

Review of Southern Ocean polynyas and dense water formation in a high-resolution, coupled Earth System Model by Jeon et al.

This study explores the ability of the coupled model E3SM to simulate coastal polynyas and Dense Shelf Water (DSW) formation. Both features are misrepresented in most global models which is problematic as DSW formation in coastal polynyas is the precursor for Antarctic Bottom Water formation. The study makes use of E3SM-HR, a newly developed version of E3SM with a higher horizontal resolution. E3SM-HR can simulate coastal polynyas reasonably well, setting the model apart from other global coupled models. Biases occur in regions where polynyas occur next to fast ice which is not simulated by the model. The model forms open ocean polynyas which do occur in the Weddell Sea but are much less common than simulated in the model. The formation of open ocean polynyas is a prevalent problem in global models and results from a too weak stratification allowing excessive deep convection in winter. The study further examines the ability of E3SM-HR to form DSW on the continental shelf and finds that dense water is formed but it is not dense enough to form Antarctic Bottom Water. The reason for the water not being dense enough is due to a lack of onshore transport of salty Circumpolar Deep Water (CDW). The study states that a too strong Antarctic Slope Current driven by too strong winds resulting from a deep subpolar pressure system in E3SM-HR is the reason for the lack of onshore CDW transport and preconditioning of the water column.

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 provides 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 disadvantage 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.
 - 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.
- 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.
- 3) The important finding of the study is that the subpolar low-pressure system around Antarctica is too low with consequences for the ASC, sea ice transport,

preconditioning of the water column, and DSW formation. Can you think of ways to test this hypothesis, or do you have ideas how to fix the problem in E3SM-HR? Adding a paragraph would be a valuable addition to the conclusions.

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?

L45: What model biases? Please elaborate.

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?

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.

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.

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).

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

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

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.

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

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

L230-231: I am not sure I understand the sentence. 28kgm^{-3} is the density found in E3SM-HR as the threshold for AABW formation? And Orsi et al. (1999) find that it needs to be 28.28kgm^{-3} ?

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)?

L271: The example transect for the dense regime at 35°W is at the eastern end of the section characterised 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.

L275ff: 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.

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

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

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?

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

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.

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.

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?

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.

Technical comments

Abstract

L1: Rephrase to “of **the** Earth’s”.

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

L9: Replace “communication” with “exchange”.

Introduction

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

L19: Rephrase to “advection of **sea ice**”.

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

L22: Rephrase to “atmosphere **and thereby** affecting”.

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.

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).

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

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*.

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

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

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

L59: Rephrase to “this **vertical** heat transfer creates”.

L60: Rephrase to “creating AABW by **surface heat loss**”.

Data and methodology

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

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

L94: Rephrase to “mesh has a resolution”.

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.

L95: Rephrase to “with a layer thickness”.

L99: Remove hyphen between “1 and 3 months”.

L105: Rephrase to “in **the** fully coupled simulations”.

L120: Rephrase to “we use **the** SOSE data set”.

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

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

Antarctic coastal and open-ocean polynyas

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

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.**”

L158: Remove “relatively”.

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

L183: Remove comma after “large”.

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

L194: Rephrase to “the strong **subpolar** cyclonic gyre”.

L195: Rephrase to “preconditioning this convective process”.

L195: Rephrase to “pycnocline and a circulation”.

L199: Rephrase to “or **in which** embayment-like feature”.

Dense water formation

L214: Rephrase to “last 30 years of **the** E3SM-HR simulation”.

L221: Rephrase to “produced in E3SM-HR **for** all surface fluxes combined”.

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

L230: Suggest splitting the sentence after “AABW formation”.

L233-234: Rephrase to “similarly to **what has been found in previous** studies”.

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?

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

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.

L282: Rephrase to “**formed** by brine rejection”.

L283: Rephrase to “**isopycnals associated with** warm CDW **tilt** down towards the seafloor”.

L284: Rephrase to “**the isopycnals shoal** again”.

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

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

L298: Rephrase to “SOSE has **isohaline surfaces that tilt upward towards** Antarctica”.

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?

L307: Rephrase to “build-up”.

L311: Remove “same”.

Discussion

L327: Replace “ingest” with “process”.

L331: Delete “whereas”.

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.

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

L323: Remove “moreover”.

L336: Remove “random differences in”.

Summary and conclusions

L358-359: Also mention E3SM-LR.

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

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

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

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

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

Tables

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

Table 2: Rephrase to “state **estimate** datasets” and add full stop.

Table 3: Add full stop.

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.
- Figure caption: Rephrase to “(d) Total sea ice volume production **per year**”.

Figure 2

- Please use the same colour (pink) for E3SM-HR as in Figure 1.
- Figure caption: Rephrase to “(a-m) **Area-volume** diagrams”; “(n) **Integrated** polynya area”; “(o) **Integrated** polynya area”.

Figure 3

- Figure caption: Rephrase to “(c) November from NCDR (**year 2017**)”; (i) November (**model year 54**).

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...”

Figure 5:

- Panel (a): Is the WMT rate shown on the map the integrated WMT rate over all density classes?
- Figure caption: Add information that the figure is from E3SM-HR output.
- “Note that the green and pink curves do not sum to the gray curve.” What is missing?

Figure 6

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

Figure 7-9

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

Figure 10:

- The diverging colormap is confusing, please use a sequential colormap.
- Colorbar should start at zero and not have an arrow, see comment on Figure 6.
- Showing a difference plot (SOSE-E3SMR-HR) would help identifying regions where sea ice thickness differs.

Figure 11:

- See last comment on Figure 10. Difference plots make it easier to see where the models differ from observations.
- Please use sequential colormap for sea surface neutral density.

New references

Stewart, A. L., and A. F. Thompson (2015), Eddy-mediated transport of warm Circumpolar Deep Water across the Antarctic Shelf Break, *Geophys. Res. Lett.*, 42, 432–440, doi:10.1002/2014GL062281.

Foppert, A., Rintoul, S. R., & England, M. H. (2019). Along-slope variability of cross-slope eddy transport in East Antarctica. *Geophysical Research Letters*, 46, 8224–8233. <https://doi.org/10.1029/2019GL082999>

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