Responses to reviewer's comments for "Contribution of meridional overturning circulation and sea-ice changes to large-scale temperature asymmetries in CMIP6 overshoot scenarios"

Reviewer 1:

We are grateful to the reviewer for the comments and suggestions, all of which have been helpful for improving the manuscript. We answer to each of the comments below, providing in gray the comments from the review and in black our responses.

Review of 'Contribution of meridional overturning circulation and sea -ice changes ot large-scale temperature asymmetries in CMIP6 overshoot scenarios'. By Roldán-Gómez
An analysis is conducted three different overshoot scenarios from 13 different coupled models. The focus is determining the spatial patterns of SST anomalies that emerge in the overshoot period. They find different spatial patterns emerge depending on whether there are large changes in the AMOC or sea-ice. The AMOC influence is greater when there is a larger reduction in NA mixed layer. This happens when the models have a larger climatological MLD to start with. These findings are in the main well-reasoned and the work should make a useful contribution to the literature. It is noted that the paper represents a considerable amount of analysis across multiple models to reach these conclusions. Indeed, aside of minor specific comments, my main general comment is that the authors need to make a greater effort to distil the research (and in particularly the number of figure panels) into that which is necessary to reach these conclusions.

<u>R1C1</u>
General Comments
A greater effort should be made to distil the research into that which is necessary to convince the reader of their conclusions. In particular, there is an overabundance of figures.
Although only 15 figures, this is made up of over 140 figure panels. I would encourage the authors to aggressively cull this number. There are a number of ways to evaluate if they are all necessary. Some of the plots contain linear regression, many of these could be probably best summarized by a table of the correlation values (and if they are significant or not). Furthermore, the authors may want to consider if they need to include results from all the scenarios. In particularly do the additional insights obtained from SSP1-1.9 warrant its inclusion.

Considering this comment, we have removed the following panels and the associated references in the text:
- Figure 2d, providing results consistent with those from Roldán-Gómez et al. (2025)
- Figure 5c-d, providing similar results to Fig. 5a-b
- Figure 6, since the link between OHT, AMOC and MLD is already illustrated in Fig. 8 and Fig. 11
- Figure 8c-d, providing relationship between AMOC and OHT
- Figure 9c-f, not discussed in the text
- Figure 11a-b, providing consistent results with those from Fig. 11g-h
- Figure 12f, 13f, 14f and 15f, not relevant for the discussion

Even if the results may be similar to those of SSP5-3.4OS, we still consider that the results for SSP1-1.9 are relevant, since this experiment includes more models and simulations than SSP5-3.4OS, and allows for a more complete assessment of model discrepancies. In addition, it also allows for assessing the role of internal variability, since it contains large ensembles of simulations, like those from CanESM5, MIROC6 and MPI-ESM1-2-LR.

For the figures with regressions, as discussed in the answer to R1C22, the multi-model regression is important, but it is not the only information provided by these figures. The behavior of each individual model is also interesting, and would be lost if the figures are replaced by tables with regression coefficients.

R1C2

Further Points
Abstract
Line 8: In the abstract. Candidate mechanisms are listed: 'Changes in the sea ice, changes in the ocean circulation and heat transport, and thermal inertia of the ocean have been identified as potential sources of hysteresis '. It would be helpful when listing these to enumerate these and when listing them elsewhere in the manuscript, to use consistent terminology. (For example, later in the manuscript 'AMOC' is used rather than 'ocean circulation and heat transport '). This will help the reader relate the analysis in the manuscript with the abstract. For example, the term 'Thermal inertia' is not mentioned in the manuscript beyond the introduction.

We have replaced "Changes in the sea ice, changes in the ocean circulation and heat transport, and thermal inertia of the ocean" by "Changes in the sea ice, the Atlantic Ocean Heat Transport (OHT) and the Atlantic Meridional Overturning Circulation (AMOC),", and have kept them elsewhere to use consistent terminology in the abstract and in the rest of the manuscript. We have removed the mention to thermal inertia, as it has not been addressed in our analyses.

R1C3

Line 30. A figure illustrating the time series of CO2 concentration in two scenarios, would help the initiated.

Time series of CO_2 concentration for the two scenarios are included in Fig. 2a-b (yellow curves).

R1C4

Line 65. In light of the range of processes mentioned in the existing literature (line 40-44) why have the authors decided to focus on the "ocean dynamics and sea-ice changes"?

The work has been focused on the ocean dynamics and sea ice changes because of the large uncertainties existing for these two factors, as detailed in the introduction: "However, there are large uncertainties in these changes, with responses of the AMOC to forcing changes that strongly depend on the model considered (Sgubin et al., 2017)."

We have added a clarification on this: "This work analyzes overshoot scenarios from CMIP6

(SSP5-3.4OS and SSP1-1.9) to better understand why models present a different level of irreversibility in ocean dynamics and sea ice changes, and how this translates into the emergence of different large-scale temperature asymmetries in the post-overshoot climate."

R1C5

Yes, all the available simulations for all the CMIP6 experiments including overshoot (SSP5-3.4OS and SSP1-1.9) were considered in the analysis.

We have added a clarification on this: "The analyses are based on all the available simulations of CMIP6 overshoot experiments SSP5-3.4OS and SSP1-1.9, listed in Table 1"

As discussed in the answer to R1C1, we still consider that the results for SSP1-1.9 are relevant, since this experiment includes more models and simulations than SSP5-3.4OS, and allows for a more complete assessment of model discrepancies. In addition, it allows for assessing the role of internal variability, since, unlike SSP5-3.4OS, it contains large ensembles of simulations, like those from CanESM5, MIROC6 and MPI-ESM1-2-LR.

R1C6

We have clarified the definition of post-overshoot period in that paragraph: "The post-overshoot state is defined as a 20-year period after stabilization for SSP5-3.4OS EXT (from 2220 and 2239) and as the last 20 years of simulations for the SSP1-1.9 and the SSP5-3.4OS ALL ensemble (from 2080 to 2099)"

R1C7

As stated in the answer to R1C4, these mechanisms have been selected because there are known discrepancies among the models.

We have added a clarification on this: "In a second step, some mechanisms and processes potentially contributing to these temperature asymmetries are explored. Considering the large model differences existing for these variables (Sgubin et al., 2017), the analyses are focused on the global, Atlantic and Pacific OHT, the Atlantic mass transport, the sea ice concentration, and the Mixed Layer Depth (MLD) provided by the models."

R1C8

We have more specifically pointed out in the text to the relevant time series, instead of to the whole figures, as follows:

- "For example, for the extended simulation of MRI-ESM2-0 in SSP5-3.4OS (gold line in Fig. 2a) and for the ensemble average of MIROC6 (brown line in Fig. 2b), MIROC-ES2L (orange line in Fig. 2b), MPI-ESM1-2-LR (dark grey line in Fig. 2b), and MRI-ESM2-0 (gold line in Fig. 2b) in SSP1-1.9, the global average of SST after overshoot is lower than that of before."

- "For example, the simulations with MRI-ESM2-0 show a EN-ES asymmetry larger than 2ºC at the end of SSP5-3.4OS (year 2300; gold line in Fig. 3a) and close to 0.3ºC at the end of SSP1-1.9 (year 2100; gold line in Fig. 3b), while for other simulations like those with IPSL-CM6A-LR (purple line in Fig. 3a,b) this asymmetry is not clearly found."

- "this is only found for some simulations like those from MRI-ESM2-0 and IPSL-CM6A-LR (gold and purple lines in Fig. 3c,d), while some others like those from CNRM-ESM2-1 (dark orange line in Fig. 3c) or MIROC-ES2L (orange line in Fig. 3d) do not show a clear asymmetry. Less discrepancies exist for the SSW-SSE asymmetry (Fig. 3e,f), for which most model simulations show colder temperatures in the western sector after the overshoot, even if some particular simulations like those from EC-Earth3 show comparable temperatures in both regions (turquoise line in Fig. 3f)."

- "As for the case of temperatures, the temporal evolution of OHT for individual models (Fig. 5) highlights a strong inter-model dispersion. MRI-ESM2-0 shows a strong decrease of Atlantic OHT (gold line in Fig. 5a,b), while other models like CanESM5 and IPSL-CM6A-LR (blue and purple lines in Fig. 5a,b) show a more limited decrease. In the Southern Ocean, some models like CNRM-ESM2-1 (dark orange line in Fig. 5c) and IPSL-CM6A-LR (purple line in Fig. 5c,d) show a relevant strengthening of the northward OHT at the end of the run, while others like MRI-ESM2-0 (gold line in Fig. 5c,d) do not show relevant changes with respect to the pre-overshoot state."

- "As shown in Fig. 6a,c, the average of the SSP5-3.4OS EXT ensemble (gray line) shows a larger sea ice area in the NH and a smaller sea ice area in the SH after overshoot, but this mean response is dominated by the simulations from MRI-ESM2-0 (gold line in Fig. 6a,c), to a lesser extent, CNRM-ESM2-1 (dark orange line in Fig. 6a,c)"

As for the answer to comment R1C1, we have removed Figure 6. Figure 7 would then become Figure 6.

R1C9

Line 121. 'After the stabilization'. Stabilization of what. Could the authors refer to specific years.

In this context, "after the stabilization" means when the global temperature is already stabilized. This happens at a different time depending on the model and on the experiment.

To avoid any misunderstanding, we have replaced "After the stabilization" by "At the end of the simulations (2300 for the extended simulations of SSP5-3.4OS and 2100 for the others)".

R1C10

As stated in the text, it refers to "larger than the expected value considering the situation before the overshoot with the same global average of surface air temperature (horizontal brown line) or the situation before the overshoot with the same CO_2 concentration (horizontal yellow line)"

We have added the exact years in the text and to avoid the term "expected": "is larger than that of the situation before the overshoot with the same global average of surface air temperature (horizontal brown line; reached in 2034 for SSP5-3.4OS and in 2030 for SSP1-1.9) or the situation before the overshoot with the same CO_2 concentration (horizontal yellow line; reached in 2015 both for SSP5-3.4OS and SSP1-1.9)"

R1C11

Yes, this is true. The comment was mostly refering to the relative value of MRI with respect to the other models. For both experiments, at the end of the run the simulations from MRI show the largest changes. But indeed, when comparing both experiments, the changes are much more relevant for SSP5-3.4OS, which extend much further in time.

