Response to the reviewers' comments

We thank the reviewers for the constructive comments which helped us to improve the manuscript. We have taken them into account in the revised manuscript. Detailed responses to the comments are given below each comment.

Reviewer 1:

Review comment on "Polar winter climate change: strong local effects from sea ice loss, widespread consequences from warming seas" by Naakka et al.

Summary:

This manuscript addresses the question how future changes in sea-ice cover and sea surface temperature impact the polar climate system in both the Arctic and Antarctic. For this purpose, four different atmospheric general circulation models are utilized to conduct sensitivity simulations with modified sea ice and sea surface temperature conditions (individually and combined). One outcome of the study is that changes in sea-ice cover dominate the climate impact locally in (formerly) ice covered regions, whereas sea surface temperature changes have more widespread effects on air temperature, sea level pressure and precipitation.

I think the study addresses a very relevant scientific question and provides novel approaches, in particular the combined and split sensitivity simulations to sea ice and sea surface temperature changes in both hemispheres. I found the description of the scientific methods, i.e. the experimental set-up and the database, to be clear and understandable, and the provided results support the authors conclusions. Overall, I think the study was conducted very thoroughly and provides interesting insights into a relevant scientific topic. However, I have some points that I think should be addressed before publication. This mostly concerns the discussion of the key results of the study in the context of existing literature, as well as some more technical remarks.

General Comments:

1.) Discussion of results: I like the description of the experimental set-up and the presentation of the results, however, it was challenging for me to find out in the end what exactly the key findings of this study are compared to the existing literature in the field. This specifically concerns the discussion of the results for the variables near surface temperature and precipitation. For changes in sea level pressure, the findings of the study are set into the context of existing literature between lines 410 and 417. I am missing similar sections for the near surface temperature and precipitation changes. For both parameters I only found one place each in the discussion section where references to existing literature were provided (line 397 and line 427, respectively). Particularly the first 3 paragraphs (lines 380-409) of the discussion section actually bring up a lot of new results/information by referencing a lot of new supplementary figures, maybe this part can be shortened (or shifted to the results section) to provide more room for setting the key findings of the study into the context of the literature.

Response:

We thank the reviewer for the suggestion. We modify manuscript according to reviewers' suggestions.

Changes in the manuscript:

We have moved the discussion about turbulent surface fluxes and their impact on the meteorological variables to the results section and added a comparison between our results and the results in existing literature in the discussion section. Especially, we compare our results with the new (published after we submitted our manuscript) article of Yu et al. 2024.

2.) Comparison of hemispheres: I think it is a nice feature of this study that both hemispheres are included, however, I am missing a summary about similarities or differences between both hemispheres. Without such a summary, I am wondering how useful it is to tackle both hemispheres within one single publication? I think Figure 3 (which I actually like a lot) is a bit of a wasted opportunity here, since it provides a nice summary on the (partly different) results of the model experiments for both hemispheres, but is only referred to very rarely throughout the manuscript (if I am correct it is not once referenced in the manuscript text for the Arctic).

Response:

We thank the reviewer for the suggestion. We modify manuscript according to reviewers' suggestions.

Changes in the manuscript:

We add a short section about similarities and differences between the hemispheres at the end of the result section. The results shown in Figure 3 is also discussed in the new section. In addition, figure 3 is more often referred in the results section when referring the figure is relevant.

3) Choice of the four (atmospheric) models: I think it is a nice feature of this study that sensitivity experiments are conducted with a (small) ensemble of models instead of one model only. However, I was missing an explanation why these particular four models were chosen for the study and a related discussion what uncertainties maybe come with the model selection.

Response:

The set of four models is, in practice, an ensemble of opportunity: these are the models with which we could do the experiments, given the expertise in the CRiceS consortium. In the consortium there was expertise in running these four models and also interest to further develop two of these models, namely NorESM2 and EC-Earth3. In fact, these four models belong to two model families so NorESM2 and CESM2 have the same dynamical core similarly as EC-Earth3 and OpenIFS and therefore it was interesting to compare, what/how large are differences between models belonging to different model families and models which have similar dynamical core but different parameterizations in some physical processes. The similarities and differences between these models are discussed in section 2.2. In addition, the motivation behind the model selection has been added in the beginning of the model description section and two sentences about effects of the number of models in the ensemble has been added in discussion.

