Responses to reviewer's comments for “Contribution of meridional overturning circulation and sea-ice changes to large-scale temperature asymmetries in CMIP6 overshoot scenarios” (2nd round)

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.

I thank the authors for their detailed responses to my previous comments and for the substantial work invested in revising the manuscript. The revisions have improved the clarity and structure of the paper, and the added explanations help strengthen the overall narrative. That said, I believe further work is still needed before the manuscript can be accepted. I recommend moderate revisions: the manuscript is publishable after clarifying the role of internal variability, slightly expanding the interpretation of MLD–AMOC links, and refining some methodological justifications. Improvement of the text, particularly in the captions of the figures, is also needed, and minor comments are provided.

R1C1

Moderate comments

1. While Fig. 1 and Appendix A help, the rationale for including/excluding certain basins in the main analysis could be explained earlier in the methods section.

As a general answer, all the analyses based on SST consider all the basins. The suitability of this choice has been verified in the Appendix A by comparing the cross-basin SST with the Atlantic SST. A per-basin analysis is only considered for the OHT and mass transport, for which it is well known that there is a different behavior for Atlantic and Pacific.

This has been clarified in the beginning of the methods section:

- “In a first step, analyses are focused on annual Sea Surface Temperatures (SST), to characterize the temperature asymmetries generated during the overshoot. For that, the temporal evolution of SST and the difference between pre- and post-overshoot states are analyzed, considering all the ocean basins.”.
- “The asymmetries have been evaluated for all the basins together, considering the results from Roldán-Gómez et al. (2025) and the existing connections between Atlantic, Southern Ocean and Indo-Pacific basins (Li et al., 2024). To confirm that the results are not sensitive to this choice, results for EN, ES and ENM but including only the Atlantic basin (ENATL, ESATL and ENMATL) are included in Appendix A.”

R1C2

2. It would be helpful to justify why Atlantic-only asymmetries are not given more prominence given the strong AMOC focus.

Even if the asymmetries are associated with the AMOC, there are mechanisms that redistribute the heat between different basins. This is already discussed in the introduction: “Li et al. (2024) show that the post-overshoot state in SSP5-3.4OS is characterized by a persistent weakening of Atlantic Meridional Overturning Circulation (AMOC), with impacts on the OHT also for the Southern Ocean and, to a lesser extent, for the Indo-Pacific basin.”

A clarification has been added in the Appendix A: “Despite this minor difference, the results shown in Fig. A1 and A2 are generally in line with those from Fig. 5 2, 7 and 9, with ENATL-ESATL asymmetries behaving in a similar way as EN-ES asymmetries and ENMATL-ENH asymmetries behaving in a similar way as ENM-ENH asymmetries. This similarity confirms that even if the AMOC is mainly focused on the Atlantic basin, the changes in the OHT impact also the Southern Ocean and the Indo-Pacific basin (Li et al., 2024).”

R1C3

3. The paper notes the role of internal variability (e.g., differences between ensemble members in Figs. 9d and 10h), but a more quantitative assessment would strengthen the argument. For example, could a formal separation of forced vs. internal variability be attempted (e.g., through signal-to-noise ratios)?

Even if the results show a contribution of internal variability (particularly for models and experiments providing more simulations, like SSP1-1.9 for CanESM5 and MIROC6), for a complete characterization of internal variability larger ensembles would be needed to be able to isolate the forced signals.

For analysing the role of internal variability in irreversibility processes (and in particular in the link between sea ice and ENM-ENH asymmetries), the optimal selection of experiments may be different from the one of this paper (in particular to consider large ensemble experiments). This would exceed the scope of this paper, focused on analyzing the CMIP6 overshoot scenarios.

R1C4

4. The analysis shows strong correlations between climatological MLD and AMOC slowdown, but the causal mechanisms could be better explained. Are high MLD models more sensitive to buoyancy forcing, or is this an artefact of model resolution/parameterization? A brief physical interpretation would be useful.

There is certainly a contribution of model resolution/parameterization, which is already mentioned in the discussion: “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. The 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.”

However, other factors may also contribute to link climatological MLD and AMOC slowdown. To

identify all the contributing factors a more detailed per-model analysis would be needed.