We have reworded the sentence as: "The comparison of different models (Fig. 3) for indices that represent the aforementioned asymmetries reveals that these asymmetries are not equally present in all models. For example, the simulations with MRI-ESM2-0 show a EN-ES asymmetry larger than 2ºC at the end of SSP5-3.4OS (year 2300; gold line in Fig. 3a) and close to 0.3ºC at the end of SSP1-1.9 (year 2100; gold line in Fig. 3b), while for other simulations like those with IPSL-CM6A-LR (purple line in Fig. 3a,b) this asymmetry is not clearly found."

R1C12

We have included the magnitude of the asymmetry and the time at which this can be seen (end of simulations): "The comparison of different models (Fig. 3) for indices that represent the aforementioned asymmetries reveals that these asymmetries are not equally present in all models. For example, the simulations with MRI-ESM2-0 show a EN-ES asymmetry larger than 2ºC at the end of SSP5-3.4OS (year 2300; gold line in Fig. 3a) and close to 0.3ºC at the end of SSP1-1.9 (year 2100; gold line in Fig. 3b), while for other simulations like those with IPSL-CM6A-LR (purple line

in Fig. 3a,b) this asymmetry is not clearly found."

R1C13

3.1 Line 150-156. What does the variety in the results reveal?

As discussed in section 4, the different temperature asymmetries shown by the models are indicative of a different representation of ocean dynamics and sea ice mechanisms in the models. Some models like MRI-ESM2-0 show strong alterations of the AMOC, some models like CNRM-ESM2-1 highlight persistent changes in the sea ice, and some others like IPSL-CM6A-LR and CanESM5 simulate a relevant impact of the SMOC. These discrepancies between models can be associated with different climatological values for the MLD in the Subpolar North Atlantic region and in the Southern Ocean depending on the model. Models showing the largest climatological MLD also allow larger MLD decreases, producing a stronger AMOC slowdown, and then a larger hysteresis in the meridional overturning during the overshoot.

It is preferred to keep this discussion in section 4, and keep section 3.1 only for the presentation of temperature results.

R1C14

Line 173. SO higher mean values of OHT are found in SSP5-3.4OS-ALL (middle panel) but not SSP5-3.4OS EXT (left) or SSP1-1.9 ALL (right)

Right, this is a mistake. We have corrected this as: "In the Southern Ocean, higher values of northward OHT are found on average between 60ºS and 30ºS for the SSP5-3.4OS ALL ensemble (Fig. 4a, center), but this is not the case for the SSP1-1.9 ALL ensemble (Fig. 4a, right) and the SSP5-3.4OS EXT ensemble (Fig. 4a, left)". Thank you for noticing this.

R1C15

Line 175. 'Some models like MRI-ES2.0'. The wording of this sentence is a little strange as figure Fig. 5 abcd show that MRI-ES2 is an outlier, i.e. there are no other models like it.

The wording has been changed to: "MRI-ESM2-0 shows a strong decrease of Atlantic OHT (gold line in Fig. 5a,b), while other models like CanESM5 and IPSL-CM6A-LR (blue and purple lines in Fig. 5a,b) show a more limited decrease."

R1C16

Line 177. 'moderate strengthening of OHT in SO in Fig 5ef'. Could the authors specify the post-overshoot years in which OHT is moderately strengthened.

It refers to the end of the simulations with respect to the pre-overshoot period with the same CO_2 concentration.

To avoid any ambiguity, we have reworded the sentence as: "In the Southern Ocean, some models like CNRM-ESM2-1 (dark orange line in Fig. 5c) and IPSL-CM6A-LR (purple line in Fig. 5c,d)

show a relevant strengthening of the northward OHT at the end of the run, while others like MRI-ESM2-0 (gold line in Fig. 5c,d) do not show relevant changes with respect to the pre-overshoot state.

R1C17

Indeed, the IPSL shows a behavior for the WS MLD very different from the other models. But this result is still relevant, since this shows that a model with strong changes in the WS MLD may also show strong changes in the OHT at 50ºS during the overshoot.

