Response to Reviewer 3 for "Southern Ocean polynyas and dense water formation in a high-resolution, coupled Earth System Model" by Jeong et al.

We thank Reviewer 3 for their helpful and constructive comments. In order to address the reviewer's central concern - separating text results drawn from figures presented in this study and results drawn from the literature - we have revised the manuscript considerably. Also, we included CTD observational data for validating the model cross-shelf sections. These results are now shown in Figure 7. Please find our responses to each point raised by the reviewer below (the reviewer's comments are noted in italics and our reference to manuscript line numbers refers to the revised version of the manuscript).

This study explores the ability of the coupled model E3SM to simulate coastal polynyas and Dense Shelf Water (DSW) formation... The study is well structured and the figures are appropriate. The study presents a problem common to many models and the detailed description of the model performance regarding polynyas and dense water formation provide a beneficial contribution to the community.

My main comments can be summarised as follows:

1. Data selection (section 2.2 Ocean, sea ice, and atmosphere state estimates)

a. Please explain the advantage and disadvantages of the SOSE and WOA data sets. Section 2.2 reads as if SOSE provides only surface values while WOA also provides subsurface data. The cross-slope transects of Fig 7-9 show SOSE data (=subsurface data). A short discussion of which data set is appropriate for the comparison would be helpful.

Thank you for this suggestion. We have now added a short discussion in Section 2.2 (please see lines 120-128) as well as included CTD in-situ observational data to better evaluate the model for the cross-shelf sections (new Figure 7).

b. What are the uncertainties of the observational datasets? Figure 2 shows uncertainties for the sea ice products, but nothing is presented for the oceanographic datasets. Differences between the model and observations/reanalysis products are also introduced by different temporal and spatial resolution which are not discussed. See specific comments below for suggestions.

We agree with the reviewer on these points. We have now added the following text mentioning potential caveats with quantifying uncertainties in the discussion section (please see lines 345-347): "Different temporal and spatial resolutions also introduce discrepancies between observations/reanalysis products and model results. A potential caveat to note is that we only used one high-resolution and one low-resolution model simulation, thus not providing a quantification of structural model uncertainty."

2. The text is at times not clear about what results are drawn from figures presented in this study and what results are drawn from the literature. Please revise section 4.2 which discusses the different shelf regimes in Fig 7-9 comparing the model to SOSE and to observations from Whitworth et al. 1998.

We would like to thank the reviewer for this helpful comment. We have now substantially changed section 4.2, clarifying the points raised by the reviewer and also providing additional evidence for our main conclusions. Please refer to revised section 4.2 (text in blue contains the main changes).

Specific comments

L1-2: The process described here is true for the formation of DSW. AABW forms when DSW escapes the continental shelf where it flows down the continental slope and entrains CDW and *surface waters as described in L24-26. What is described here is only a part of the process. Can you adjust the sentence?*

Agreed. We have modified that sentence as follows: “Antarctic coastal polynyas produce dense shelf water, a primary source of Antarctic Bottom Water that maintains global overturning circulation.”

L45: What model biases? Please elaborate.

We have removed “and/or model bias” from that sentence after carefully reviewing Dinniman et al. 2016 and Thompson et al. 2018.

L50-54: Please specify if “coupled” refers to ocean-sea ice models or atmosphere-ocean-sea ice models. Can you comment on the performance of ocean-sea ice models where the atmosphere is prescribed?

The “coupled” refers to ocean-sea ice models. We have changed the sentence to “coupled ocean-sea ice models with prescribed atmosphere” (line 51). We also comment on the performance of ocean-sea ice models on lines 54-55 as follows: “However, these models tend to simulate larger coastal ice production due to the lack of sensible and latent heat flux transferred from the ocean to the atmosphere.”

L130: Is the definition for coastal polynyas the same in the model as in the observational data sets? You mention the definition you use to define coastal polynyas in E3SM, but not the definition for the observational data sets.

We have now clearly stated how the coastal polynyas are defined in the model and in the observations: please see text in blue on lines 136-138.