We have included this in the discussion section, as a future work: “Despite these preliminary results, a more detailed per-model analysis would be needed to fully understand the physical mechanisms explaining this relationship. Identifying such relationships between climatological characteristics and projected changes could enable potential emergent constraints (Hall et al., 2019), if a robust observational estimate of MLD could be obtained.“

R1C5

5. The R^2 values are low for the ensemble means, yet the text emphasizes a link in some models. It would be useful to present a table summarizing which models exhibit statistically significant relationships and under which scenario.

When considering a single model, we have only one point (ensemble average) or a few points (if considering individual simulations) in Fig. 7, 8, 9, 10 and A2. This is not enough to make any statement on the significance of relationships for individual models. What we can say is that certain models show larger values for one of the indices and also larger (or smaller) values for another.

This is done for example in these sentences:
- “The models with the most negative differences in the northward Atlantic OHT, like MRI-ESM2-0 and CNRM-ESM2-1, are also those showing the coldest temperatures in EN with respect to ES”
- “For the case of SSP1-1.9, MRI-ESM2-0 and CNRM-ESM2-1 are also the models showing the strongest OHT reduction and EN-ES asymmetry”
- “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.”
- “the models with a larger OHT increase (e.g. UKESM1-0-LL, IPSL-CM6A-LR, and CNRM-ESM2-1) tend to simulate the largest temperature asymmetries”

R1C6

6. The SMOC–SSW/SSE asymmetry link is weaker (low R^2). Could eddy compensation or wind stress changes be confounding factors here? Even a brief discussion of alternative explanations would strengthen the section.

Yes, indeed. There are other factors that can contribute to temperature asymmetries in the SH. The paragraph has been completed with that: “For the case of SSW-SSE asymmetry, the large spread among the models reduces the R2 coefficient between OHT and temperature differences, to 0.43 for SSP5-3.4OS EXT (Fig. 10e) and to 0.17 for SSP1-1.9 ALL (Fig. 10f). Other factors like eddy compensation or wind stress changes may also have a relevant role in this area, contributing also to reduce the R2 coefficient.”.

R1C7

7. The multi-model means give equal weight to each model regardless of ensemble size. While this

is reasonable, the authors could comment on whether weighting by number of realizations changes the conclusions.

The overall conclusions are not changed, but from a methodological point of view, weighting per simulation and not per model would give a strong weight to some particular models (with a larger number of simulations). Considering the strong differences across the models, this is not suitable, as this could mask the variability within the other models.

This has been clarified in the methods section: “Considering the disparity in the number of simulations available for each model (only one SSP1-1.9 simulation for CNRM-ESM2-1, FGOALS-g3 and GFDL-ESM4, and up to 50 SSP1-1.9 simulations for CanESM5 and MIROC6), the use of the same weight for each simulation would generate an ensemble average mostly driven by a few models with large ensembles. To avoid that, the ensemble averages of the ALL and EXT ensembles are computed by averaging all the simulations from each model to obtain a per-model average in a first step and by averaging all the models in a second step, so that all the models contribute with the same weight to the multi-model average.”

R1C8

8. The manuscript is generally well written but could be tightened in places to avoid repetition (e.g., several paragraphs restate that responses are model-dependent and linked to MLD climatology).

To avoid repetition:

- The first paragraph of section 3.2 :

“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).”

Has been replaced by:

“The alteration of the meridional overturning circulation plays a major role on the regional hysteresis in case of overshoot (Li et al., 2024)”

- The following sentence has been removed from the last paragraph of the discussion:

“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.”

R1C9

Minor comments
General:
- Sometimes “mid-latitudes” and other times “medium latitudes” are used — standardize to “mid-latitudes.”

All the occurrences of “medium latitudes” have been replaced by “mid-latitudes”.

R1C10

- Several long sentences would benefit from breaking into two for readability, especially those containing multiple subordinate clauses (e.g., the sentence starting “The analysis of these scenarios shows that even if global temperatures revert…”).

The sentence has been divided as: “The analysis of these scenarios shows different behaviors for global and regional climates. Even if global temperatures revert, the impact on regional temperature, precipitation and climate extremes may remain for decades (Pfleiderer et al., 2024).”

The same has been done for the following sentences:
- “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. In these scenarios, global average temperature surpasses the target of 1.5◦ C above pre-industrial levels (United Nations / Framework Convention on Climate Change, 2015) and is reduced to the target afterwards with net-negative emissions (Gasser et al., 2015).”
- “The analysis of the SSP1-1.9 and SSP5-3.4OS scenarios confirms the relevant role of hysteresis mechanisms in shaping regional temperature and precipitation after global temperature overshoots. Hysteresis is understood as the dependence of the climate system not only on the current CO2 concentration but on the CO2 pathway.”

