Response to Reviewer 2 for "Southern Ocean polynyas and dense water formation in a high-resolution, coupled Earth System Model" by Jeong et al.

We thank the reviewer for their helpful and constructive comments. Please find our responses below (the reviewer's comments are noted in italics and our reference to manuscript line numbers refers to the revised version of the manuscript).

The authors investigate dense water and polynya formation in two versions of the Energy Exascale Earth System Model. The manuscript is clearly structured and the results are well presented. Some of the arguments don't seem to be supported by the material and the results need to be expanded upon.

Main comments here:

1. Could you give recommendations for development? What are the key improvements needed here (easterlies and Ekman transport)?

Thank you for this suggestion. We have now added a paragraph discussing these points in section 5: see text in blue starting from line 326.

2. You mention the impact of the overly strong polar easterlies and associated Ekman transport throughout the paper and abstract. However - you do not seem to directly calculate the Ekman transport. Can you do this and compare to observations?

We have followed the reviewer's suggestion and calculated the Ekman transport for the E3SM-HR simulation and the ERA5 data. The results are shown in Figure 3 of the Supplementary Material and discussed on line 297.

3. The mean-state open ocean stratification is important for the formation of open ocean polynya in models. What does the open ocean stratification look like in these models compared to observations? Is it overly weak (explaining the convection in HR model) or overly strong (explaining no convection in the LR model)?

We thank the reviewer for this question. Indeed, compared with SOSE, the upper ocean stratification in the interior Weddell Sea is too strong in E3SM-HR and too weak in E3SM-LR. We have not included results showing this in the paper but i) we have added a discussion mentioning this on lines 196-199 and 206-208, and ii) we have included potential density results for E3SM-HR and E3SM-LR at the surface and at 200 m depth in Figs. 1, 2 below, for the reviewer's convenience.

4. You mention that the model is fully coupled. The ocean-ice interaction is very important for DSW and presumably the coastal polynya development. Please include a discussion of this.

We have explicitly mentioned air-sea interaction processes in various parts of the manuscript. Please see, for example, lines 145, 184, 241-244.

Minor comments:

Line 18: Are you referring to katabatic winds? If so, please introduce term as you use it again later.

Thank you from bringing this up. We now use the term "katabic winds" throughout the manuscript.

Line 20: Are coastal polynya important for other aspects of the earth system e.g., marine biology or biogeochemical cycles?

Indeed. We have now added a sentence on line 22.

Line 20: You may introduce that these are areas of high sea ice production. Also, coastal polynya may form due to oceanic currents.

Done. Please see line 17.

Line 46: Could add citation to On the Role of the Antarctic Slope Front on the Occurrence of the Weddell Sea Polynya under Climate Change.

Done.

Line 55: You may introduce the two types (coastal and open) of polynya in paragraph one.

Done. Please see lines 26-29.

Line 134: You can have open ocean convection that doesn't form polynya in models (e.g., Dufour et al 2017 and Lockwood et al 2020).

We are not entirely sure what sentence the reviewer is referring to. If this is the sentence: "These polynyas are generally observed in conjunction with deep convection events in the ocean..." (now on line 28), then we do not think that this implies that whenever there is deep convection a polynya forms. But rather that deep convection is always found in OOPs.

Line 181: Moved westward with an average velocity of 0.013 $\mathrm{m\,s^{-1}}$ *(Gordon 1978, 1982).*

Thank you for the clarification. Revised text is now on line 175.

Line 193: Episodic open ocean deep convection events in the Weddell Sea have been linked to anomalies in the Southern Annular Mode index (Gordon et al. 2007; Cheon et al. 2014; Francis et *al. 2019; Campbell et al. 2019; Cheon and Gordon 2019). Have you considered the representation the SAM in these models?*

We have now added a sentence describing the studies mentioned by the reviewer in the revised version of the manuscript, lines 191-192.

Line 209: You can have convection and dense water formation without polynya formation (see Dufour et al. 2015 and Lockwood et al. 2020). Please check if the LR model is in fact creating dense water and convection, just without polynya formation. Convection can be calculated via. the mixed layer depth (see de Lavenge et al. 2015).

In addition to Fig. 2, we have included Fig. 3 (maximum mixed layer depth) below from both E3SM-HR and E3SM-LR. Clearly, there is no evidence of deep convection in the low-resolution simulation. We have added a sentence clarifying this on lines 206-208 of the revised manuscript.