Changes in the manuscript:

The text added in the beginning of the model description section: "Three ESMs (CESM2, NorESM2, and EC-Earth3) and one AGCM (OpenIFS) were used in the study. The selection of models allows us to compare differences between models belonging to the same as well as different model families. CESM2 and NorESM2 are based on the same dynamical core but differ for some parametrizations of physical processes. Similarly, EC-Earth3 and OpenIFS belong to the same model family. Our model selection also is affected by the fact the study is part of the CRiceS-project (Climate Relevant interactions and feedbacks: The key role of sea ice and Snow in the polar and global climate system) which aims to improve the description of polar atmospheric processes in ESMs, in particular NorESM2 and EC-Earth3."

The sentences added in the beginning of the model description section: "Our ensemble is produced by four models, which should capture a larger part of the internal climate variability compared to an ensemble generated by only one model. However, our ensemble only represents two model families meaning that the results are more dependent on each other than four completely independent models."

4.) More of a technical comment: In Figures 4-9 there are contour lines which are not explained in the caption, please add a description. Reading the manuscript text, though, I am wondering how useful these contours are anyway. A lot of the discussion seems to evolve around matches/mismatches between spatial patterns of changes in e.g. sea-ice cover and atmospheric variables. Would it maybe be more helpful to include the changes in sea-ice cover and sea surface temperature, respectively, as contour lines into the subplots of Figures 4-9 (instead of the current contours of I assume the basic state of air temperature etc.)? If you prefer to keep the information on the basic state in the figures, showing it only in one of the subplots (since it is always the same pattern anyway) might improve the visual clarity of the remaining figure panels.

Response:

Contour lines in the figures 4 – 9 presents baseline state of each variable and descriptions about the contours were added in the captions. Thanks for the suggestion to add SST and sea ice changes contours instead, but we prefer to keep the baseline state in the background.

Specific comments (line by line):

• Lines 256-257: "The warming over regions that originally had sea ice is predominantly driven by decreases in sea ice cover, whereas the warming over the continent and ice shelves is mainly caused by warmer SSTs". I think the finding that warming SSTs and not the sea-ice retreat drives the warming of the Antarctic continent is quite interesting and could be highlighted more! Either here or in the discussion/conclusions section.

Response:

We thank the reviewer for the suggestion. We modify manuscript according to reviewers' suggestions.

Changes in the manuscript:

We have added the following text in the discussion section: “In the inner Antarctic, the near surface warming is in particular strongly associated with the increase in SST as the decrease in sea ice cover causes small or even negative changes in 2m temperature over the inner continent, most likely due to a very weak advection of the near surface-air from the ocean to the inner continent.”

• Line 264: I think the formulation that “All models except NorESM2” indicate a negative change in sea level pressure is, even though technically correct, a bit misleading. Figure 3b shows that actually the sea level pressure change in the CESM2 model is close to zero (probably no significant signal?), so that in the end actually one model shows an increase, one does not show any change, and two models show a decrease…

Changes in the manuscript:

New version: “The models do not agree on the average change in MSLP (*Δ*MSLPfull) over the Antarctic region: NorESM2 shows a positive *Δ*MSLPfull on average, EC-Earth3 and OpenIFS show that the average *Δ*MSLPfull is negative, whereas the average *Δ*MSLPfull is small in CESM2 (Fig. 3b).”

• Line 296: Here it is referred to precipitation changes “between 90°E – 120°E”, but no longitude labels are included in the related Figure 6. This makes it a bit hard to find the region that is mentioned in the text…

Changes in the manuscript:

The description of the area has been modified. New version: “in the coastal areas between longitudes of the Indian Ocean side of the Antarctic (90°E - 120°E; right-hand side of the figure panels).”

• Lines 437-439: This conclusion is unclear to me. If SST and sea-ice changes contribute “about the same” to average warming >60° N/S, how does this imply that “a major part of the polar near-surface warming […] is a response to remote SST forcing”?

