Reviewer #1: This submission addresses relevant and timely scientific sea ice modelling questions – in particular, how different model parameters, and combinations of model parameters, influence both sea ice budgets in the Southern Ocean as well as comparison with satellite data. The sea ice components of global climate models tend to rely on parameterizations dominated by Arctic studies. This paper is a new look at parameterizations targeting Antarctic sea ice, and recommends ten new combinations of parameters for the NEMO4.0-SI3 sea ice model that would result in better comparisons with satellite-based observations of Southern Hemisphere sea ice area and extent. The paper is well written overall, with methods and assumptions clearly outlined.

We thank you for the constructive comments on the earlier version of the manuscript. We have revised our manuscript following the comments, in the following we answer each specific point (in blue).

The submission will be stronger with some revisions including:

1. Set the broader context. This submission explores sea ice parameterizations primarily aimed at reducing RMSE between the model output and satellite observations for total Southern Hemisphere Sea Ice Extent and Sea Ice Area. These are very limited metrics for model performance – e.g. Notz, 2014 and Notz, 2015. The experiments in this paper are thoughtful and provide interesting insight into sea ice models yet the results presented here are not presented within the larger context, and only look at a very limited metric (climatological mean SH SIA, SIE). Other metrics that are valuable include variability, trends, and particularly for the Antarctica regional means, variability and trends. How would the recommended parameterizations, for example, impact (or not) NEMO's future scenario simulations? Do they impact variability and trends? Are the improvements to SH SIA, SIE also seen in all regions or are they regionally different? (or if beyond the scope of this paper some mention and discussion…)

We totally agree with the reviewer that SIE and SIA are very limited metrics for assessing the model, and other valuable metrics should include (regional) variability and trends, as revealed by Notz (2014) and Notz (2015). This was precisely the starting point of this paper, i.e., to use more physically meaningful metrics than SIE and SIA for model evaluation and optimisation. Our chosen metric is the sea ice budget, which decomposes sea ice variability into advection, divergence and other processes (mainly thermodynamic). Therefore, our aim in this study is (Lines 73-75) "to quantify the sensitivity of the Southern Ocean SIC and sea ice volume (SIV) budgets to key parameters in a coupled ocean-sea ice model by constructing a GP emulator, and furthermore, to verify whether the model parameters can be adjusted to obtain near-realistic SIC budget components." Moreover, we believe that the first three sentences of the abstract clearly communicate this point.

Indeed, in Fig. 2 we show the climatological mean SH SIA, SIE, which, as mentioned, are the primary metrics. On the one hand, these metrics verified that the ocean-sea icemodel forced by the atmospheric reanalyses we used was working reasonably well, and more importantly, provided good evidence that our approach to optimise parameters by reducing the RMSE between the modelled and observed SIC budget makes good sense, i.e. although the default NEMO4-SI3 parameters can already produce reasonable SIE and SIA seasonal cycles, their physical processes are likely to differ significantly from the reality.

As for the model results, our analysis is unfortunately limited to the period 2008-2017, which is only a decade, and not sufficient to support investigations of the impact of these parameters on inter-decadal sea ice trends. In terms of regional differences, we have added Fig. B6 which illustrates that the optimisation improves the SIC budgets in all regions (Line 511).