Lines 258: Although you're correctly taking the transects from the respective areas following Thompson et al 2018 - the Western and Eastern Weddell Sea transects seem very close together. I'd like to see how this model holds in another region of Fresh Shelf (e.g., along the Ross sea). Also, can the LR model capture the hydrography?

As the reviewer suggested, we re-selected the three transects for representing three types of shelves, and now they are at the same location as those considered in Thompson et al. (2018). We also compared the vertical temperature and density fields of the E3SM-HR simulation with CTD observations rather than SOSE. The revised vertical cross-sections are shown in Figure 7.

Line 295: Could you produce depth average velocities around the full Antarctic?

Please see the depth-averaged oceanic currents speed for E3SM-HR and SOSE in Fig. 4 below. As expected, the model currents are stronger along the Antarctic coast with respect to SOSE.

Line 325: Have you considered comparing to very high-resolution simulations like the MITGCM or LCM-4320?

Thank you for this suggestion. However, we are unable to compare with those simulations at the moment. Instead, we compared our E3SM-HR results with CTD observations in Figure 7.

Figure 6. c-d The vectors are difficult to see in the figures.

Thank you for the suggestion. We modified the vectors to make them more visible.

LIST OF FIGURES

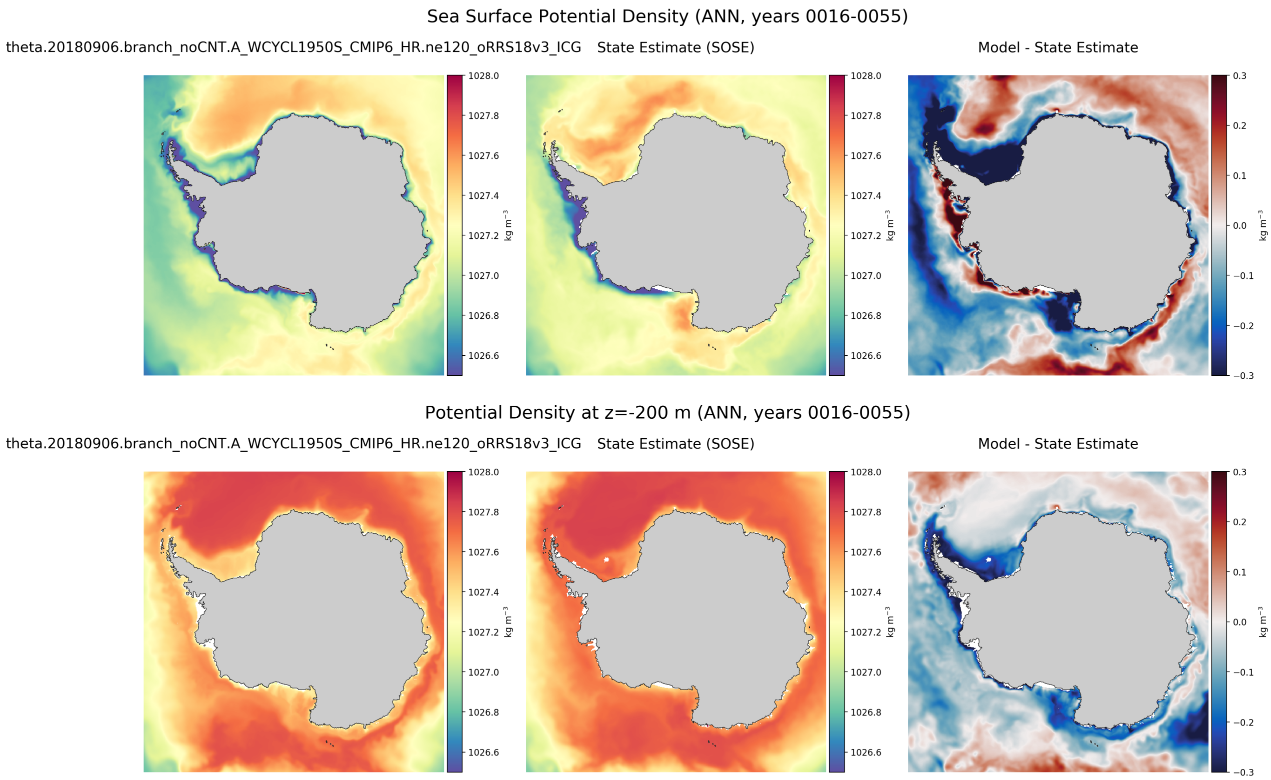


FIG. 1. Potential density (σ_0) from E3SM-HR (left) and SOSE (middle) at the surface (upper) and 200 m depth (lower). Right panels show model-SOSE biases.