Changes in the manuscript:

The word “major” has been changed to “substantial” as we wanted to indicate that both the increase in SST and sea decrease in ice cover have important effects on the near surface warming in the polar regions.

Reviewer 2:

Review for “Polar winter climate change: strong local effects from sea ice loss, widespread consequences from warming seas” by Naakka et al.

Summary

This manuscript presents sea ice and SST experiments conducted with four global climate models to evaluate the effects of sea ice loss, SST warming, and their nonlinear (or residual) contributions. Key findings include: (1) Decreasing sea ice cover has a larger impact on precipitation and temperature changes in regions where sea ice is reduced, while SST warming dominates the response elsewhere. (2) Nonlinear contributions are relatively small. (3) There is significant inter-model variability in the magnitude and spatial distribution of mean sea level pressure (MSLP) responses. Additionally, the circulation responses from sea ice loss and SST warming can counteract each other in certain regions. Overall, the topic is interesting and the findings also align with previous studies. However, the authors should provide greater context by discussing relevant literature, particularly from PAMIP-related work, and clearly highlight the novelty of their contribution. A major revision is recommended.

General Comments

(1) My initial reaction to this manuscript is that the authors are aware of the Polar Amplification Model Intercomparison Project (PAMIP) experiments but chose not to leverage the available PAMIP datasets, which include more climate models and larger ensemble sizes (100 to 300 members). While the authors' modeling efforts are extensive, the novel insights gained from their experiments appear limited. The authors shared details on the difference of their experimental design from PAMIP protocol and I would encourage them to clarify more on what additional information they have found from these new experiments.

Response:

We thank the reviewer for this comment and agree that we could explain more clearly how our simulation design contributes to novel findings and different aims compared to PAMIP. Firstly, the choice of the four models was based on the available expertise within the CRiceS consortium – all four models are actively used by the authors of the manuscript. We already have follow-up manuscripts in review and in preparation, where we go into more details on differences in the model results and the reasons behind them. In general, the four models belong to two model families: NorESM2 and CESM2 have the same dynamical core while EC-Earth3 and OpenIFS are similar so that we can compare differences between models that are from the same model families but have different parameterizations for some physical processes. Based on the ongoing analysis, there will also be further development of in particular two of the models, namely NorESM2 and EC-Earth3. Our simulation setup was designed with these aims in mind. Secondly, we use simulated SSTs and sea ice conditions from one specific model (ACCES-ESM1.5) instead of a combination of observations and average conditions from a set of models (as in PAMIP). We believe this will give more consistency between our present-day and future simulations, and thus more straight-forward interpretability of the results. Thirdly, the changes of SST and sea ice in our experiments are much larger than in the PAMIP atmosphere-only simulations as the global average 2m temperature change associated with the changes in SST and sea ice in the ACCES-ESM1.5 model used in our experiments is 4.4 K, whereas the SST and sea ice forcing used in the PAMIP future simulation is taken from conditions where the global average 2m temperature increase from the preindustrial time is 2K.

Changes in the manuscript:

We revised the manuscript by adding a couple of sentences for motivation for running the experiments with these models in the beginning of section 2.2: “Three ESMs (CESM2, NorESM2, and EC-Earth3) and one AGCM (OpenIFS) were used in the study. The selection of models allows us to compare differences between models belonging to the same as well as different model families. CESM2 and NorESM2 are based on the same dynamical core but differ for some parametrizations of physical processes. Similarly, EC-Earth3 and OpenIFS belong to the same model family. Our model selection also is affected by the fact the study is part of the CRiceS-project (Climate Relevant interactions and feedbacks: The key role of sea ice and Snow in the polar and global climate system) which aims to improve the description of polar atmospheric processes in ESMs, in particular NorESM2 and EC-Earth3.” and modifying the paragraph about differences between our experiments and PAMIP experiments which now highlights stronger warming in our simulation than in PAMIP simulations. The new version of the paragraph: “Note that our experimental setup is different to e.g. the Polar Amplification Model Intercomparison Project (PAMIP, Smith et al., 2019). In the PAMIP experiments, mostly short (1 year) simulations were performed with large ensembles of initial states, whereas our experiments consist of long (40 years) simulations. The PAMIP simulations address pre-industrial, present-day and future climates, whereas our simulations focus only on differences between present-day and future climates. The changes in sea ice cover and SSTs were also substantially larger in our experiments than in the PAMIP atmosphere-only simulations. In ACCESS-ESM1.5 i.e. the model we use for the SST and sea ice forcing fields, the global average increase in 2m temperature between the baseline and future period (using the SSP 5-8.5 scenario) is 4.4 K, whereas the warming in the PAMIP simulations warming is approximately 2 K comparing future and pre-industrial conditions. In our future simulations, the Arctic Ocean is almost ice-free during the whole year (Fig. 1), which helps to boost the signal-to-noise ratio of the simulated climate responses. Another difference compared to the PAMIP experiments is that our forcing fields are only based on output from one model (ACCESS-ESM1.5) whereas PAMIP uses a combination of observations and multi-model averages.”