R1C11

- Keep tenses consistent when describing findings from the literature — mix of present (“is characterized”) and past (“was associated”) could be harmonized.

As suggested, the past tenses have been replaced by present tenses:
- “increasing phase is not totally released “
- “Hysteresis in the sea ice coverage is also identified”
- “This regional irreversibility, understood as a post-overshoot state different from the pre-overshoot state with the same CO2 concentration levels and with the same global temperature, is associated with hemispherical temperature”
- “Changes in the sea ice and ocean circulation are identified as potential sources of hysteresis”
- “Relevant hysteresis mechanisms are found on the large-scale hydrology”

R1C12

Abstract:
• line 6: “at regional level” → “at the regional level”

The sentence has been modified as suggested in the comment.

R1C13

• line 7: “the situation post-overshoot may differ from the situation pre-overshoot…” → “… regional conditions post-overshoot may still differ from those pre-overshoot...”

The sentence has been modified as suggested in the comment.

R1C14

• line 3 and 10 “the sea-ice” → “sea-ice”

The two occurrences have been modified as suggested in the comment.

R1C15

Introdution:

- In the paragraph line 53 starting by “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), please include the papers from Bellomo, 2021 https://www.nature.com/articles/s41467-021-24015-w

Reference to Bellomo et al. (2021) has been included.

R1C16

- move Table 1 to after the section titre “Method”

Table 1 has been moved after the section title “Method”.

R1C17

- line 25: "recovering the pre-overshoot temperatures" → remove “the” → “recovering pre-overshoot temperatures”.

The sentence has been modified as suggested in the comment.

R1C18

- line 37: "hemispherical temperature asymmetries" → should be “hemispheric temperature asymmetries”

The sentence has been modified as suggested in the comment.

R1C19

- line 44: "Relevant hysteresis mechanisms have been found on the large-scale hydrology" → “on” → “in”.

The sentence has been modified as suggested in the comment.

R1C20

- line 54: "a decrease of OHT" → should be “a decrease in OHT”. In the the text, I fould 6 other occurences of “a decrease of”, please change it to “in” pages 14, 17 (twice), 20, 21, 23

All the occurrences of “a decrease of” have been replaced by “a decrease in”. Accordingly, all the occurrences of “a increase of” have been replaced by “a increase in”.

R1C21

Method:
line 89: “Focus” was used in the sentence before. This paragraph is hard to follow. The term “stabilization”, “pre overshoot state” or “post overshoot state” have not been defined before, and we get a bit lost with the different periods. Consider adding a simple scheme (timeline) to help visualise.

The paragraph has been reworded to make it more clear: “In a first step, analyses are focused on annual Sea Surface Temperatures (SST), to characterize the temperature asymmetries generated during the overshoot. For that, the temporal evolution of SST and the difference between pre- and post-overshoot states are analyzed, considering all the ocean basins. To highlight the long-term variability, the temporal evolutions are filtered with a 10 year moving average. The post-overshoot state is defined as a 20-year period from 2220 to 2239 for SSP5-3.4OS EXT and from 2080 to 2099 for the SSP1-1.9 and the SSP5-3.4OS ALL ensemble.”

R1C22

Results:
Figure 2 and others: Caption still needs to be a lot reduced. For example, change: “The minimum-to-maximum spread comprised by the individual simulations within each ensemble is included with a shading” by “enveloppes are the min-max values”. If EXT and ALL ensembles have been defined in “Method”, there is no need to repeat the definition in the caption. Colors for ALL and CNRM model are too similar, change CNRM model to brown for instance. Unclear why we have “CanESM5-EXT” only, and not the extended model simulations. In multi-panel figures (e.g., Fig. 3, Fig. 7), it might help to label subplots with the asymmetry name directly (EN–ES, ENM–ENH, SSW–SSE) for faster reading.

As suggested, captions have been modified to:
- Change the sentence explaining the shading: “Envelopes show the min-max values within each ensemble”.
- Remove the definition of ALL and EXT ensembles: “including the ALL and EXT ensembles, the ensemble average for each individual model and the individual extended simulations”.

