR), your surface fresh water forcing can change. So, I am wondering if your surface fresh water forcing in all your run is

similar. As you discuss impact of mixed layer depth on error in depth, I think it is quite important for the discussion in section 3.4.

- In depth (deeper than 1500m) the resolution of the atmospheric model seems to play a big role in it. All the model using T127 atmospheric model have the same error. It is less clear in temperature but it still looks significant deeper than 2000m.
- You should add discussion on it or maybe remove REF simulation from the paper.
- P7L5: By stronger deep cell, what do you mean? do you mean deep overturning cell?
- All the discussion about Gibraltar:
  - Could you add precision about the geometric error in your configuration (ie model strait width compare to reality)?
  - In Figure 6, we clearly see that the salinity in depth is much more saline than the observations. What is the quality of the water masses going out of the Med. Sea at Gibraltar? Does it impact your analysis?
  - Gibraltar is a shallow sill and the connection with the deep layer of the ocean is made via cascading of the dense water (Gibraltar overflow). However, the modelisation of this process is quite challenging in ocean model. So, is the Gibraltar overflow well represented in yours simulations? If no, what are the impact of it on your simulations and sensitivity. You should mention the Med. overflow in your discussion, its representation in FESOM and its importance compare to the geometrical factor you mentioned.
- About the discussion in surface conditions:
  - See comments earlier on fwf
  - P8L18: 'no heat sources': Could you precise if you are using a geothermal heating. If yes, maybe reformulate the first sentence.
  - Could you mention the effect of the contribution of the advection from the other basin into your analysis domain.
  - Gulf Stream and NWC: There is many modelling paper reporting issue in modelling these area, discussing the possible reason for it and the impact on the large scale. You should not only mention resolution as possible reason. You can mention for example the numerical scheme used (penduff et al., 2007: <https://www.ocean-sci.net/3/509/2007/os-3-509-2007.pdf>), or the representation of the DWBC (Zhang and Vallis, 2007: <https://journals.ametsoc.org/doi/10.1175/JPO3102.1>). Resolution dependence is also visible in Marzocchi et al., 2015: <https://www.sciencedirect.com/science/article/pii/S0924796314002437#f0010>)
  - P10L2 please precise 'This region (hatched in Fig. 7). Do you mean the difficulty to simulate a correct NWC and GS ?
  - You mention that the issue with the Gulf Stream and NWC is not in direct contact with the outcropping isopycnals you are interested in but the representation of the GS and NWC strongly impact the North Atlantic Current which reach the latitude you are interested in. So it could be the location of the outcropping region is determined by the path of the NAC. Could you add discussion about this.
- About the along-isopycnal bias propagation:
  - See comments about Gibraltar above

- For the mixed layer source, see comments about surface fwf above. About the realism of the >500m convection, could you show comparison with observation or at least reference showing what the mixed layer depth should be.
- As you are talking about deep bias, I think it is worth adding discussion about the Nordic Sill overflow. Is the representation of the Nordic sill in your various configuration affect your conclusions?
- 4 supplementary documents in half a page of discussion I found it too much. Could you find a way to represent the point you want to make in a figure? Often reader like me do not take the time to get back on their browser, find the link, click on it and watch 4 movies.
- You focus on the large improvement between LR and HR, but I found that there is also a large improvement between REF and LR (it let suggest also that the atmospheric model resolution is also important in decreasing the bias in depth.). See comments above on maybe removing REF from the document as LR and REF has roughly the same resolution.
- Please reformulate the conclusion of this section based on the comments above.
- About the SST bias you mention at the end, please mention a reference to a figure.
- Displacement and tilt of isopycnal:
  - You explain why the slope of the isopycnal is different but I think you should add clearly, why this leads to temperature bias along the isopycnals?
  - All your paper is focussing onto the depth 1000m. So I suggest for clarity to remove the discussion on the 200-300m depth range P15L7 to L14.
  - In your supplementary materials we clearly see in the LR case an error propagating from the Good Hope cap toward south America. Do you know why this propagation and not a bias intensifying all along the Atlantic Southern ocean?
  - You mentioned that this strong bias in the Atlantic is due to difficulty of GM to balance the Ekman transport. So, why the error is so large in the Atlantic sector only? The other sector are quite good in LR and REF compare to HR.
- Initialisation method:
  - P15L17: I found the mention of 'usually based on a smoothed climatology as done in this study' confusing. I suggest to remove it. If you effectively smoothed the climatology, mention it in the previous sentence and in the model configuration section.
  - P15L19: what is the time scale you imply exactly by 'fast' adjustment? days? months? years?
  - About the example you mention (bias in the east North America), I will be more cautious. I agree that if the Gulf Stream is to north, you will have a warm bias in the Northern Recirculation Gyre but based on the information you show, we don't know if PHC is representing this coastal area with strong boundary current correctly (you have strong temperature front in this area). You should at least put PHC sst in Figure 7.
  - Could you add precision about the time needed for the eddy fields to develop in your configuration?

- P15L28: I think you should add a specific plot to show this instead of claiming it 'evident' on a supplementary material video. I had to watch back and forth frame by frame to be convince.
- Conclusions:
  - In the model configuration section and introduction, you insist a lot on the local resolution, its benefice to run climate model. I was expecting it to be mentioned at the beginning and in a stronger way than you did.
  - I found the word 'the three worst performing CMIP5 model' not well chosen here without mentioning the criterion used for the assessment.
  - Rewrite the discussion on Gibraltar based on the comments on the overflow and Med. Sea water property.
  - P17L33: By 'outcropping often happens too far to the north compared to observations', please clearly specify what you imply? Do you imply that isopycnals outcrop in a region with stronger heat fluxes, warmer atmosphere ...?
  - Most of your paper is on the deep bias and you mentioned an example of bias developing at 200m depth. As I mentioned earlier, to keep your paper focus you should maybe get rid of the paragraph discussing this.
  - P18L5 to L13: You should move this paragraph earlier in the conclusion, maybe at the beginning.
  - P18L29: 'we have shown major improvement'. You need to add limitation to this statement. You only show major improvement on the T/S bias at 1000m. We don't know at all if it improve the MOC, MHT, bottom water formation.

### 3 Figure and table comments

- Fig. 1:
  - replace left/right by 'a)' and 'b)' and add it on the figure
  - Comments on what you should see 'In the first hundreds meter ...' should go into the text not in the caption.
  - Mean abs. error in the top 300m is hard to see (overwritten by blue and red line), maybe consider using transparency and envelope.
- Fig. 2: remove XR if you follow my comments on removing XR from the text.
- Fig. 3:
  - As for Fig. 1, replace left/right by 'a)' and 'b)' and add it on the figure
  - Comments on what you should see 'With the medium- and ...' should go into the text not in the caption.
- Fig. 6: split left column from the right column and put a label for each figure and use it in the caption.
- Fig. 7: add a label for each figure and add PHC sst figure and maybe use the same colorbar as in figure 6.
- Fig. 8: remove red line, as they are not commented on this figure.
- Fig. 9: If you remove discussion on 30.8 and 30.5 isopycnal line, do not forgot to remove it here. You are not commented the green line in this figure, so please remove it.
- Supplementary movies : please and a date on each frame, so we know where we are when we look at it (discussion on initial condition)
- Table 1: Add interannual std and climate change signal in the top or bottom cells.

- Table 2: Remove XR line and remove the internal name (not used in the manuscript).