R1C18
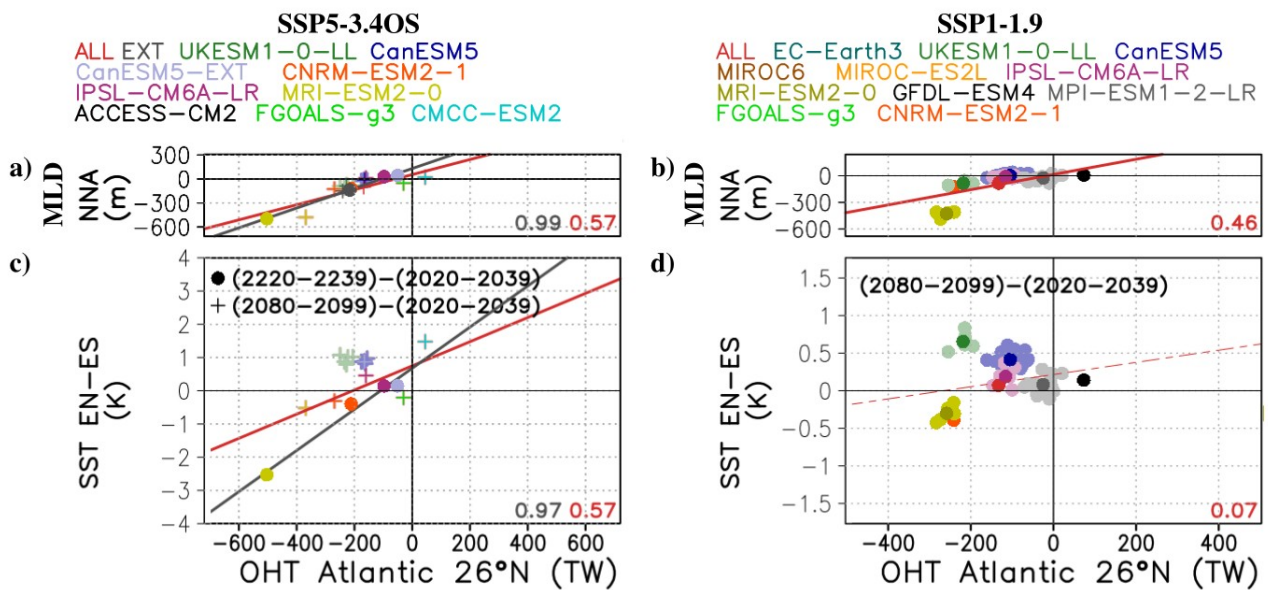
We have thickened the solid lines in Fig. 8, 9, 10 and 11 (new 7, 8, 9 and 10). To improve the readability of the figures, we have also replaced dotted lines by long-dashed lines.
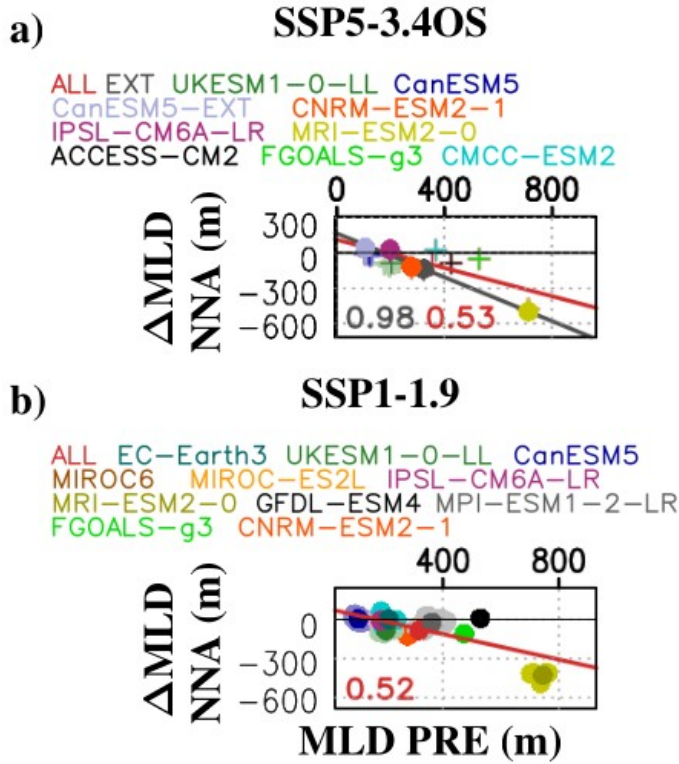
Panels c-d have been removed from Fig. 8 (new 7), since the relationship between AMOC and OHT is well established.
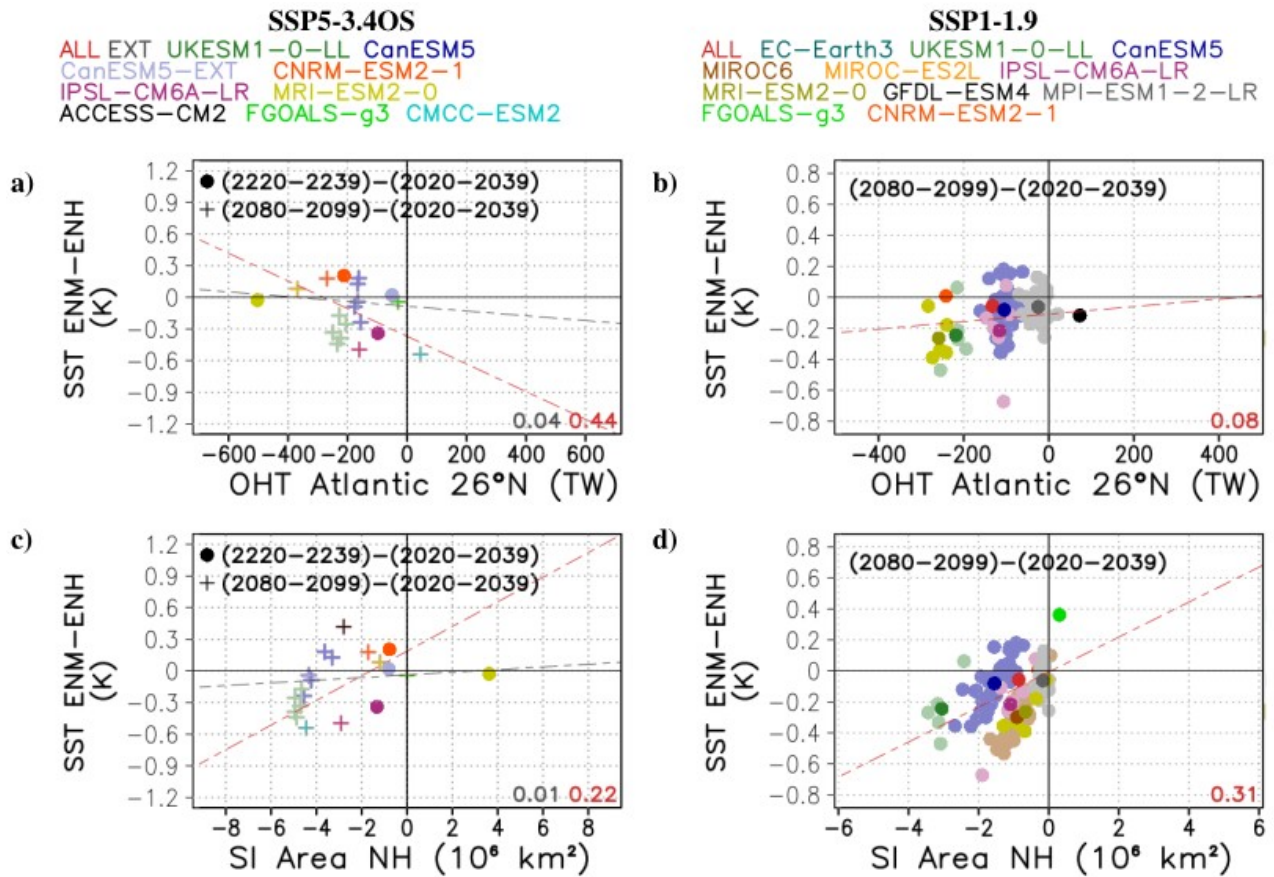
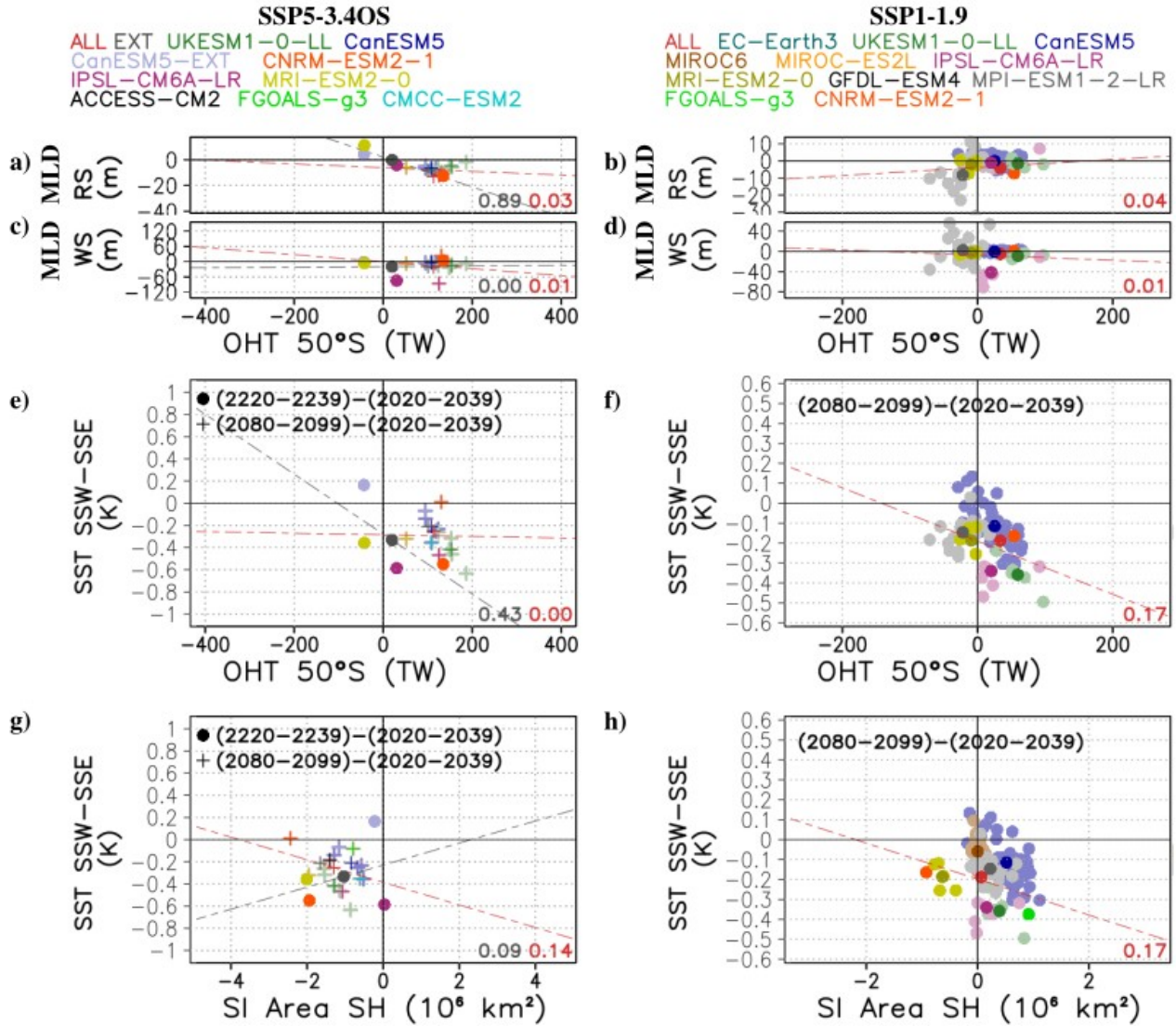The new figures would be then as follows:

New Fig. 7:

New Fig. 8:

New Fig. 9:

New Fig. 10:

SSP5-3.4OS

ALL EXT UKESM1-0-LL CanESM5
CanESM5-EXT CNRM-ESM2-1
IPSL-CM6A-LR MRI-ESM2-0
ACCESS-CM2 FGOALS-g3 CMCC-ESM2

SSP1-1.9

ALL EC-Earth3 UKESM1-0-LL CanESM5
MIROC6 MIROC-ES2L IPSL-CM6A-LR
MRI-ESM2-0 GFDL-ESM4 MPI-ESM1-2-LR
FGOALS-g3 CNRM-ESM2-1

Line 199. Suggest 'Figure 8e and f) shows…'. The description of Figure 8 is not quite correct. EN-ES is only related to OHT. AMOC and MLD are related to OHT not to EN-ES SST. It might be more useful to have EN-ES vs OHT and EN-ES vs MLD.

We decided to use the OHT as pivot for the comparisons, since the OHT can be directly linked on one side to the EN-ES (changes in the heat transport physically relate to changes in temperature) and on the other side to the MLD (changes in the MLD may impact the AMOC, and then the OHT). Even if the links between EN-ES and OHT and between OHT and MLD indirectly imply a link between EN-ES and MLD, directly presenting EN-ES vs MLD may mask the physical process explaining the relationship between these two variables.

We have reworded the sentence as "Figure 7c,d shows how the EN-ES temperature asymmetry — as characterized by the difference between the post-overshoot (2220-2239 and 2080-2099) and pre-overshoot (2020-2039) states — in individual simulations and their ensemble mean relate to changes in Atlantic OHT at 26ºN."

The link between OHT and AMOC and MLD in NNA is commented later on in the paragraph: "The relationship between Atlantic OHT at 26ºN and the MLD in NNA (Fig. 7a,b) is almost linear, with significant correlations of 0.99 for SSP5-3.4OS EXT (Fig. 7a) and 0.46 for SSP1-1.9 ALL (Fig. 7b)"

R1C20

Fig 8f) What is the physical explanation for the lack of correlation between EN-ES SST and OHT in SSP1.1.9?

Looking at Fig. 3b, the EN-ES SST at the end of the SSP1-1.9 simulations does not seem fully stabilized, which suggests that they are still in a transient part of the post-overshoot state. Very likely this is the reason why the correlations between EN-ES SST and OHT are not emerging. If we focus for example on the simulations of MRI (with strong OHT and strong EN-ES SST in the SSP5-3.4OS experiment) we see that for SSP1-1.9 the EN-ES SST is still decreasing at the end of the run.

R1C21

There is no reference in text to Figure 9 c through f). I suggest these panels are removed.

As suggested, we have removed the panels c to f, and keep only the panels a and b.

R1C22

Line 215. 'The contribution of sea ice change seems more important'. Don't the dashed lines in Figure 10 indicate the contribution of sea-ice change is insignificant? I suggest the references to the influence of sea-ice are removed.

The dashed lines in the figure indicate that there is no significant correlation between sea ice area changes and ENM-ENH SST when considering all the models. However, when looking at the ensembles of individual models (e.g. SSP1-1.9 simulations of CanESM or MIROC6), those simulations with the largest changes in sea ice are also those showing the largest temperature asymmetry.

This has been discussed in section 4: "The contribution of each mechanism may also depend on the individual simulation of a given model, suggesting a relevant role of internal variability. This is found for example in Fig. 9d, in which different ensemble members of CanESM5 and MIROC6 show a different relative contribution of NH sea ice changes to the ENM-ENH asymmetry"

To avoid misunderstanding, we have reworded the sentence as: "The ENM-ENH temperature asymmetry cannot be clearly linked to changes in the Atlantic OHT (Fig. 9a,b). A certain contribution of sea ice changes (Fig. 9c,d) is found for some of the models. Indeed, in models like UKESM1-0-LL, CMCC-ESM2, IPSL-CM6A-LR, CanESM5 and MIROC6 the individual simulations with a larger decline in the NH sea ice area after the overshoot, show the strongest ENM-ENH asymmetry for those models."