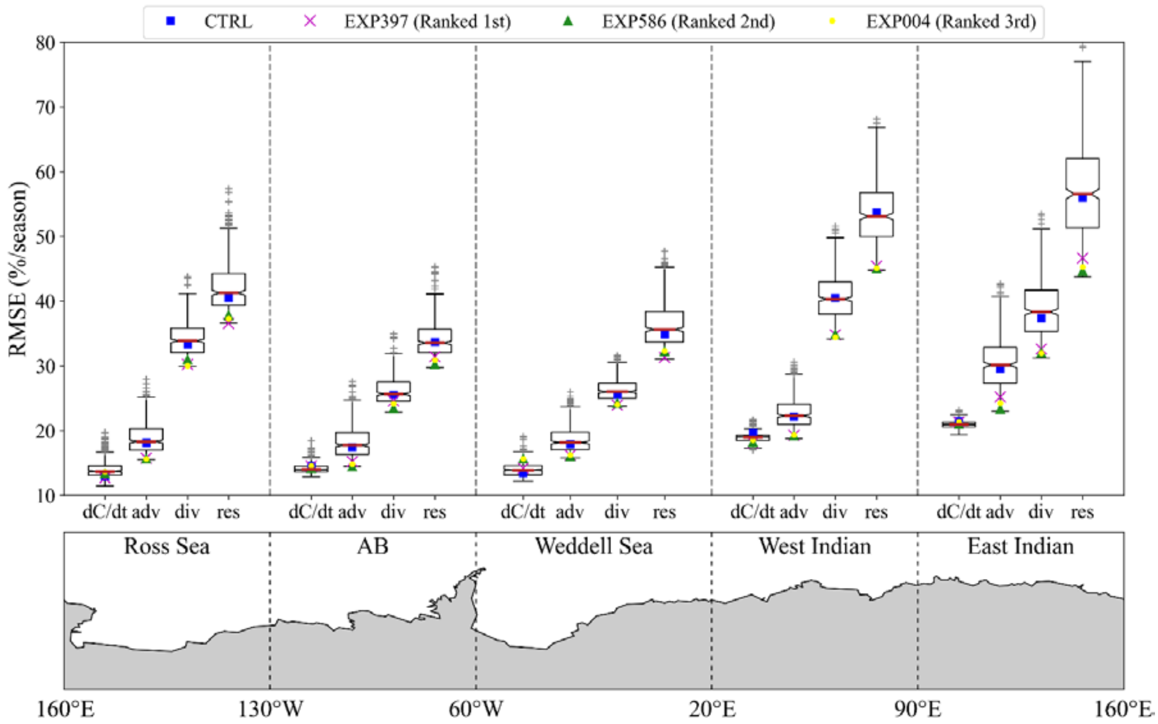

Fig. B6. As Fig. 7, but the RMSE of each SIC budget term is averaged over four seasons and counted separately in each Southern Ocean sector. The vertical dotted line marks the demarcation of each sector. AB=Amundsen-Bellingshausen Seas.

2. Some discussion of why these parameterizations are better in the SH and some differences between Antarctic sea ice and Arctic sea ice and why these differences might lead to these different parameterizations (I am assuming current NEMO parameterizations are based on Arctic work).

We have added Fig. B8 to illustrate that several of the parameter sets that are associated with top performing Southern Ocean SIC budgets also perform better in the Arctic SIE simulations compared to the NEMO4-SI3 default values (Lines 521-523), which at least gives us more confidence that these parameter sets are reliable. However, it must be re-emphasised that these parameters are highly dependent on the atmospheric forcing data used.

The added text reads (Lines 521-527) "In addition, Fig. B8 shows that the recommended parameter sets also provide some improvements in the Arctic SIE and SIA simulations compared to the default parameters, as reflected by more sea ice in summer months, which is closer to observations than in the CTRL experiment.

However, given that SIE and SIA are limited metrics (Notz, 2014; Notz, 2015) and that the key parameters affecting sea ice simulations may not be the same between the northern and southern hemispheres due to the vast geographical differences (e.g. ocean and land locations, atmospheric and oceanic circulations), whether these parameter sets, which perform well in the Southern Ocean SIC budget, can be safely applied to the Arctic merits further investigation."

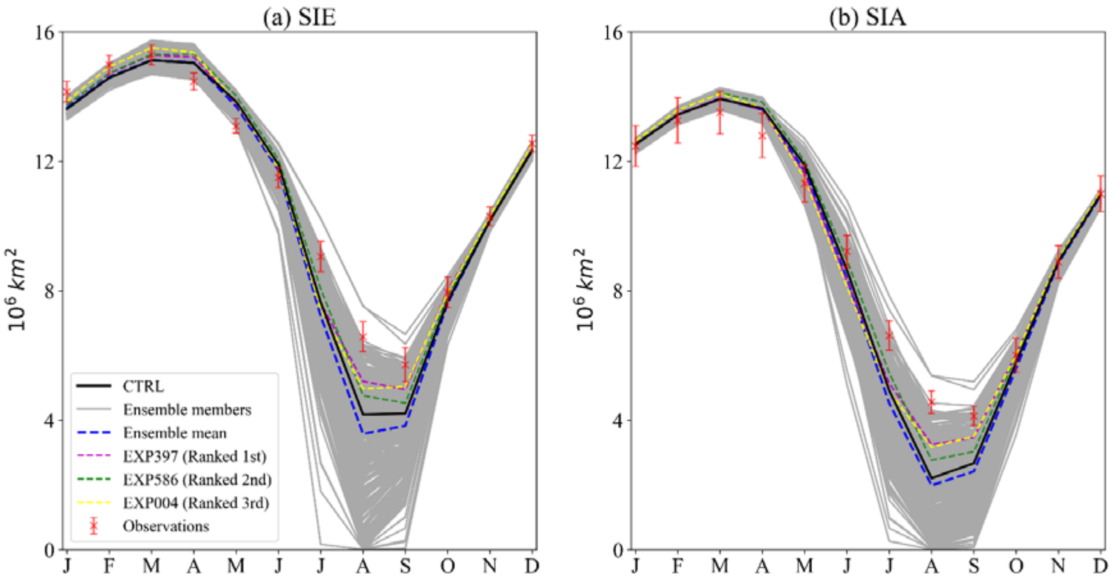

Fig. B8. Simulated monthly climatologies of Arctic (a) sea ice extent (SIE) and (b) area (SIA) from 2008 to 2017, ensemble model means and results from four sets of experiments of interest are also highlighted. The SIE and SIA calculated from the CDR, AMSR-E/AMSR2, CERSAT and OSISAF are used as references in the form of mean ± one deviation.