L145: "Cold katabatic winds blowing off Antarctica create sea ice" Please elaborate on the connection between katabatic winds, latent heat flux, and sea ice production. It might be helpful to add some references or explain in more detail how Fig 1 shows the connection between winds and sea ice production.

Thank you for this suggestion. We have now added more detail as suggested on lines 144-146, as follows: "Cold katabatic winds blowing off Antarctica in E3SM-HR (Fig. 1a) push the thick sea ice offshore, leading to open water. Consequently, intensive latent heat fluxes transfer from the ocean to the atmosphere makes favorable conditions for sea ice production in the Antarctic coastal polynyas (Fig. 1b)."

L147-148: Please be clear about what is directly shown in the figure and what are the conclusions or hypotheses you draw from the figure. High sea ice production rates are shown, but the generation of cold and saline water and the transport down the continental slope are an assumption (i.e. not shown in Fig 1b).

Apologies about this. The sentences that are not related to the description of the figure have now been removed.

L185: Please clarify why Dufour et al. (2017) is referenced here. Did they use the same/different data? Or a model?

We have now modified the sentence (line 181) as follows: "Similar to a previous study comparing the difference between low and high-resolution climate model results (e.g.; Dufour et al. 2017), E3SM-LR does not exhibit OOPs at any point in the simulation."

L189: "thus allowing for dense-water formation in E3SM-HR" → Is this an assumption or shown in Fig 3?

Thank you for pointing this out. We modified the sentence on line 185 as follows: "which can potentially affect the dense-water formation in E3SM-HR."

L200-203: Not shown in figure. Please be clear about what is shown on the figure and which statement is based on previous work and add reference accordingly.

Apologies for the confusion. We have now reorganized the text of the two paragraphs on lines 190-199 and 200-204, adding clear reference to previous work and to our Figure 4.

L210-213: Do the models in the cited studies simulate coastal polynyas similar to E3SM-HR?

We have now removed that sentence.

L225-226 and 227-228: How do the WMT rates compare to observed values or to models that are able to produce DSW?

Thank you for raising this question. We have now compared the model results to the observational study of Pellichero et al. 2018 (please see lines 224 and 227).

L230-231: I am not sure I understand the sentence. 28kgm-3 is the density found in E3SMHR as the threshold for AABW formation? And Orsi et al. (1999) find that it needs to be 28.28kgm-3?

Apologies for the confusion. We modified the sentence (see lines 227-230) as follows. "In the high density ranges above 28.0 $\mathrm{kg\,m^{-3}}$, a local maximum WMT rate of 3.0 Sv is seen at a neutral density of 28.2 $\mathrm{kg\,m^{-3}}$. Whitworth et al. (1998) and Orsi et al. (1999) define AABW as having neutral densities higher than 28.27 $\mathrm{kg\,m^{-3}}$. We consider 28.0 $\mathrm{kg\,m^{-3}}$ to be a suitable minimum threshold of AABW in the E3SM-HR simulation."

L252-253 and L256-257: The text is not clear about what is new about the connection between wind and the ASC. Do the authors try to make the point that (i) wind is one of the drivers of the ASC (established knowledge) or that (ii) the strong winds in E3SM-HR are thought to be the reason for the strong ASC (this study)?

We have now clarified the text on lines 258-259 as follows: "Therefore, we hypothesize that the strong winds over the continental shelf may be one of the drivers of the strong ASC in E3SM-HR."

L271: The example transect for the dense regime at 35°W is at the eastern end of the section characterized by a dense shelf (e.g. Thompson et al. 2018). Why was this transect chosen? The dense shelf is better established in the western Weddell Sea.

Thank you for pointing this out. We re-selected the position of the dense shelf as shown in Thompson et al. (2018). Please refer to Figure 6d for section location.

L275: How was the exact transect location picked in the model output? The ASC varies substantially on small scales and comparing the observational transect with the simulated transect which is likely not exactly at the same location (limitations due to model grid) may introduce an error.

We have now re-selected the transect locations to coincide with the cross-sections shown in Thompson et al. 2018, where CTD observational data is also available for comparison with the model results. Please refer to the revised Figure 7.