As discussed in the answer to R1C22, the significance test shows that the relationship between sea ice changes and ENM-ENH asymmetry is not consistently found for all the models, but this does not prevent the changes in the sea ice to be relevant for certain models. This is for example the case for IPSL-CM6A-LR, CanESM5 and MIROC6.

This is discussed in the text: " Despite this consistent behavior, the R2 coefficients when considering ensemble averages are small, with only 0.22 for SSP5-3.4OS ALL (Fig. 10c) and 0.31 for SSP1-1.9 ALL (Fig. 10d), evidencing important differences across the models."

To avoid misunderstanding, we have removed "Unlike for the ENM-ENH asymmetry" from that sentence.

Reviewer 2:

We are grateful to the reviewer for the comments and suggestions, all of which have been helpful for improving the manuscript. We answer to each of the comments below, providing in gray the comments from the review and in black our responses.

Review of the manuscript: "Contribution of meridional overturning circulation and sea ice changes to large-scale temperature asymmetries in CMIP6 overshoot scenarios"
The manuscript, "Contribution of meridional overturning circulation and sea ice changes to large-scale temperature asymmetries in CMIP6 overshoot scenarios" by Pedro José Roldán-Gómez et al., presents an insightful investigation into the interplay between the Atlantic Meridional Overturning Circulation (AMOC), sea ice dynamics, and temperature patterns under overshoot climate scenarios. By analyzing a variety of CMIP6 models and focusing on different ensemble and temporal configurations, the study provides a nuanced understanding of the mechanisms shaping global and regional temperature asymmetries. I find the study extremely relevant for advancing our understanding of climate system responses to transient forcing. The use of multiple models and ensemble approaches enhances the robustness of the findings. The study is very valuable to the climate modeling and policy-making communities. However, I recommend a major revision, primarily due to issues with length, and figure overload that currently hinder the readability and accessibility of the results. I believe it requires significant revisions to enhance clarity, organization, and conciseness. Below, I outline both general and specific suggestions for improving the manuscript. I believe that, with a more concise and structured presentation, the manuscript could make a strong contribution to the literature on overshoot scenarios and climate feedback mechanisms.

R2C1

General Comments:

The "Results" section could benefit from clarification and reorganization. It is hard to read, as the authors compare multiple dimensions simultaneously: scenarios (SSP5-3.4OS and SSP1-1.9), pre- and post-overshoot periods, global averages and regional differences, EXT and ALL ensembles. It contains 13 figures, made of several plots and maps, which are overloading the manuscript. I suggest selecting the most relevant figures, increase their quality and illustrate the inter model results description in a more efficient and concise way.

We have reorganized the "Results" section as follows:

- Remove those figures that are not needed for the discussion, as indicated in the answers to R1C1, R2C16, R2C18 and R2C22.
- Better describe the pre- and post-overshoot periods, as indicated in the answers to R1C6 and R2C13.
- Move sea ice results to a dedicated subsection, as requested in comment R2C21.
- Move spatial patterns of individual models to Appendix B, as requested in comment R2C16.
- Re-organise the sections as: "Temperature changes", "Meridional overturning circulation changes", "Sea ice changes" and "Contributions to temperature changes across different models", as explained in the response to comment R2C15.

R2C2
Specific Comments:
Abstract:
Line 7: add a comma after "through it"

To address comment R2C4, we have done a reorganisation of the abstract, in which this comment is no longer applicable.

R2C3
Line 8: Remove one instance of "changes in"

The sentence has been reworded to address the comment R1C2 as: "Changes in the sea ice, the Atlantic Ocean Heat Transport (OHT) and the Atlantic Meridional Overturning Circulation (AMOC),"

R2C4
Line 10: The sentence beginning with "This work analyzes…" should be the first sentence of the abstract, describing the method before the results. Also, specify how many models are considered.

As requested, we have moved the sentence to the beginning of the abstract, with some slight rephrasing that now includes the number of models: "This work analyzes overshoot simulations from 13 models, including the SSP5-3.4OS and SSP1-1.9 experiments from the Coupled Model Intercomparison Project Phase 6 (CMIP6), to assess how regional temperatures after overshoot

differ from those of before, and how these differences may be impacted by changes in the sea ice and ocean circulation, including the Atlantic Ocean Heat Transport (OHT) and the Atlantic Meridional Overturning Circulation (AMOC). The overshoot scenarios, characterized by…"

The final part of the abstract has been adapted accordingly: "Changes in the sea ice and ocean circulation have been identified as potential sources of hysteresis, highlighting the impact of oceanic changes in the behavior of atmospheric variables in case of overshoot. The analyses from this work show that the relative contribution of each mechanism strongly depends on the model. Inter-model differences in the contributions of the meridional overturning can be associated with different climatologies of Mixed Layer Depth (MLD) in the northern North Atlantic (NNA) and in certain areas of the Southern Ocean. Despite these differences across models, both ocean circulation and sea ice changes contribute to shaping the regional temperatures after overshoot."

R2C5
Line 13-18: Mechanisms are described for only three models; this is too detailed for the abstract. The abstract also needs to be shortened — please remove these lines.

As suggested, we have removed the following sentence: "Certain models like MRI-ESM2-0 are mainly impacted by changes in the Atlantic Meridional Overturning Circulation (AMOC), others like CNRM-ESM2-1 show a relevant impact of sea ice changes in high-latitude areas, and others like IPSL-CM6A-LR show also a relevant impact of changes in the Southern Meridional Overturning Circulation (SMOC)."

R2C6
Introduction:
Line 1 and 3: The verb "increase" is used twice — consider rephrasing to avoid repetition.

We have rephrased as: "The growing probability of exceeding the temperature targets of the Paris Agreement of 2015 (Raftery et al., 2017), as a result of delays in implementing effective mitigation measures (IPCC, 2022), increases the likelihood of overshoot scenarios"

R2C7
Line 27: "is recovered" please rephrase to clarify

We have replaced "is recovered afterwards with net-negative emissions" by "is reduced to the target afterwards with net-negative emissions"

R2C8
Line 33: Please describe what "OS" in SSP5-3OS stands for. Also introduce "SSP"

We have included the meaning of OS and SSP, as: "Considering the increasing interest in these overshoots, the Coupled Model Intercomparison Project Phase 6 (CMIP6; Eyring et al., 2016) included in the ScenarioMIP (O'Neill et al., 2016) two scenarios with Shared Socio-economic Pathways (SSP) that reach a peak before starting a forcing decline: SSP5-3.4OS and SSP1-1.9. Both

of these represent Overshoot Scenarios (OS), but at different forcing levels."

R2C9

We have added the reference as follows: "In global warming conditions, a decrease of OHT is generally found (Mecking and Drijfhout, 2023), both in the NH and in the SH, but models disagree on the presence of tipping points, with only some models showing a local convection collapse in the subpolar North Atlantic, and only a few of them presenting a full AMOC disruption (Sgubin et al., 2017). Changes in the AMOC also depend on the emission scenario and the associated loss of sea ice (van Westen and Baatsen, 2025). A collapse of the AMOC may have important impacts at a global scale (Orihuela-Pinto et al., 2022), stressing the need to understand in which conditions it may occur (Jackson et al., 2023). Baker et al. (2025) show that the collapse of the AMOC is unlikely even under extreme forcing conditions, and may only occur in case a strong Pacific Meridional Overturning Circulation (PMOC) emerges."

R2C10

As suggested, we have done the following changes:
- "The analyses have been based" was replaced by "The analyses are based"
- "combined ensembles have been also considered" was replaced by "combined ensembles are also considered"
- "The ensemble averages of the ALL and EXT ensembles have been computed" was replaced by "The ensemble averages of the ALL and EXT ensembles are computed"
- "a longitude-latitude grid has been considered" was replaced by "a longitude-latitude grid is considered"
- "all the simulations have been remapped" was replaced by "all the simulations are remapped"
- "In a first step, analyses have been focused" was replaced by "In a first step, analyses are focused"
- "analyses have been based on temporal evolutions" was replaced by "analyses are based on temporal evolutions"
- "This post-overshoot state has been compared" was replaced by "This post-overshoot state is compared"
- "potential differences in aerosol emissions between SSP5-3.4OS and SSP1-1.9 have been assessed" was replaced by "potential differences in aerosol emissions between SSP5-3.4OS and SSP1-1.9 are assessed"
- "the regions included in Fig. 1 have been considered" was replaced by "the regions included in Fig. 1 are considered"
- "of the NH has been characterized" was replaced by "of the NH is characterized"
- "of the Southern Ocean has been characterized" was replaced by "of the Southern Ocean is characterized"

- "potentially contributing to these temperature asymmetries have been explored" was replaced by "potentially contributing to these temperature asymmetries are explored"
- "the analyses have been focused on the global" was replaced by "the analyses are focused on the global"
- "A set of indices have been defined" was replaced by "A set of indices are defined"
- "the temporal evolution of these indices have been evaluated" was replaced by "the temporal evolution of these indices are evaluated"
- "In particular, the asymmetry between NH and SH has been characterized" was replaced by "In particular, the asymmetry between NH and SH is characterized"

The same approach has been considered for the other sections:
- "different mechanisms potentially contributing to regional hysteresis in case of overshoot have been analyzed" was replaced by "different mechanisms potentially contributing to regional hysteresis in case of overshoot are analyzed"
- "Temperature asymmetries between NH and SH and between mid and high latitudes of the NH have been analyzed" was replaced by "Temperature asymmetries between NH and SH and between mid and high latitudes of the NH are analyzed"
- "These asymmetries have been partly associated" was replaced by "These asymmetries are partly associated"
- "the same analyses have been performed only for the Atlantic basin" was replaced by "the same analyses are performed only for the Atlantic basin"

R2C11
Line 84: Ocean outputs have also been regridded to 2.8 degrees? Why, since the coarsest model has a resolution of 1.7 degrees? Please justify.