3. These parameterizations are determined from current conditions. Any thoughts as to whether or not they would be expected to be constant and/or changing in a warming world?

Main principle is that parameterizations describe unresolved physics of models, therefore also these parameter values are likely to change under changing circumstances. The direction and amount of the change varies from parameter to parameter and non-linearities in the climate systems make the estimation of changes particularly tricky. For example, the air-ice drag coefficient would change due to changing sea ice and snow surface roughness and changing atmospheric stability. In a warming world the first order effect is intensified hydrological cycle and precipitation which could be more in liquid form potentially reducing surface roughness and air-ice drag. At the same time, the atmospheric boundary layer could become less stable potentially increasing the air-ice drag coefficient. The estimation of the net effect is not easy. And there are regional and seasonal differences in terms of parameter responses. In summary, one could expect the parameter values to change.

We added the following sentence in the revised manuscript (Line 568) "The recommended parameter sets are determined from current conditions and one could expect their optimal values to change in a warming world."

4. In the first paragraph in the Introduction, the authors discuss how climate models in general do not capture the observed trends in SH sea ice. While this is true, at no point in this paper are the parameterizations discussed in light of the trends! The parameterizations are compared only to the climatological mean SIA, SIE – not the variability or the trends (or regionality). The spread in representation of the mean annual cycle of SIE is quite large between CMIP6 models (e.g. Roach et al., 2020), however there are climate models that capture the climatological annual cycle of SH SIE. Clarify the introduction a bit to match the research and results presented.

We agree that the interpretation of sea ice trends in the first paragraph of the introduction may distract the reader from the fact that in this paper we are not optimising model parameters based on sea ice trends. In fact, our focus is on the sensitivity of the Southern Ocean sea ice budgets (which we believe are more valuable metrics than SIA and SIE) to the parameters, and thus we propose some reliable parameter sets. To make this more clear, we modified the first paragraph to (Lines 24-31):

"Several state-of-the-art climate models have successfully simulated the near-realistic annual cycle of sea ice area (SIA) (Holmes et al., 2019), but they typically still fail to capture the observed sea ice variability and trends (Zunz et al., 2013; Turner et al., 2013; Shu et al., 2015; Shu et al., 2020). This implies that standard metrics commonly used for model evaluation, such as sea ice extent (SIE), SIA and total volume (SIV), are rather rudimentary and of limited use in improving the model skill (Notz, 2014; Notz, 2015), and better metrics are needed to optimise models."

It is true that some CMIP5 and CMIP6 models could capture the realistic SIE seasonal cycles, but not the sea ice trends. Furthermore, it has also been shown in several studies that these realistic SIEs are also caused by large biases in the dynamic and thermodynamic contributions to sea ice variability that cancel out each other (e.g., Uotila et al., 2014; Lecomte et al., 2016; Holmes et al., 2019). The relationship between sea ice budgets and sea ice trends is a very interesting topic and our ongoing work, but beyond the scope of this paper.

5. It may be interesting to add three panels to figure 2 showing variability (STD) of each of these as well……….or not if beyond the scope..

Thanks for your valuable suggestion, but it is beyond the scope of this study to investigate how the accuracy of sea ice budget simulations affects the modelling of sea ice variability and trends. However, this is an interesting topic we are now working on.

6. Passive microwave images will lead to underestimates of SIC in thin ice regions. Any thoughts to whether or not this influences how one compares model output to satellite (you only consider areas of SIC 15% and higher. What about regions where model output is > 15% SIC and sea ice thicknesses less than 5 cm or 5-20cm where satellite observations underestimate SIC?

We only calculate the sea ice budget for grids with SIC > 15% because sea ice velocity observations are more reliable in this interval, and therefore allows for a fair comparison of modelled and observed SIC budgets (Holmes et al., 2019). At the same time the effect of observed underestimates in the region of SIC < 15% on the SIC budget calculation is excluded, and in any case the SICB is rather insensitive to such SIC underestimates (Holland and Kimura, 2016).