(2) Partly related to the first comment, many of the findings presented in this manuscript have already been explored in the context of PAMIP experiments. For instance, the impacts of sea ice loss and SST warming on atmospheric circulation, as well as the role of nonlinearity, have been examined by Yu et al. (2024) using PAMIP data. The authors should explicitly highlight the novel aspects of their findings to distinguish their work from existing studies and demonstrate its unique contribution.

Response:

Thanks for pointing out the paper by Yu et al. 2024. When we wrote our manuscript, the paper of Yu et al. 2024 had not been published (our manuscript was submitted in November 2024) and therefore we were not aware of their results. We have added a comparison between our results and the ones by Yu et al. 2024 in the discussion section. One key novelty of our work is that in contrast to many previous studies is that, our study addresses both the southern and northern polar regions.

Changes in the manuscript:

We have added a comparison between our results and the ones by Yu et al. 2024 in the discussion section, and we have added the section where we compare the Arctic and Antarctic in results section.

(3) PAMIP recommends using ensemble sizes of at least 100 members, which has been shown to be barely sufficient for capturing the atmospheric circulation response (e.g., Peings et al. 2021; Sun et al. 2022). In contrast, the authors' simulations are based on a 40-year mean, which could be significantly influenced by internal variability. This could complicate model comparisons and potentially explain the disagreement in regional MSLP patterns, as seen in Fig. 3 and other spatial maps. The authors should address the limitations associated with their smaller ensemble size and clarify how they account for internal variability.

Response:

While we agree that internal variability is a substantial source of uncertainty (especially for atmospheric circulation (e.g. MSLP) as discussed below), two factors help to boost the signal-to-noise ratio of the climate responses in our work.

- First, the global average increase in 2 m temperature between the baseline and future (using the SSP5-8.5 scenario) periods in ACCESS-ESM1.5, from which the SST and sea ice forcing were taken, is 4.4 K, whereas in PAMIP simulations, the warming between pre-industrial and future conditions is approximately 2 K. The strong warming in our experimental setup leads to large changes in thermodynamic meteorological variables such as 2m temperature and precipitation, and likely also acts to strengthen the changes in the circulation, even if a linear increase of the circulation response with global-mean warming is not necessarily expected.
- Second, much of our analysis focuses on multi-model means, which are computed based on 4 (models) times 40 (years) = 160 years. Thus the ensemble-size used for calculating multi-model means is over 100 members and comparable with ensemble sizes of the PAMIP experiment.

We compared the results of the four models against each other to evaluate the robustness of our conclusions. The comparison shows that, in spite of model differences and internal variability, we generally obtain the same conclusion by analyzing each model individually. The differences between models are discussed in the manuscript and in the revised version we highlight that the differences between models provide an indication of the uncertainty in our results. In the discussion section, we also highlight that the internal variability of modelled climate states plays a large role in interpreting circulation responses to changes in SST and, in particular, sea ice cover. Peings et al. (2021) showed that even a 100-member ensemble is not able to capture the whole internal variability of a single model. Therefore our 4 model times 40 years ensemble is probably not able to capture the whole internal variability associated with dynamical variables, such as MSLP, which further increases the uncertainty associated with the MSLP responses.