Regarding the colors, brown is already used for MIROC6, so it cannot be used for CNRM. As explained in the answer to R2C1, considering the number of models included in the figures, we could not find another color scheme that provides a better readability than the selected one. To

avoid any misunderstanding on the figures, we have increased the width of the lines, so that the colors are clearer.

Regarding the CanESM5-EXT, we have indeed all the extended simulations in the figures. But for MRI-ESM2-0, CNRM-ESM2-1 and IPSL-CM6A-LR there is only one simulation of SSP5-3.4OS, which is the extended one. There is then no need to distinguish between ensemble average and extended simulation, as done for CanESM5. To avoid any misunderstanding, we have clarified this in the methods section: “For MRI-ESM2-0, CNRM-ESM2-1 and IPSL-CM6A-LR the only available SSP5-3.4OS simulation covers the extended period, so there is no difference between the extended simulation and the ensemble average. However, for CanESM5 there is one simulation covering the extended period and 4 simulations covering only until 2100. In that case, the extended simulation is identified as CanESM5-EXT, while the average of the 5 simulations is identified as CanESM5.”

Regarding the label of subplots, we have kept the (a), (b), ... labeling (following journal recommendations), but we have included the asymmetry name when citing them in the text:
- “gold line of SST EN-ES in Fig. 3a”
- “gold line of SST ENM-ENH in Fig. 3b”
- “purple line of SST EN-ES in Fig. 3a,b”
- “gray line of SST ENM-ENH in Fig. 3c”
- “red line of SST ENM-ENH in Fig. 3d”
- “gold and purple lines of SST ENM-ENH in Fig. 3c,d”
- “dark orange line of SST ENM-ENH in Fig. 3c”
- “orange line of SST ENM-ENH in Fig. 3d”
- “turquoise line of SST SSW-SSE in Fig. 3f”

R1C23

line 148: "Less discrepancies exist" → "Fewer discrepancies exist"

The sentence has been modified as suggested in the comment.

R1C24

line 160: “Atlantic ocean” → “Atlantic Ocean”

The sentence has been modified as suggested in the comment.

R1C25

line 173: "has been also identified" → "has also been identified"

Considering the comment R1C11, the sentence has been changed to present tense.

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.

The manuscript by Roldán-Gómez et al. investigates temperature asymmetries in response to a hypothesized future reduction in greenhouse gases (GHGs). Based on multi-model simulations from CMIP6, the authors show that these asymmetries are primarily driven by sea ice and large-scale ocean circulation processes, particularly the meridional overturning circulation in the Atlantic and Southern Oceans. The Atlantic overturning circulation contributes to hemispheric-scale temperature asymmetries, while the Southern Ocean overturning largely shapes the zonal asymmetry in the Southern Hemisphere. In addition, sea ice changes dominate the temperature response across the middle to high latitudes of the Northern Hemisphere. Despite these robust mechanisms, substantial inter-model discrepancies persist, which may influence the projected temperature response to mitigation efforts. Overall, the findings are interesting and the manuscript is clearly written. I recommend minor revision with several specific comments.

R2C1

1. Several figures are difficult to interpret and would benefit from revision. For example, Figs. 2a–b, 3, 5, and 6 contain lines that are too thin to be easily distinguished, and the color schemes use shades that are too similar to be clearly identified. I also suggest that the authors consider adjusting the colors of the vertical lines to improve readability.

As suggested, Fig. 2a-b, 3, 5 and 6 have been modified, to:
- Increase the width of all the lines.
- Use black color for the vertical lines with the year before the overshoot with the same CO2 concentration (dashed line) and global surface air temperature (solid line) as at the end of the run.
- Use black color for the horizontal lines with the value of the variable for the years with the same CO2 concentration (dashed line) and global surface air temperature (solid line) as at the end of the run.

Considering the number of models included in the figures, we could not find another color scheme that provides a better readability than the selected one.

The references in the text have been adapted accordingly.