The ocean outputs have been regridded to 2.8 degrees to have the same grid as for the atmospheric variables.

R2C12
Table 1: The first line of the caption is too long and redundant. When you mention "available simulations," do you mean that all available simulations on ESGF nodes were used? Please specify.

Yes, all the simulations available on ESGF nodes were considered.

We have simplified the caption to: "Table 1. Models and simulations considered in this work, resolution of atmospheric (ResA) and ocean component (ResO) of each model and associated references. For the SSP5-3.4OS, the simulations covering the extended period (up to 2300) are included in the column (EXT)."

R2C13
Line 93-99: The description of the periods is unclear; please consider adding a figure for illustration.

To also address comment R1C6, we have improved the description of the post-overshoot period as follows: "The post-overshoot state is defined as a 20-year period after stabilization for SSP5-3.4OS EXT (from 2220 and 2239) and as the last 20 years of simulations for the SSP1-1.9 and the SSP5-3.4OS ALL ensemble (from 2080 to 2099)"

The justification for the pre-overshoot period is already included in the following paragraph: "The post-overshoot state has been compared with the pre-overshoot state with the same global average of surface air temperature, which is reached in 2034 for SSP5-3.4OS and in 2030 for SSP1-1.9, and the pre-overshoot state with the same CO_2 concentration (Meinshausen et al., 2020), reached in 2015 both for SSP5-3.4OS and SSP1-1.9. Considering these dates and in order to use a reference period large enough to focus on the long-term variability, our pre-overshoot reference for all analyses (except those stated otherwise) is the period from 2020 to 2039."

We prefer not to add a new figure, to avoid increasing the figure overload mentioned in comments R1C1 and R2C1.

R2C14

Figure 1: This figure is key; please make it twice as large. Some suggestions: add land in color, and draw the RS, WS, and NNA rectangles completely (over land as well).

Following the suggestion, land has been colored and the RS, WS and NNA rectangles have been completed.
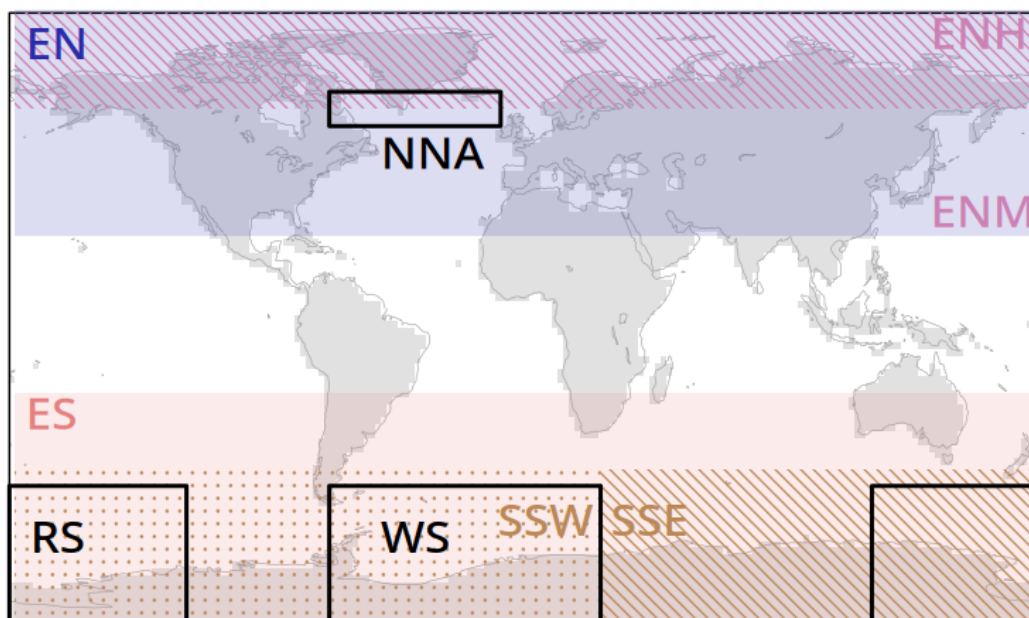
We have used this new version as Figure 1 and increased the size to cover the whole text width.

R2C15

Results:
- The description of the results needs reorganization (see general comments). Inter-model

comparison results are discussed in the first subsection, yet another subsection is labeled "Differences across models".

Also, following the suggestions in comment R2C21, the sea ice results have been moved to the new section 3.3.

The section "Differences across models" mostly discusses the correlation between temperature asymmetries and circulation and sea ice changes, and how this correlation strongly depends on the model. In the previous sections, model differences are already discussed, but focusing on individual variables (temperature in section 3.1 and circulation and sea ice in section 3.2).

To avoid any misunderstanding, we have renamed the section 3.3 (now 3.4) as "Contributions to temperature changes across different models"

We have reformulated the first paragraph of this section as: "Considering the large discrepancies across the models in the simulation of temperature changes (Fig. 3), the OHT responses (Fig. 5), and the concomitant sea ice changes (Fig. 6), the contribution of each mechanism to large-scale temperature asymmetries must be analyzed on a per-model basis."

Another change has been implemented in response to comment R2C16. We have moved the discussion of spatial patterns for individual models to Appendix B.

R2C16
- The number, size, and selection of figures must be improved. Some suggestions are provided for Figure 2, which are expected to be applied to other figures (up to Figure 15) where possible. Consider moving Figures 12 to 15 - which focus on one model - to the appendix.

As suggested, we have moved Figure 12 to 15 to Appendix B, and rename them as Figure B1 to B4. We also removed the panel e (MLD) from these figures and included it in a new Figure B5.

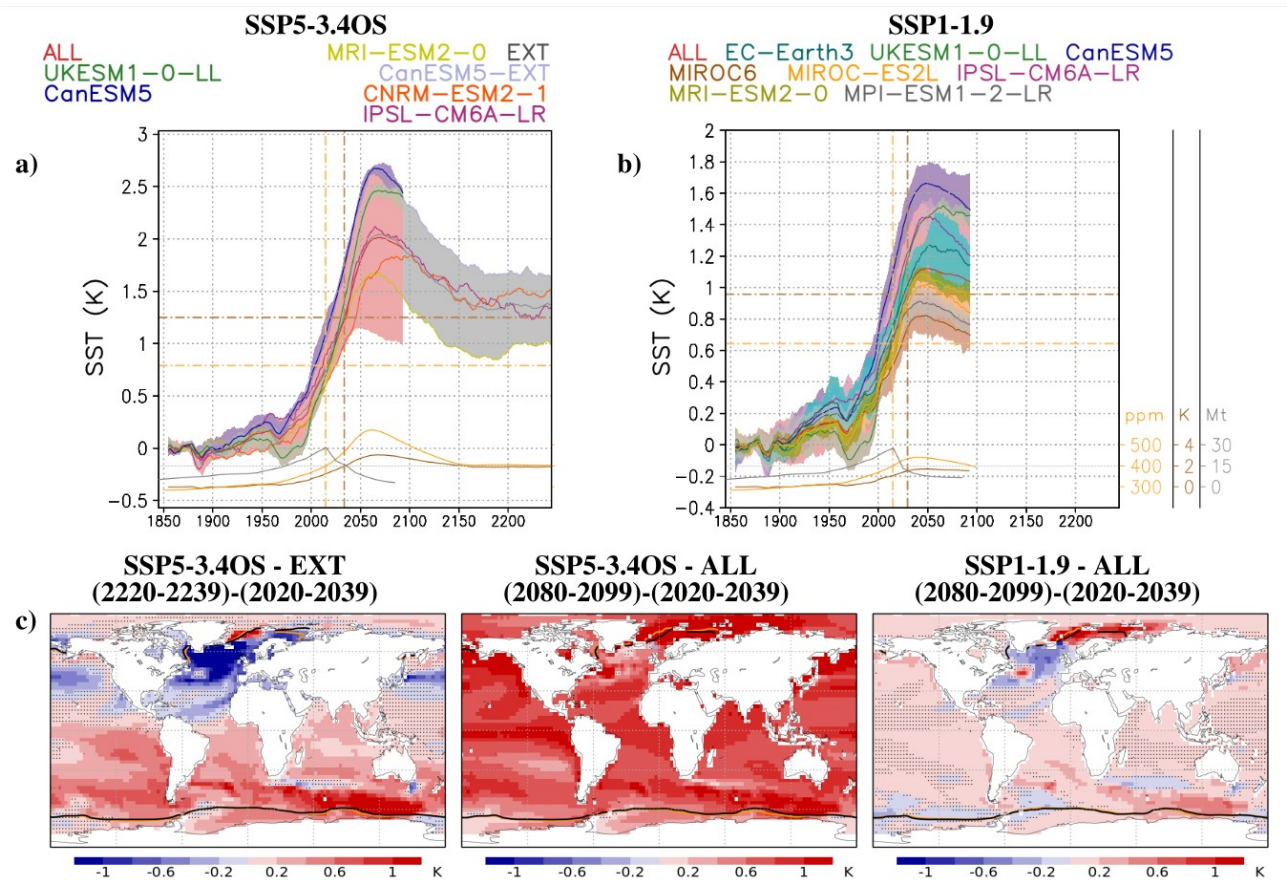We have also removed the panel f (year of the maximum) from these figures.

R2C17
- Figure 2: The size of the plots and maps is much too small; sea ice concentration is impossible to see, while the caption is unnecessarily long. Increase plot size, change the plot legend to use complete model names (e.g., "CAN" to "CanESM5"), and remove redundant explanations from the caption. Similarly, comparisons between periods need not be described in such detail in the caption.