L287: Why chose this transect if SOSE does not show a dense shelf here? See comment L271.

As mentioned above, we no longer use SOSE for the vertical cross-section plots.

L287-288: Does E3SM-HR show V-shaped isopycnals along the shelf break at all?

We have looked at a number of sections in the Weddell as well as Ross Sea and we were not able to see V-shaped isopycnals using the 30-year average climatological fields.

L289: Please comment on the fact that SOSE does not show a dense regime, but Whitworth et al. (1998) does. What does this mean for the comparison between E3SM-HR and SOSE to evaluate the model?

We no longer use SOSE for the vertical cross-section plots.

L308: Please see comment L304 regarding the poleward Ekman transport. The argumentation is based on enhanced Ekman transport but no evidence is presented.

Thank you for pointing this out. We have now added a plot of poleward Ekman transport computed from the E3SM-HR simulation and from ERA5 fields in the Supplementary Material.

L311: Please see general comment on section 2.2 regarding the choice of observational dataset used to compare the model to. The discussion would benefit from an introductory sentence which states how the model compares to the chosen observational/reanalysis datasets.

We updated Section 2.2 and clarified which dataset is used for each comparison.

L323-L330: The first paragraph of the discussion talks about one drawback of the reanalysis products, namely that they are not coupled. Is this the biggest uncertainty when comparing E3SM-HR with reanalysis data? If not, I suggest moving this paragraph further down.

We have followed the reviewer's suggestion and moved this paragraph further down.

L343-356: Can you comment on the importance of ice shelves for polynyas? Should they be added to the discussion of mechanisms that are not represented in E3SM?

We have now added this sentence on lines 330-332: "Another important but missing piece of E3SM-HR is the representation of ice shelves, which closely interact with coastal polynya and DSW (Jeong et al. 2020)."

L384-388: The paper finds that the deep subpolar low-pressure system is the reason for model biases. Can you think of ways to test this hypothesis or do you have ideas how to fix the problem? Adding a sentence or two would be a nice addition to the conclusions.

We have done additional analysis and presented more evidence for our hypothesis in the revised version of the manuscript. Please see Figure 7 and related discussion, and the Ekman transport figure in Supplementary Material.

Technical comments

We sincerely appreciate Reviewer 3 for taking the time to read our manuscript in detail. We have followed all the reviewer's suggestions, except for those cases where the text had been modified to the point that the suggestion was no longer applicable.

Abstract

L1: Rephrase to "of the Earth's".

Corrected (now on line 25).

L9: Delete “hence” or alternatively rewrite “and hence to too little”.

Corrected.

L9: Replace “communication” with “exchange”.

Corrected.

Introduction

L17: Rephrase to “areas of ice-free surface water or of thin, ... ”.

Corrected.

L19: Rephrase to “advection of sea ice”.

Corrected.

L21: Rephrase to “important role in the climate”.

Corrected.

L22: Rephrase to “atmosphere and thereby affecting”.

Corrected.

L23: I suggest changing the order “resulting from high rates of surface cooling and sea ice production”. Sea ice production is a result of surface cooling and should be listed second.

Done.

L24: Replace “The latter” with “Point 2”. It is not clear to me what “the latter” refers to (the entire second point or the sea ice formation only).

Corrected.

L27: Rephrase to “as AABW is an important sink”.

Done.

L37: Rephrase to "are dense due to" or "are cold and salty due to". Highlighting that the water is cold and dense would only be informative when it is compared to a situation where the water is warm and dense.

Done.

L41: Add citation for onshore CDW transport, e.g., Stewart et al. 2015, Foppert et al. 2019.

Thank you. References added.

L56: Rephrase to "Instead, many GCMs create AABW" to prevent repetition of the word often in the next sentence.

Corrected.

L57: Use the acronym GCM. Either always write the full name or always write the acronym. Please go through he entire manuscript and check for consistency for all acronyms.

Done.

L59: Rephrase to "this vertical heat transfer creates".

Corrected.

L60: Rephrase to "creating AABW by surface heat loss".

Corrected.

Data and methodology

L87: Can you specify the effect of the tuning parameters.