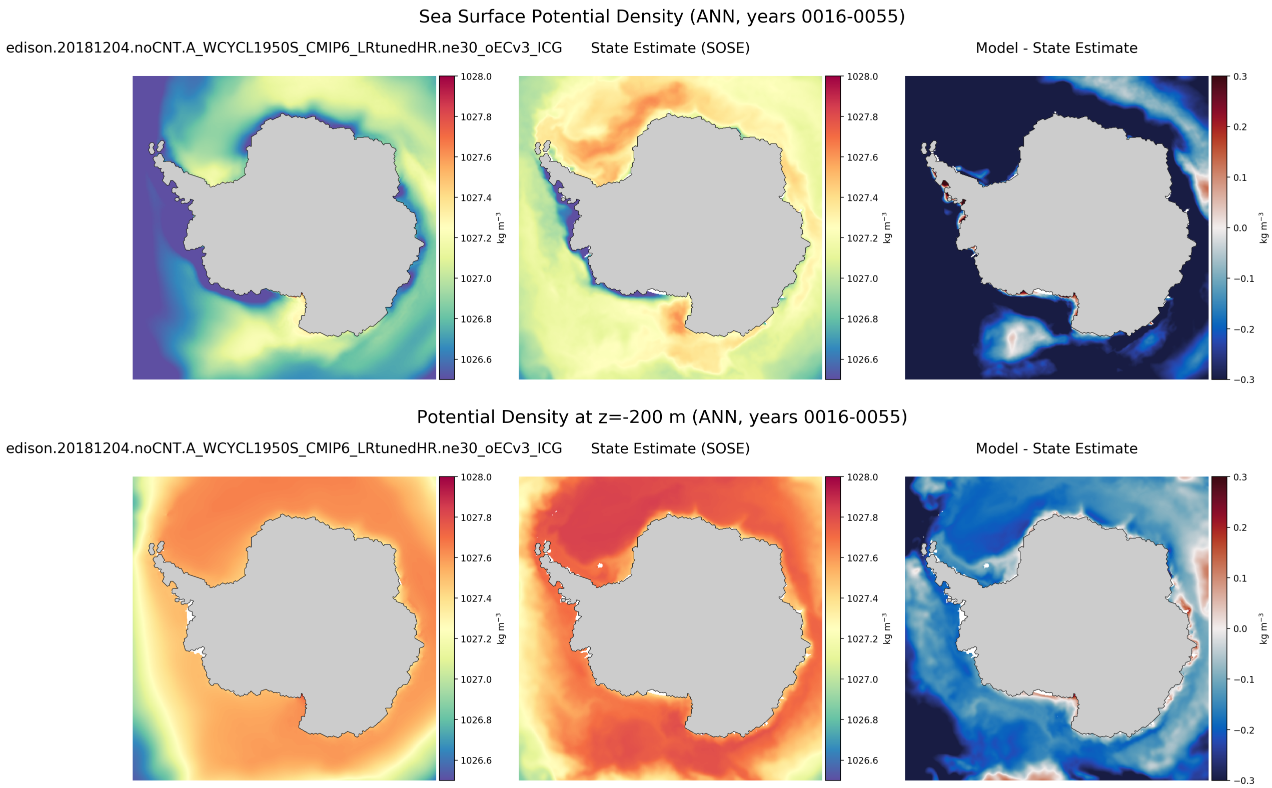
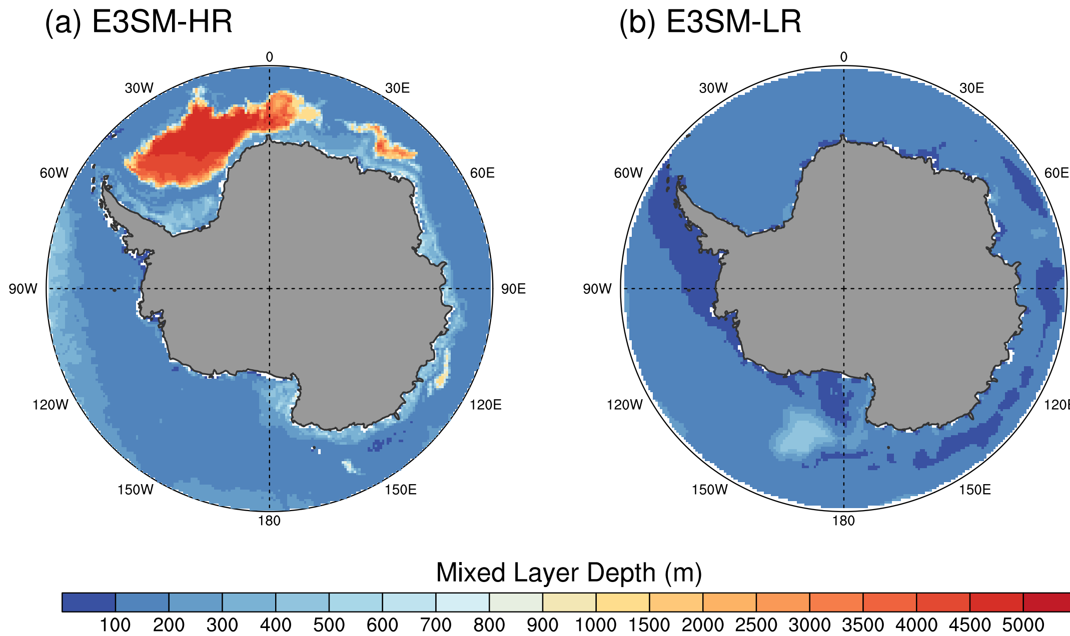