The new figures are as follows:

Figure 2:

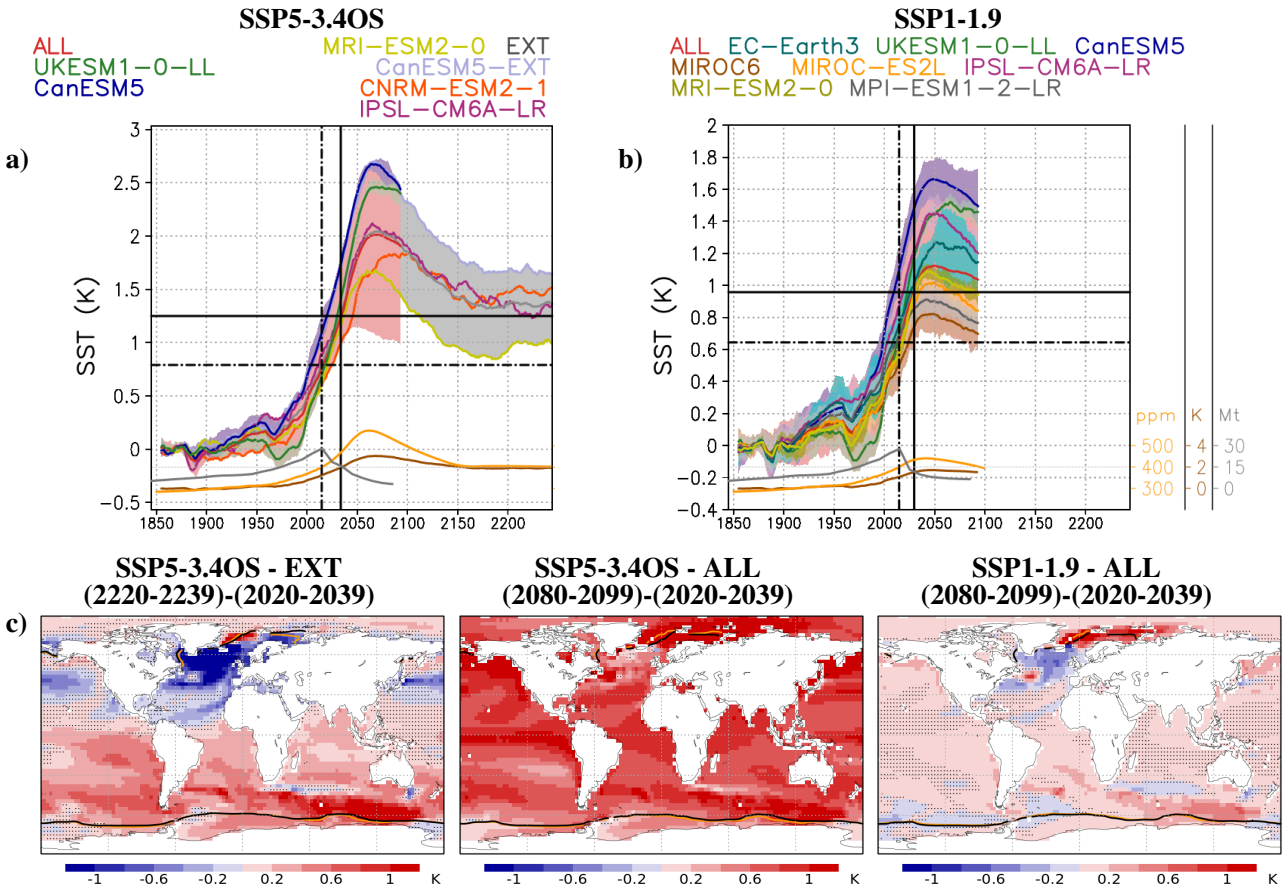
SSP5-3.4OS
ALL
UKESM1−0−LL
CanESM5
MRI−ESM2−0
CanESM5−EXT
CNRM−ESM2−1
IPSL−CM6A−LR
EXT
a)
SST (K)
SSP1-1.9
ALL EC−Earth3 UKESM1−0−LL CanESM5
MIROC6 MIROC−ES2L IPSL−CM6A−LR
MRI−ESM2−0 MPI−ESM1−2−LR
b)
SST (K)
ppm K Mt
500 4 30
400 2 15
300 0 0
SSP5-3.4OS - EXT
(2220-2239)-(2020-2039)
SSP5-3.4OS - ALL
(2080-2099)-(2020-2039)
SSP1-1.9 - ALL
(2080-2099)-(2020-2039)
c)
-1 -0.6 -0.2 0.2 0.6 1 K

Figure 3:

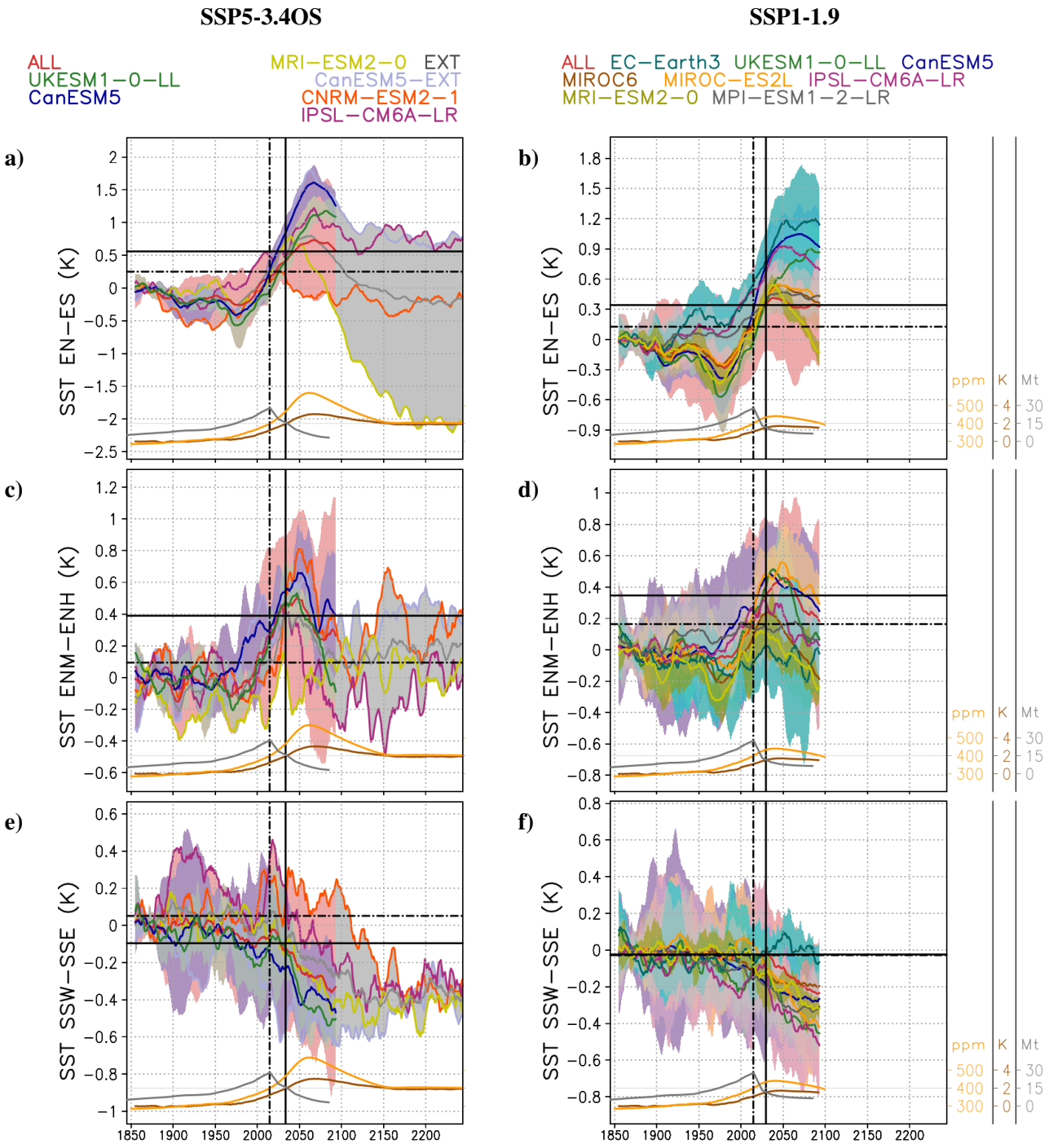
SSP5-3.4OS
SSP1-1.9
ALL
UKESM1-0-LL
CanESM5
MRI-ESM2-0
EXT
CanESM5-EXT
CNRM-ESM2-1
IPSL-CM6A-LR
ALL
EC-Earth3
UKESM1-0-LL
CanESM5
MIROC6
MIROC-ES2L
IPSL-CM6A-LR