In addition, when comparing simulated and observed SIAs (Fig. 2), the uncertainty of satellite observations at SIC <15% is worth considering. To address this, we used multiple observational products and plotted the range of observational uncertainty in Fig. 2, where model's significant overestimation of the August to October SIA is shown being somewhat weaker when the observational uncertainty is taken into account compared to if only the CDR product is used.

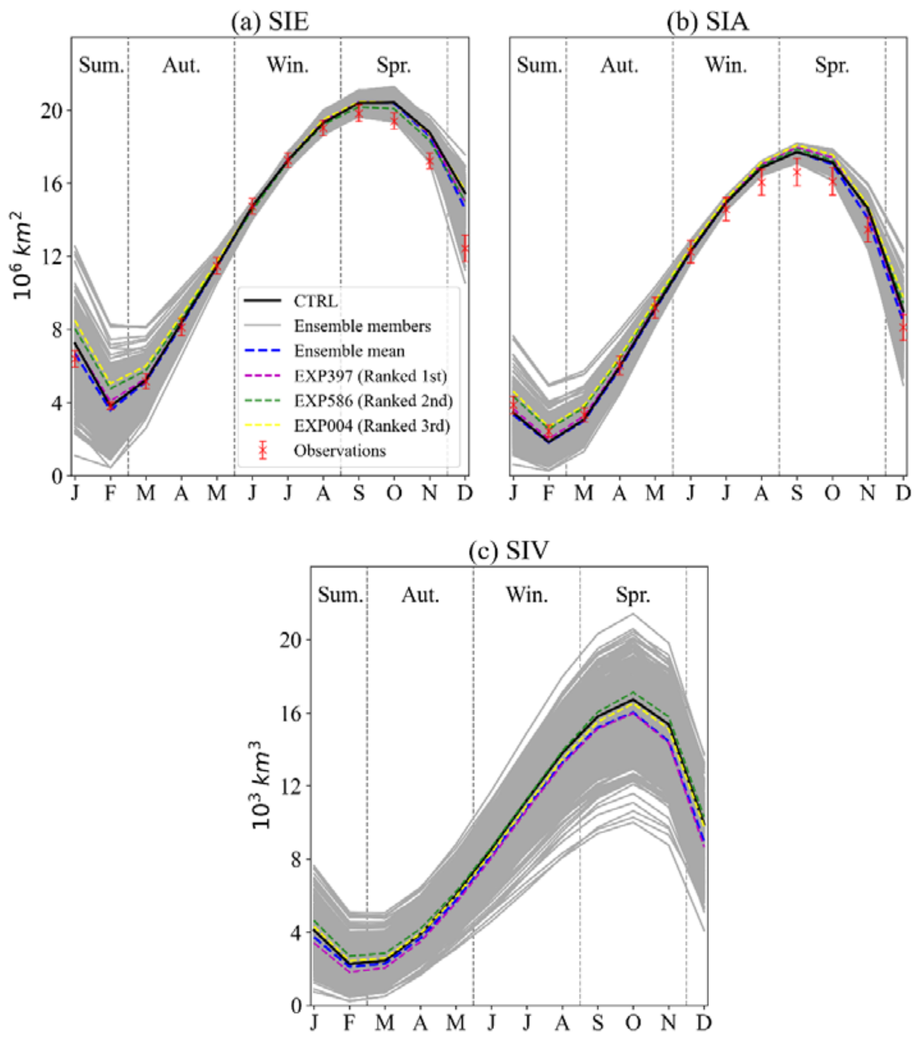

Figure 2. Simulated monthly climatologies of (a) sea ice extent (SIE), (b) area (SIA) and (c) volume (SIV) from 2008 to 2017, ensemble model means and results from four sets of experiments of interest are also highlighted. The SIE and SIA calculated from the CDR, AMSR-E/AMSR2, CERSAT and OSISAF are used as references in the form of mean ± one deviation.

The submission is well written in general however there are some times when it is a bit unclear due to grammar or word choice. I found some minor changes along these lines and I believe the manuscript would benefit from the help of a skilled editor for language word choices, etc. Here are some suggested minor changes:

Line 18: change "sensitivity" to "sensitive"

Revised.

Line 27: change "association" to "teleconnections"

The sentence in the original manuscript where this word was located has been removed.

Line 93: This is confusing. I believe you mean "number of sea ice thickness categories is 5" and I have no idea what "2 and 1 layers of ice and snow" means. How can a 5-thickness categories for sea ice only have 2 layers? Or one? Guessing just 1 layer of snow on top of sea ice?