We feel that this is too much information for this paper. Instead, we are referring to the Caldwell et al. (2019) paper.

L91: Please always use the same order (e.g., first high-resolution, then low-resolution).

Done.

L94: Rephrase to "mesh has a resolution".

Corrected.

L95: Swap order of 30km and 60km. I assume 60km is at the equator and 30km at the poles? Please use the same order as in L92.

No, the current text is correct: 60 km resolution at the mid-latitudes and 30 km at the equator and poles.

L95: Rephrase to "with a layer thickness".

Corrected.

L99: Remove hyphen between "1 and 3 months".

Corrected.

L105: Rephrase to "in the fully coupled simulations".

Corrected.

L120: Rephrase to "we use the SOSE data set".

Done.

L136: Please always use acronym (OOP) after introducing it, see comment on L57. Please check entire manuscript (e.g. L183).

Done.

L139: Rephrase to "These processes occur in areas of an ice-free ocean."

Corrected.

L144: It is not clear to me why E3SMR-LR is in brackets. I suggest to simply rephrase to "simulated in E3SM by comparing".

Corrected.

L150-152: Rephrase to "In Fig 1c, we compare E3SM-HR's accumulated sea ice volume in Antarctic coastal polynyas from March to October and as a function of longitude with the satellite estimate AMSR-E."

Done.

L158: Remove "relatively".

Corrected.

L175: Rephrase to "sum of polynya area and sea ice volume production for polynyas that are not associated with landfast ice".

Corrected.

L183: Remove comma after "large".

Corrected.

L186. Please split sentence into two "...at any point in the simulation. E3SMR-HR does produce MRPs...".

Done.

L194: Rephrase to "the strong subpolar cyclonic gyre".

Corrected.

L195: Rephrase to "preconditioning this convective process".

Corrected.

L195: Rephrase to "pycnocline and a circulation".

Corrected.

L199: Rephrase to "or in which embayment-like feature".

Done.

Dense water formation

L214: Rephrase to "last 30 years of the E3SM-HR simulation".

Corrected.

L221: Rephrase to "produced in E3SM-HR for all surface fluxes combined".

Corrected.

L225: Specify the regions where WMT is negative. Are they relevant?

Corrected.

L230: Suggest splitting the sentence after "AABW formation".

Done.

L233-234: Rephrase to "similarly to what has been found in previous studies".

Corrected.

L260: The low salinity on the shelf in the fresh regime is a result of the winds and onshore Ekman transport. Can you change the order of the sentence to distinguish between mechanism and the resulting stratification?

Done.

L263-267: Add information that the dense shelf is important for onshore CDW transport and preconditioning of shelf waters for DSW formation.

Done (see text in blue on lines 267-268).

L273-274: The sentence reads as if the data from Whitworth et al. (1998) is shown in Fig 7-9, but that is not the case. Please clarify.

The reference has now been removed.

L282: Rephrase to "formed by brine rejection".

Corrected.

L283: Rephrase to "isopycnals associated with warm CDW tilt down towards the seafloor".

Corrected.

L284: Rephrase to "the isopycnals shoal again".

Done.

L291: Check that the reference to the figure is correct. It should be referring to Fig 8 here.

Figure numbers have been double checked and corrected.

L295-297: Are the first three sentences referring to information from Thompson et al. (2018) or are they based on the model simulation?

Thank you for pointing this out. The first three sentences refer to information from Thopmson et al. (2018), which is now cited.

L298: Rephrase to "SOSE has isohaline surfaces that tilt upward towards Antarctica".

SOSE has now been replaced with CTD observational data in the revised Figure 7.

L304: This sentence focuses on the strong zonal winds and assumes an effect on onshore Ekman transport. But the meridional winds are also larger than in ERA5. Did you look at the Ekman transport in the model and its zonal and meridional components?

Thank you for this suggestion. We have now included a figure of Ekman transport in the Supplementary Material and added a discussion on lines 297-298.

L307: Rephrase to "build-up".

Corrected.

L311: Remove "same".

Done.

Discussion

L327: Replace "ingest" with "process".

Corrected.