FIG. 2. Similar to Fig. 1 but for E3SM-LR.



3 FIG. 3. Maximum depth of the mixed layer (m) in any month of the 30 simulation years for (a) E3SM-HR
4 and (b) E3SM-LR.

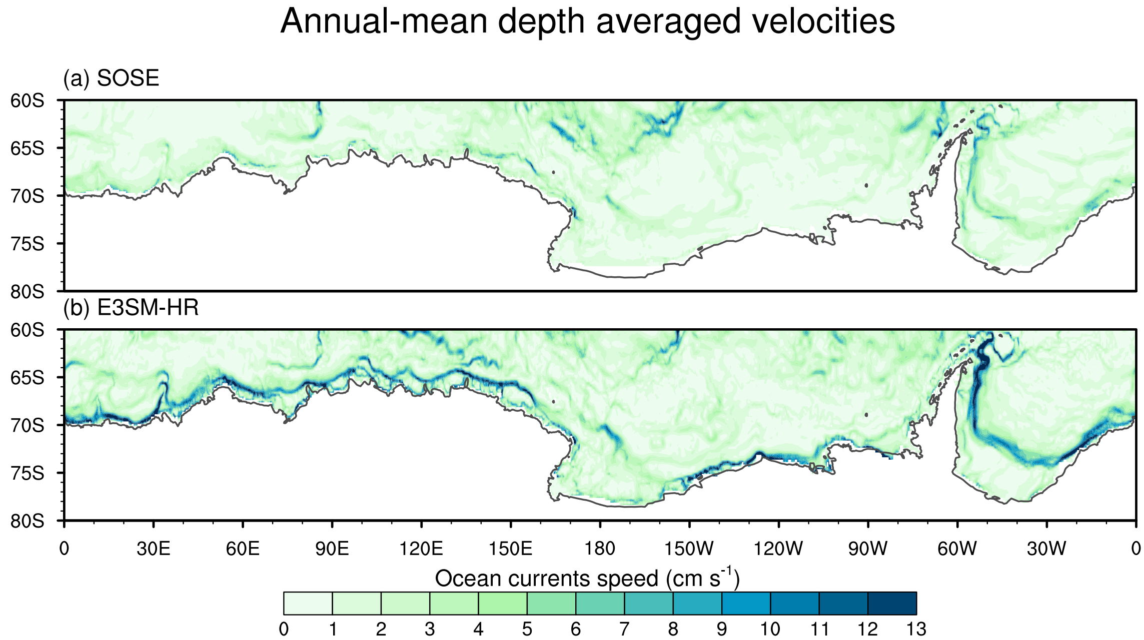


FIG. 4. Annual-mean depth-averaged oceanic currents speed for (a) SOSE and (b) E3SM-HR.