We have rephrased this sentence to make it clearer and it now reads (Line 92) "The default number of sea ice thickness categories is 5, with each category having two vertical layers of ice and one layer of snow on top of ice."

Line 110: change "marginal regions" to "marginal sea ice regions" (and define "marginal"…15-85% SIC? Or?)

We note that the expression "marginal regions" is misleading and naturally reminds the reader of the "marginal sea ice regions", when in fact we are trying to express the "edge of the sampling interval". We have now revised this phrase in Line 111.

Table 1: jpl = "number of ice thickness categories" I believe? Or? And are these set – in other words, do you change not only the number of ice thickness categories but also the category boundaries? Or just the number?

Only the number of ice thickness categories were tuned in this study, and the position of boundaries were prescribed by default by using a fitting function that following Lipscomb (2001) in NEMO4-SI3 default. We have now changed the description of jpl in Table 1 to "Number of ice thickness categories".

Table 1. The 18 parameters investigated, including their realistic ranges taken from the listed references.

Category	Symbol	Description and unit	Low	Standard	High	Reference
Ice/snow	rn_pstar	Ice strength parameter [N/m2]	5.00E+03	2.00E+04	3.50E+04	Massonnet et al. (2014)
	rhos	Snow density [kg/m3]	130	330	530	Massom et al. (2001) and Warren et al. (1999)
	rhoi	Ice density [kg/m3]	880	917	940	Timco and Frederking (1996)
	rn_cnd_s	Thermal conductivity of the snow [W/m/K]	0.1	0.31	0.5	Maykut and Untersteiner (1971) and Lecomte et al. (2013)
	rn_beta	Coefficient beta for lateral melting parameter	0.2	1	1.8	Lupkes et al. (2012)
	rn_dmin	Minimum floe diameter for lateral melting parameter [m]	2	8	14	Lupkes et al. (2012)
	rn_alb_sdry	Dry snow albdo	0.85	0.85	0.87	Perovich et al. (2002) and Brandt et al. (2005)
	rn_alb_smlt	Melting snow albdo	0.72	0.75	0.82	Perovich et al. (2002) and Brandt et al. (2005)
	rn_alb_idry	Dry ice albdo	0.54	0.6	0.65	Perovich et al. (2002) and Brandt et al. (2005)
	rn_alb_imlt	Melting ice albdo	0.49	0.5	0.58	Perovich et al. (2002) and Brandt et al. (2005)
	rn_sal_gd	Restoring ice salinity, gravity drainage [g/kg]	4	5	7.5	Nakawo and Sinha (1981)
	jpl	Number of ice thickness categories	1	5	30	Massonnet et al. (2019)
Ocean	rn_avm0	Eddy viscosity [m2/s]	1.00E-05	1.20E-04	1.50E-04	Williamson et al. (2017)
	rn_avt0	Eddy diffusivity [m2/s]	1.00E-06	1.20E-05	1.50E-05	Williamson et al. (2017)
	rn_deds	Magnitude of the damping on salinity [mm/day]	-20	-166.67	-180	NEMO System Team (2022)
	rn_ce	Magnitude of the mixed layer eddy	0.04	0.06	0.1	NEMO System Team (2022)
Coupling	rn_cio	Ice-ocean drag coefficient	2.00E-03	5.00E-03	8.00E-03	Massonnet et al. (2014)
	Cd_ice	Air-ice drag coefficient	8.00E-04	1.40E-03	2.00E-03	Massonnet et al. (2014)

Reference

Lipscomb, W. H. (2001). Remapping the thickness distribution in sea ice models. Journal of Geophysical Research: Oceans, 106(C7), 13989-14000.

Line 332 change "ice category number" to "number of ice thickness categories"

Fixed.

Line 424: add "SIC" before "CDFs"

Since the full name of the "CDFs" here is "CDFs of the area integral of the res component in the spring SIC budget " but not the "SIC CDFs", we abbreviate this here as "CDFs", and the reader can easily see what this CDFs stands for from the figure caption of Fig. 11.

References

Notz D. 2014 Sea-ice extent and its trend provide limited metrics of model performance. Cryosphere 8, 229–243. (doi:10.5194/tc-8-229-2014)

Notz, D.: How well must climate models agree with observations?, Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 373, https://doi.org/10.1098/rsta.2014.0164, 2015.

Roach, L. A., Dörr J., Holmes, C. R., Massonnet, F., Blockley, E. W., Notz, D., Rackow, T., Raphael, M. N., O’Farrell, S. P., Bailey, D. A., and Bitz, C. M. (2020). Antarctic sea ice area in CMIP6. Geophysical Research Letters, 47, e2019GL086729. https://doi.org/10.1029/2019GL086729.