L331: Delete "whereas".

Corrected.

L331: E3SM-HR has an atmospheric model component, what is the meaning of "atmospheric forcing" (HighResMIP) here? My understanding from reading section 2.2 is the output of the model simulation is used in HighResMIP. Please clarify.

We apologize for the confusion. This is meant as ”atmospheric greenhouse gas forcing”. We have clarified the sentence on lines 348-349: “The E3SM simulations presented in this paper use the fixed 1950s atmospheric forcing, which consists of greenhouse gases, O3, and aerosol for a 1950s (∼10-year mean) climatology.”

L332: Split the sentence into two: “... of a stable climate. The observations with which E3SM-HR is compared to are for a transient climate.”

Done.

L323: Remove “moreover”.

Corrected.

L336: Remove “random differences in”.

Corrected.

Summary and conclusions

L358-359: Also mention E3SM-LR.

Done.

L366: Rephrase to “Aside from the large embayment-shaped polynyas, . . . ”.

Corrected.

L368: Rephrase to “which are almost entirely due to”.

Corrected.

L273: Overly strong southward Ekman transport not shown in study.

We now included a figure of Ekman transport computed from E3SM-HR and from the ERA5 data in the Supplementary Material.

L376: Rephrase to “there is no DSW formation”.

Corrected.

L379: Rephrase to “thick sea ice in summer”.

Corrected.

Tables

Table 1: What are the atmosphere and land listed twice? What does 72 and 15 mean?

We have now clarified the fields listed in Table 1.

Table 2: Rephrase to "state estimate datasets" and add full stop.

Done.

Table 3: Add full stop.

Corrected.

Figures

Figure 1 Panel a): Why is there green shading on land? The latent heat flux from the ocean to land should only have values over the ocean.

Corrected.

Figure 1 caption: Rephrase to "(d) Total sea ice volume production per year".

Done.

Figure 2: Please use the same color (pink) for E3SM-HR as in Figure 1.

Done.

Figure 2 caption: Rephrase to "(a-m) Area-volume diagrams"; "(n) Integrated polynya area"; "(o) Integrated polynya area".

Corrected. Thank you.

Figure 3 caption: Rephrase to "(c) November from NCDR (year 2017)"; (i) November (model year 54).

Corrected.

Figure 4: Show pink box indicating the Weddell Sea region in panel (a) only and adjust the figure caption accordingly: "The pink box in (a) indicates the area..."

Corrected.

Figure 5 Panel (a): Is the WMT rate shown on the map the integrated WMT rate over all density classes?

Yes, it is. We have now clarified this in the figure caption.

Figure 5 caption: Add information that the figure is from E3SM-HR output.

Done.

Figure 5: "Note that the green and pink curves do not sum to the gray curve." What is missing?

The gray curve is the summation of the WMT rate over the whole Southern Ocean (south of 60°S). The pink curve indicates the WMT rate over the Weddell Sea and the green curve denotes the WMT rate over the Antarctic continental shelves as indicated in Figure 5a. We also notify that in the caption of Figure 5 as follows "Note that the green and pink curves do not sum to the gray curve."

Figure 6: Colorbars should start at zero and not have an arrow on the left end. Zero is the smallest possible value.

Thanks for the suggestions. We have modified the color bar.

Figure 7-9: Discuss the impact of the fact that the SOSE and E3SM-HR transects are not at the exact same position.

This comment is no longer relevant because SOSE has now been replaced with CTD observations in Figure 7.

Figure 10: The diverging colormap is confusing, please use a sequential colormap.

Done.

Figure 10: Colorbar should start at zero and not have an arrow, see comment on Figure 6.

Done.

Figure 10: Showing a difference plot (SOSE-E3SMR-HR) would help identifying regions where sea ice thickness differs.

Thank you for this suggestion. Unfortunately, the resolutions of SOSE and E3SM-HR are different from each other, therefore, we could not make the difference plot.

Figure 11: See last comment on Figure 10. Difference plots make it easier to see where the models differ from observations.

See response above.

Figure 11: Please use sequential colormap for sea surface neutral density.

Done.