Changes in the manuscript:

We have added the following text in discussion section: “It is worth noting, however, that the models in our study do not agree on the direction of the MSLP response over the northern Atlantic, meaning that there is a large uncertainty. Furthermore, in particular over the northern Atlantic, warmer SSTs generally produce a larger MSLP response than a decrease in sea ice cover in our simulations. Our multi-model mean results are produced from a 4 model×40 years ensemble. Despite the many years of simulation this may not be enough to capture the entire internal variability associated with dynamical variables such as MSLP, in particular in terms of their response to sea ice cover changes (Peings et al. 2021 and Sun et al. 2022). Our ensemble is produced by four models, which should capture a larger part of the internal climate variability compared to an ensemble generated by only one model. However, our ensemble only represents two model families meaning that the results are more dependent on each other than four completely independent models.”

Minor Comments

Lines 91-92: The statement, “In addition, the PAMIP experiments were designed to study causes and consequences of Arctic amplification in present-day climate, while our simulation setup is aimed at a future warmer climate,” is incorrect. PAMIP includes preindustrial, present-day, and future experiments. Please revise for accuracy.

Response:

This is corrected in the manuscript. See the response to reviewer’s 2 1st general comment.

Lines 92-95: The description, “Furthermore, we examined the multi-model response to changes in prescribed SSTs and sea ice cover without any influence from model-specific differences in these variables…” is somewhat confusing. It is unclear how these experiments differ from PAMIP aside from using a larger forcing scenario (2080-2099 versus ~2040-2060 for 2°C warming). Please clarify.

Response:

We have clarified the description of differences between PAMIP experiments and our experiments. The new version, see response to reviewer's 2 1st general comment

Figure 8 and Associated Descriptions: The atmospheric circulation response to Arctic sea ice loss and SST in this study appears different from the PAMIP experiments, as shown by Yu et al. (2024). Specifically, the lack of a negative NAO-like pattern over the North Atlantic-Eurasian region warrants an explanation. Could this discrepancy be due to differences in experimental design or internal variability?

Response:

Based on our results, there is a notable uncertainty associated with the MSLP changes in the Northern Atlantic as the models disagree on the direction of the response. We have added a comparison between our findings and the results of Yu et al. (2024) in the discussion section: In particular, in the North Atlantic, an increase in SSTs causes the opposite response in MSLP compared to a sea ice decrease. Yu et al. 2024 showed that a decrease in sea ice caused a weakening of the Icelandic low and southward shift of the Atlantic storm track and that increased SSTs caused a strengthening and northward shift of Atlantic storm track. Our results are consistent with Yu et al. 2024 in that they also show a decrease in MSLP due to warmer SSTs in the Northern Atlantic region leading to an overall decrease in MSLP when both sea-ice cover and SST changes are considered. However, in our study, the pattern of MSLP changes is different than in Yu et al. (2024). In general, there is a large uncertainty associated with the MSLP changes in our study as the models do not agree on the direction of the MSLP change in the Northern Atlantic.

Changes in the manuscript:

We have added discussion about internal variability in discussion section See the response to reviewer's 2 3rd general comment.

References:

Peings, Y., Labe, Z. M., & Magnusdottir, G. (2021). Are 100 ensemble members enough to capture the remote atmospheric response to +2°C Arctic sea ice loss? Journal of Climate, 34(10), 3751–3769. https://doi.org/10.1175/jcli-d-20-0613.1

Sun, L., Deser, C., Simpson, I., & Sigmond, M. (2022). Uncertainty in the winter tropospheric response to Arctic Sea ice loss: The role of stratospheric polar vortex internal variability. Journal of Climate, 35(10), 3109–3130. https://doi.org/10.1175/jcli-d-21-0543.1

Yu, H., J. A. Screen, M. Xu, S. Hay, and J. L. Catto, 2024: Comparing the Atmospheric Responses to Reduced Arctic Sea Ice, a Warmer Ocean, and Increased CO2 and Their Contributions to Projected Change at 2°C Global Warming. J. Climate, 37, 6367–6380, https://doi.org/10.1175/JCLI-D-24-0104.1