We have increased the size of the figures to cover the whole text width and thus improve their visibility.
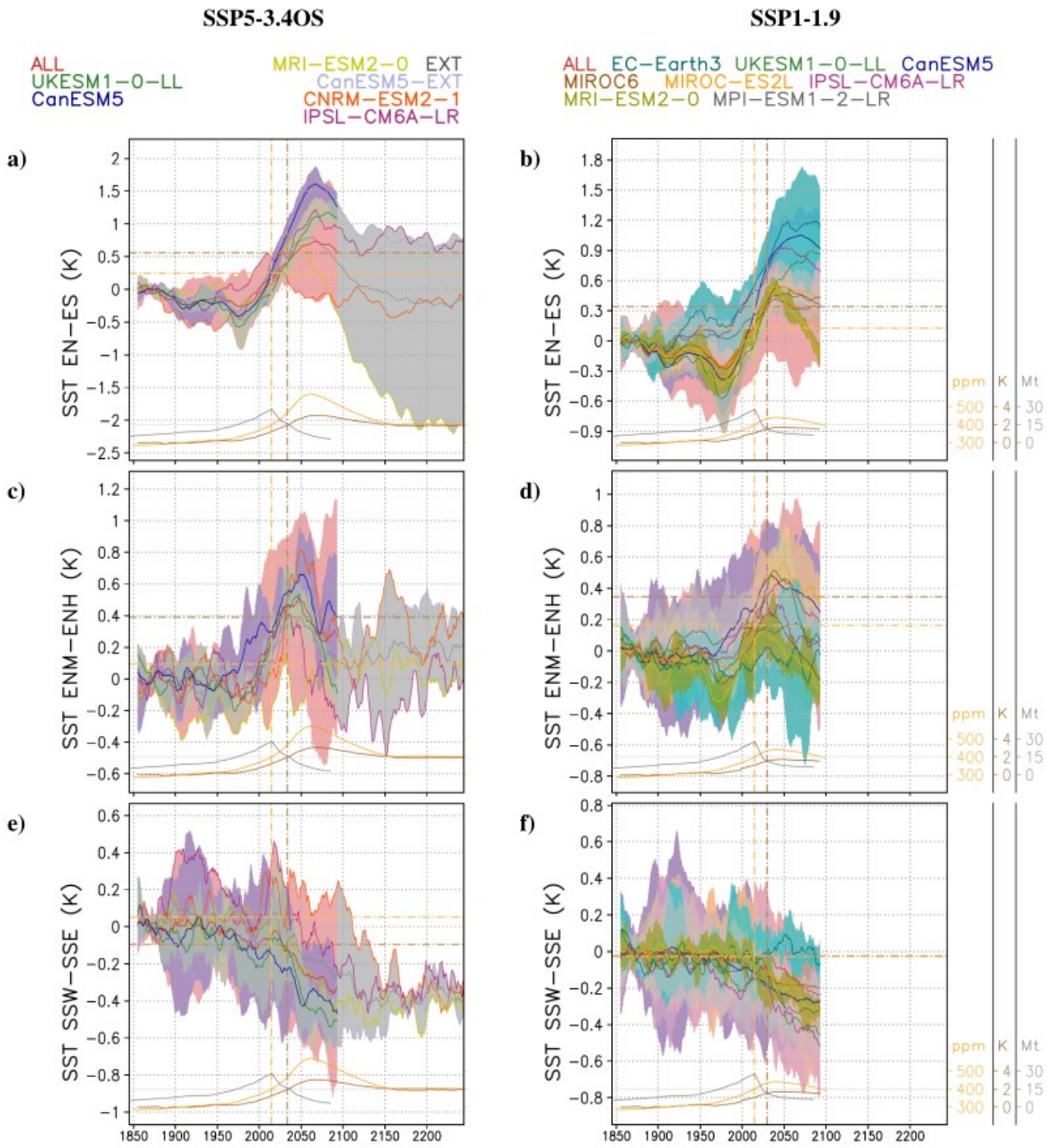
As suggested, we now included the complete model names within the figures and removed them from the caption.

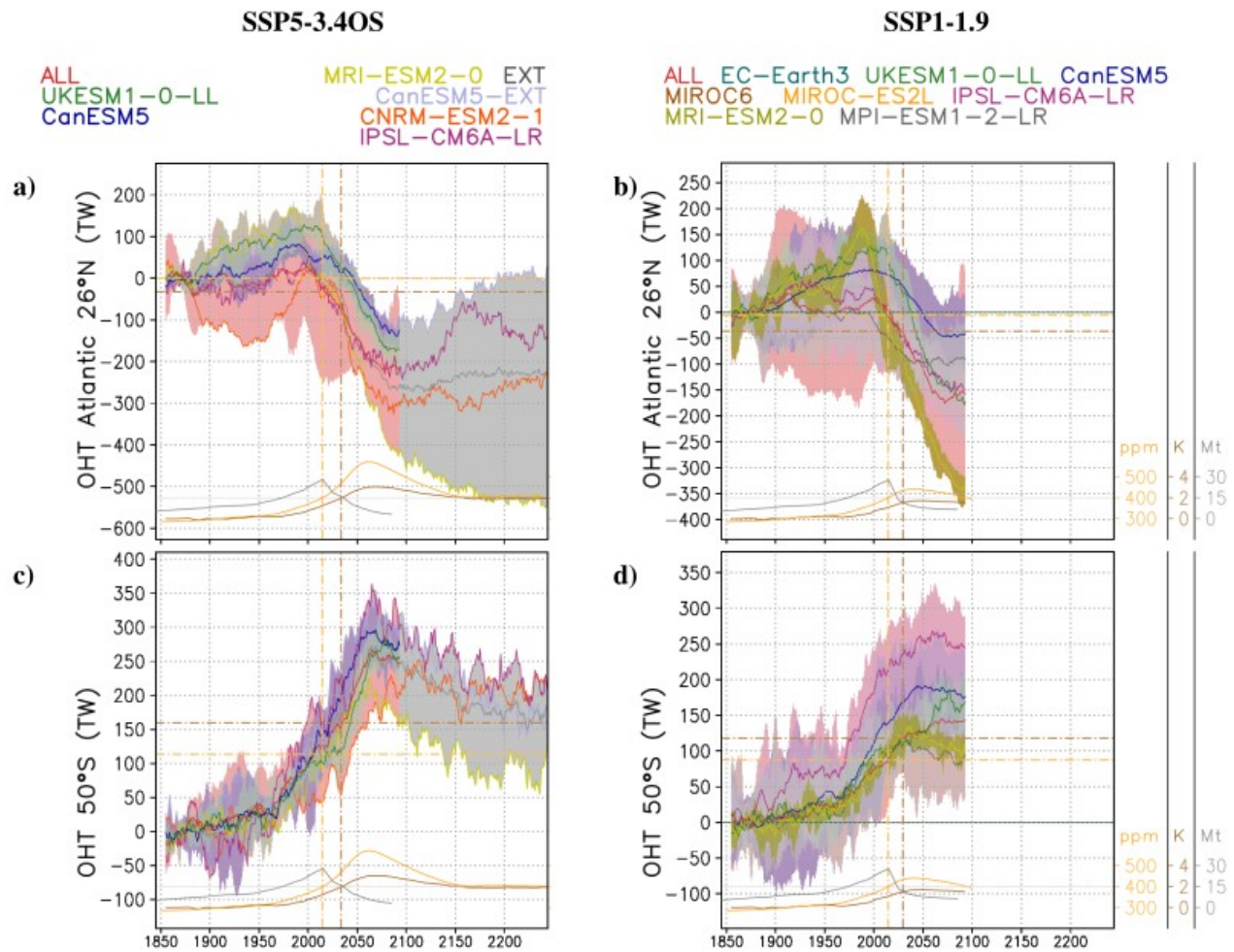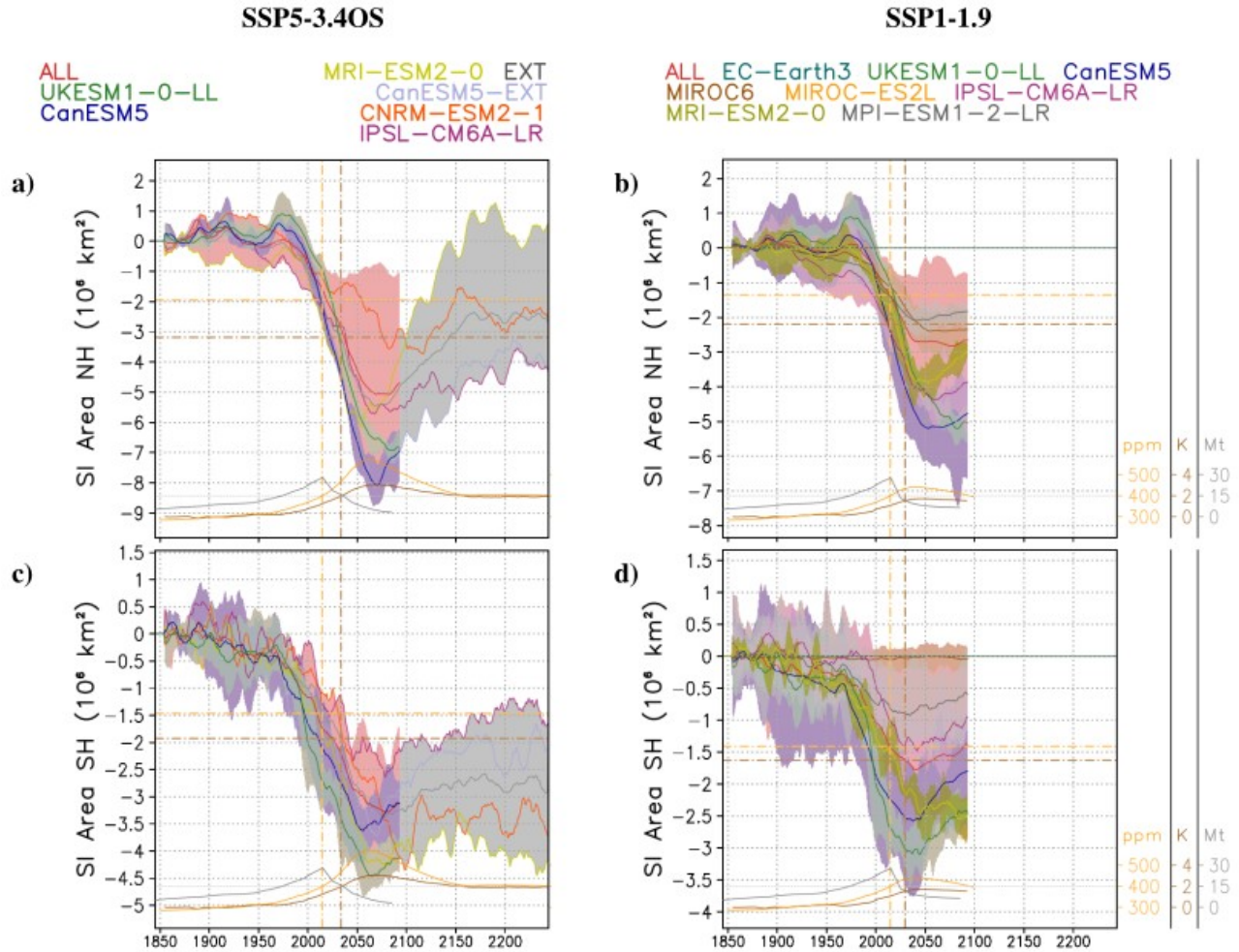The new figures would be then as follows:
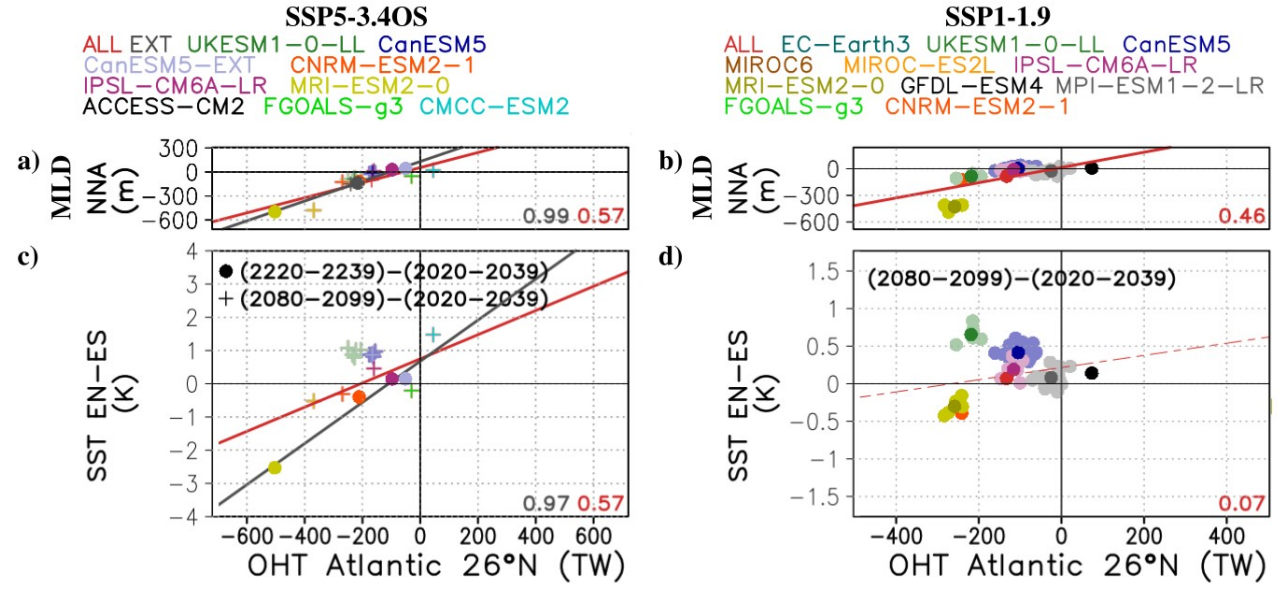
New Fig. 2:

New Fig. 3:

SSP5-3.4OS

ALL
UKESM1-0-LL
CanESM5

MRI-ESM2-0   EXT
CanESM5-EXT
CNRM-ESM2-1
IPSL-CM6A-LR

SSP1-1.9

ALL EC-Earth3 UKESM1-0-LL CanESM5
MIROC6 MIROC-ES2L IPSL-CM6A-LR
MRI-ESM2-0 MPI-ESM1-2-LR

New Fig. 5:

SSP5-3.4OS

ALL
UKESM1-O-LL
CanESM5
MRI-ESM2-O EXT
CanESM5-EXT
CNRM-ESM2-1
IPSL-CM6A-LR

SSP1-1.9

ALL EC-Earth3 UKESM1-O-LL CanESM5
MIROC6 MIROC-ES2L IPSL-CM6A-LR
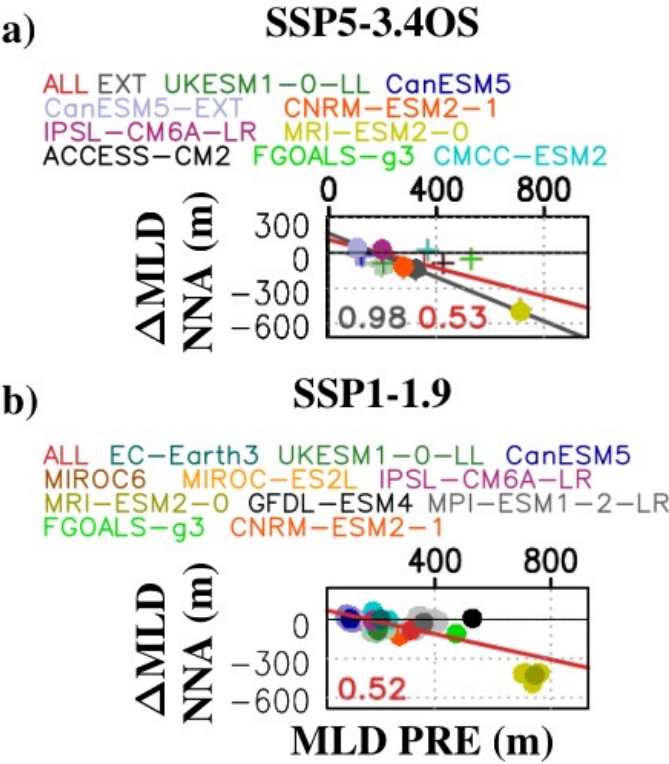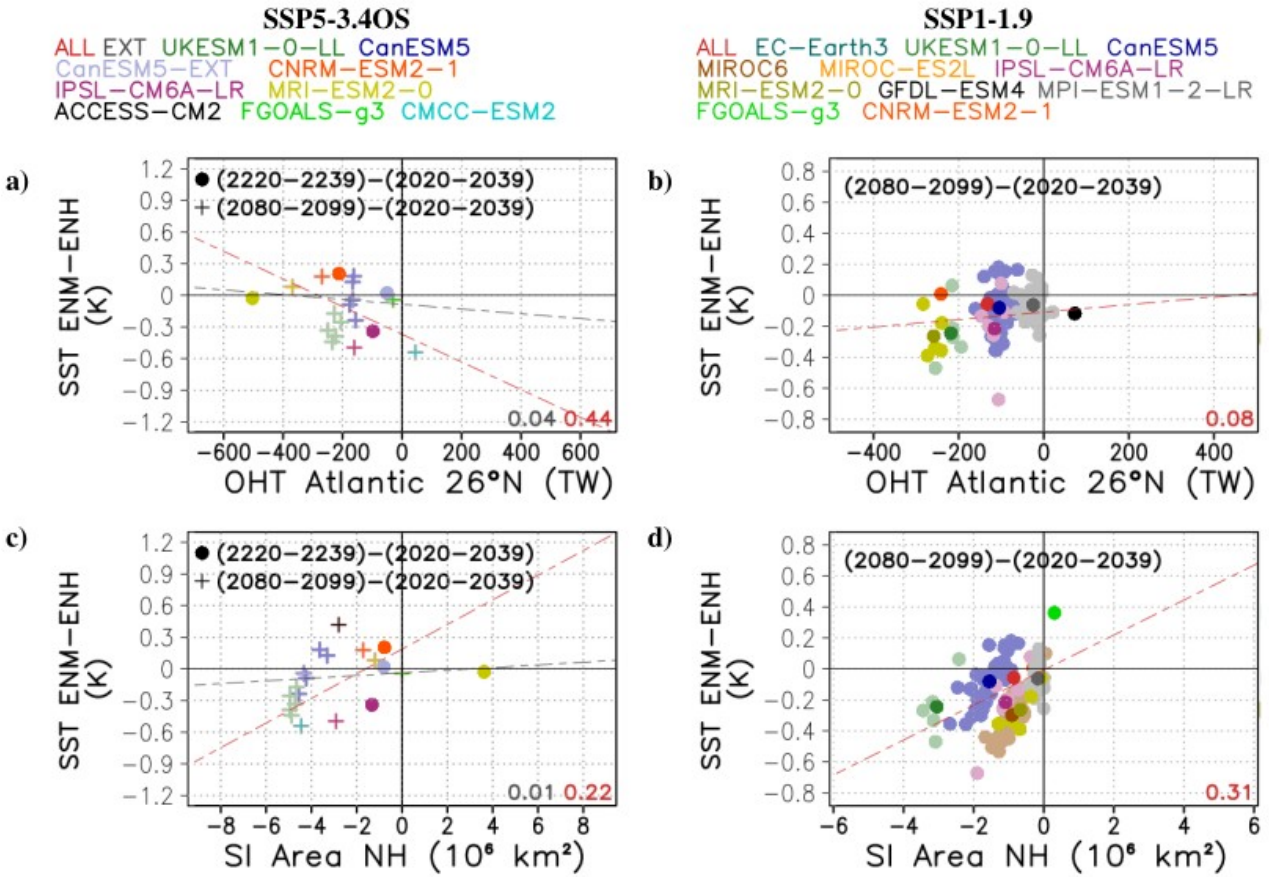MRI-ESM2-O MPI-ESM1-2-LR

New Fig. 6:

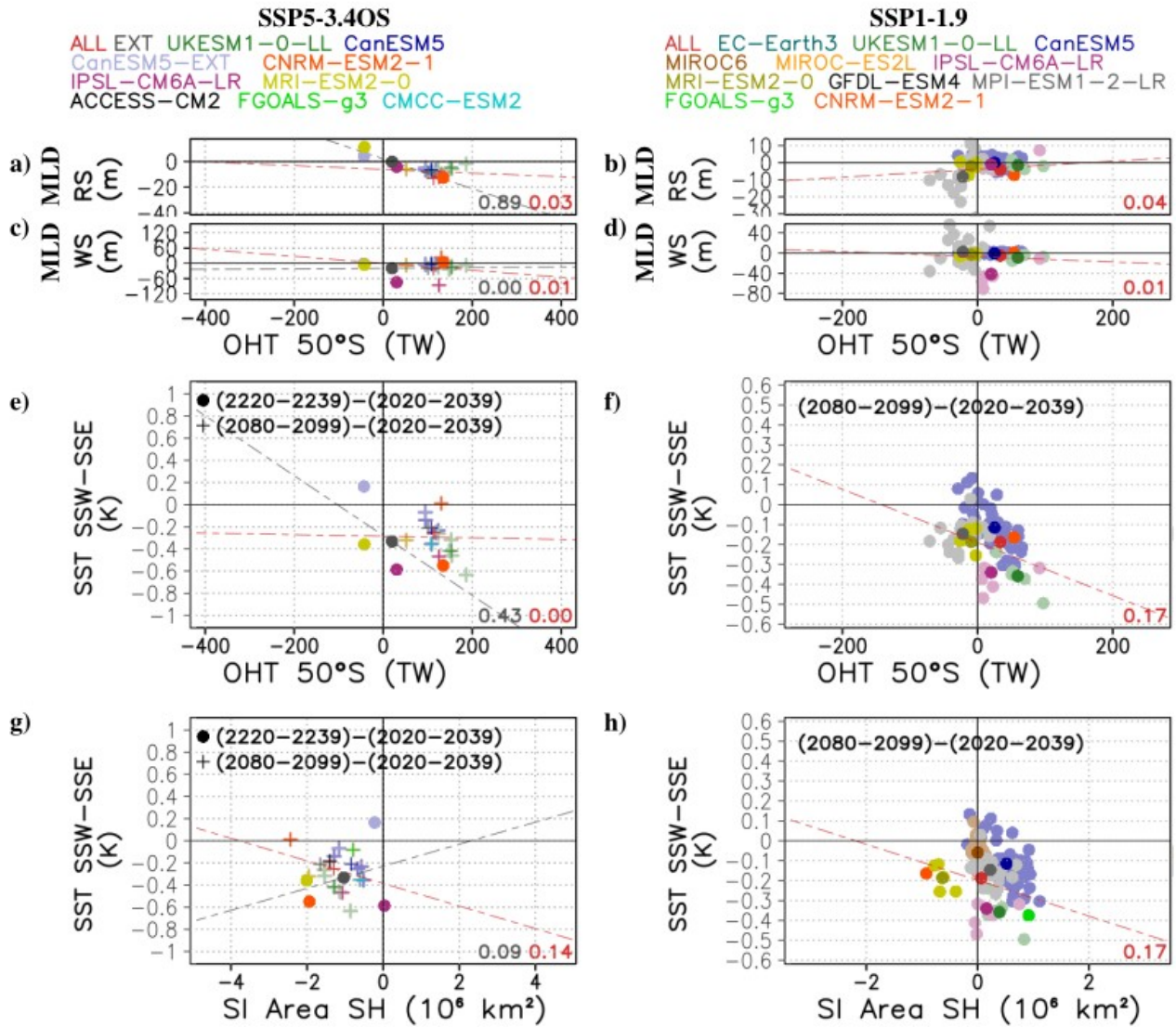New Fig. 7:

New Fig. 8:

New Fig. 9:

New Fig. 10:

Fig. A1 and A2 are modified accordingly.

R2C18

Is the year of maximum SST really relevant? As you are comparing periods, consider moving this to the appendix.

We have removed the figures with the year of maximum SST, as well as the references to these figures in the text.

R2C19

The purpose of the vertical brown line is unclear. Are the vertical and horizontal lines relevant for discussion?

The horizontal lines indicate the level of the variable in the year with the same global air temperature (brown) and CO_2 concentration (yellow) as at the end of the simulation. This allows to compare the post-overshoot value (value at the end of the simulation) with the pre-overshoot value (horizontal line). Considering that we are analysing the irreversibility of variables, this difference

between post-overshoot and pre-overshoot values is more relevant than the absolute value of the variable. We consider then that the horizontal lines are relevant for the discussion.

Regarding the vertical lines, they help to understand how the horizontal lines are derived. They represent the year with the same global air temperature (brown) and CO_2 concentration (yellow) as at the end of the simulation. The pre-overshoot value (and then the horizontal lines) is defined with the point in which vertical lines cut the time series (red for the ALL ensemble and gray for the EXT ensemble).

R2C20

Please specify how the spread is evaluated.

The spread is directly the minimum/maximum value within the ensemble. No statistical metrics are computed.

This is now clarified in the figure caption: "The minimum-to-maximum spread comprised by the individual simulations within each ensemble is included with a shading"

R2C21

- Sea ice results should be moved to a specific subsection, rather than being merged with AMOC.

These results are now included in the new section "3.3. Sea ice changes"

The introductory paragraphs of sections 3.2 and 3.3 has been adapted as follows:

- "The results from Fig. 2 and Fig. 3 show persistent changes in the regional temperatures after the overshoot, but these results strongly depend on the model. To better understand the reasons behind this behavior, different mechanisms potentially contributing to regional hysteresis in case of overshoot are analyzed. Among these mechanisms, the alteration of the meridional overturning circulation plays a major role (Li et al.; 2024)."

- "Hysteresis in the sea ice coverage has been also identified as a mechanism potentially explaining irreversibility in temperature (Li et al.; 2020). As shown in Fig. 4c, the post-overshoot state for the SSP5-3.4OS EXT ensemble average is characterized by higher sea ice concentrations in the NH and lower sea ice concentrations in the SH (Fig. 4c, left), a feature that can be linked to the reduced global northward heat transport."

R2C22

- Figures 8 to 11 are very hard to read and contain 24 different plots. Please compress the information.

The following panels have been removed:

- Panels c-d in Fig. 8 (Fig. 7 in the new manuscript), as they provide consistent results with those

from panels 8a-b.
- Panels c-f in Fig. 9 (Fig. 8 in the new manuscript), as they are not discussed in the text.
- Panels a-b in Fig. 11 (Fig. 10 in the new manuscript), as they provide consistent results with those from panels 11g-h.

Figure 10 (Fig. 9 in the new manuscript) already contained fewer panels and could not be condensed further.

Also, following comment R2C17, the figures have been simplified, by putting the legend outside the figure.

R2C23

We have added the following discussion on the AMOC-sea ice linkage: "These temperature asymmetries can be associated with several mechanisms introducing hysteresis in the climate system during the overshoot, including changes in ocean dynamics and meridional overturning circulation (Palter et al., 2018), both in the Atlantic and in the Southern Ocean (Li et al., 2024), as well as the melting of sea ice (Li et al., 2020). These processes are known to be inter-connected as revealed in the analysis of pre-industrial and global warming scenarios, with changes in OHT producing changes in sea ice, and altering then the MLD around Greenland (Meccia et al., 2022)."

R2C24

Discrepancies between models are discussed in the third paragraph of the "Discussion" section. We have completed this paragraph highlighting the limitations in model resolution and AMOC modelling, as follows: "In line with Sgubin et al. (2017), the analyses performed in this work show that the contribution of each mechanism strongly depends on the model, with some models like MRI-ESM2-0 showing strong alterations of the AMOC, some models like CNRM-ESM2-1 highlighting persistent changes in the sea ice, and some others like IPSL-CM6A-LR and CanESM5 simulating a relevant impact of the SMOC. This model-dependent behavior highlights the current uncertainties for the simulation of the ocean circulation and sea ice responses, which are probably limited by the coarse resolutions considered for these experiments, unable to resolve potentially key contributions from mesoscale eddies and sea ice leads."

R2C25

We have changed the structure of the discussion by swapping the order of paragraph 3 and 4 and moving the last sentences of paragraph 2 to paragraph 3. In such a way, the discussion is organized as follows:

- Temperature asymmetries
- Possible mechanisms explaining the temperature asymmetries
- Link between mechanisms and temperature asymmetries
- Model discrepancies

R2C26
Conclusions

The conclusion should begin by restating the study's objective and summarizing main key findings. It should briefly emphasize the study's novelty, explicitly state inherent limitations (e.g., model uncertainties), and suggest two or three clear avenues for future research, such as high-resolution model validation or observational comparison.

We have reworded the conclusions to follow the suggested structure, as follows: "This work provides a comprehensive analysis of CMIP6 overshoot scenarios, with the goal of identifying the main large-scale temperature patterns present in the post-overshoot climate, understanding inter-model differences, and how ocean circulation and sea ice changes contribute to shape these patterns. These analyses show a link between permanent changes in the OHT, AMOC and sea ice after the overshoot and the emergence of temperature asymmetries in the post-overshoot climate, between NH and SH, between mid- and high-latitude regions of the NH and between eastern and western Southern Ocean. They also show substantial inter-model differences in the relative contributions of meridional overturning circulation and sea ice changes to these asymmetries. This paper sheds light on the processes associated with a variety of model responses to the same forcing, in this case overshoot scenarios. Different processes dominate in different models, and the strength of changes in some specific features such as AMOC or MLD is associated with their model-specific mean state. Such in-depth analysis of changes and associated processes across models is the basis to better understand projected changes and can ultimately help to reduce the uncertainty of expected changes. Additional efforts would be needed to better understand model differences with regard to ocean circulation and sea ice changes, also considering new models at substantially enhanced resolution, while comparisons with observational data, in particular for the MLD and AMOC strength, could help to reduce model uncertainties."