MRI-ESM2-0
MPI-ESM1-2-LR
a)
b)
c)
d)
e)
f)
SST EN-ES (K)
SST ENM-ENH (K)
SST SSW-SSE (K)
ppm
K
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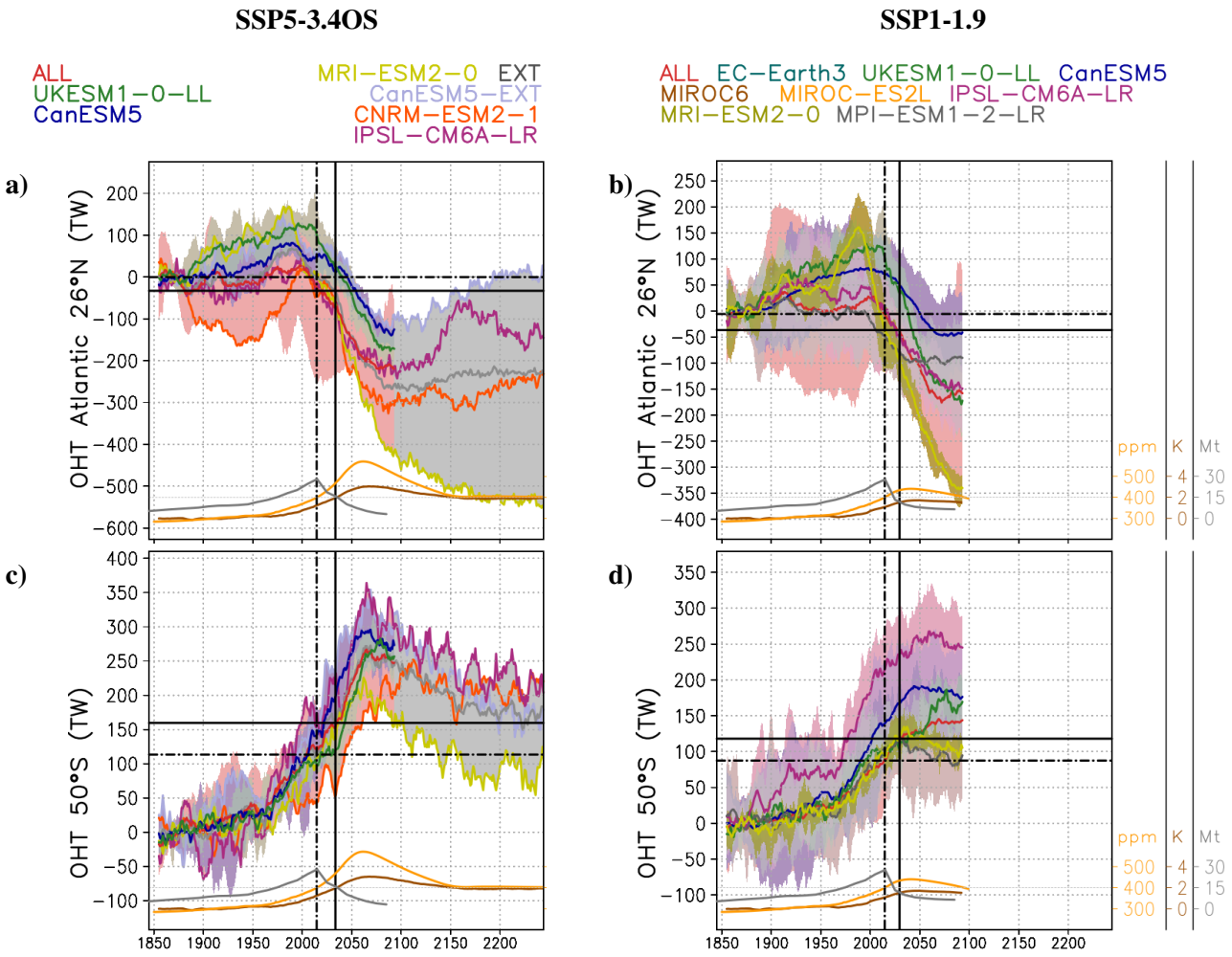
Figure 5:


SSP5-3.4OS
SSP1-1.9
ALL
UKESM1-0-LL
CanESM5
MRI-ESM2-0
EXT
CanESM5-EXT
CNRM-ESM2-1
IPSL-CM6A-LR
ALL
EC-Earth3
UKESM1-0-LL
CanESM5
MIROC6
MIROC-ES2L
IPSL-CM6A-LR
MRI-ESM2-0
MPI-ESM1-2-LR
a)
b)
c)
d)
OHT Atlantic 26°N (TW)
OHT 50°S (TW)
ppm
K
Mt
500
400
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4
2
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1850
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2050
2100
2150
2200

Figure 6:

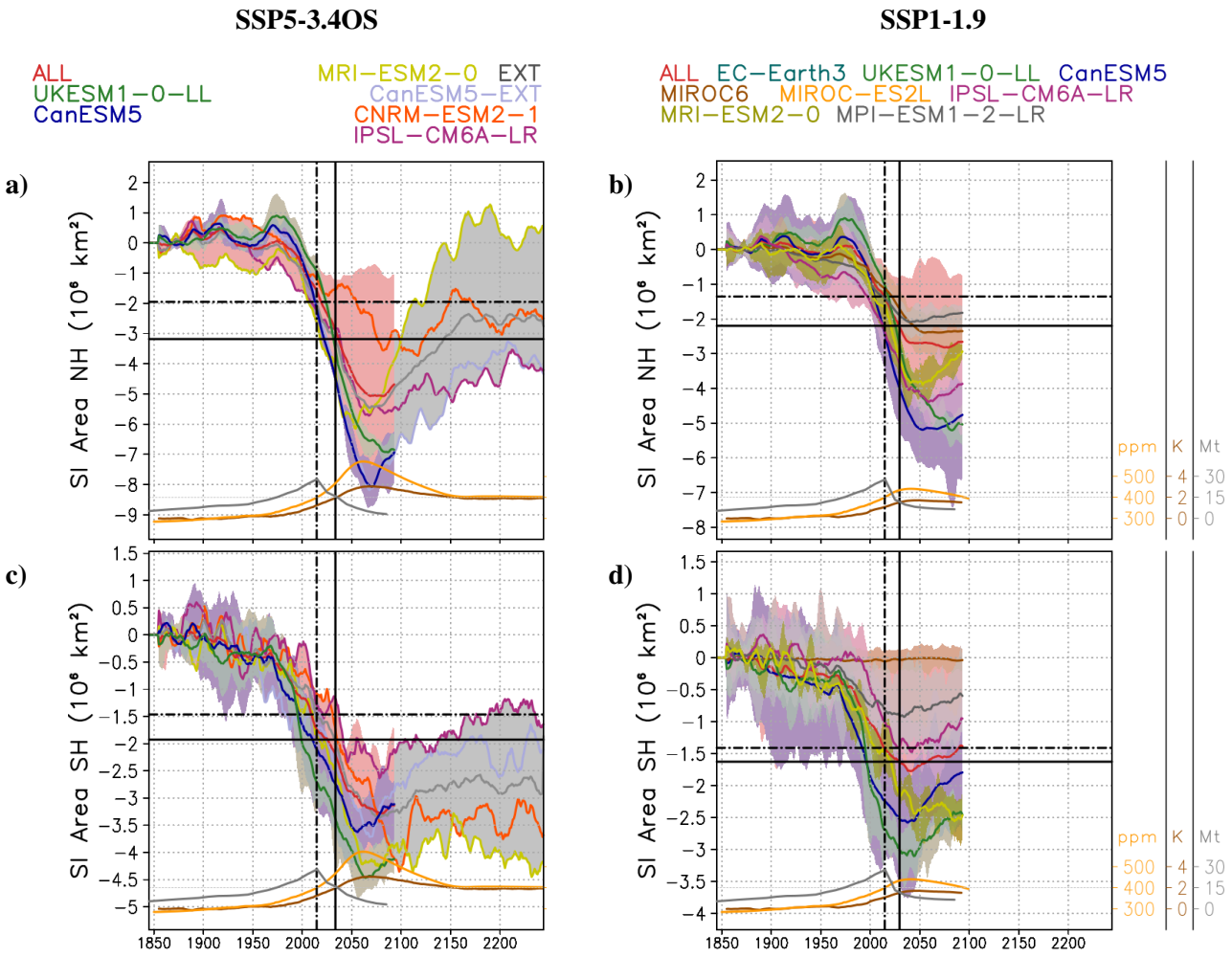
SSP5-3.4OS
SSP1-1.9
ALL
UKESM1-0-LL
CanESM5
MRI-ESM2-0
EXT
CanESM5-EXT
CNRM-ESM2-1
IPSL-CM6A-LR
ALL
EC-Earth3
UKESM1-0-LL
CanESM5
MIROC6
MIROC-ES2L
IPSL-CM6A-LR
MRI-ESM2-0
MPI-ESM1-2-LR
a)
b)
c)
d)
SI Area NH (10⁶ km²)
SI Area SH (10⁶ km²)
ppm
K
Mt
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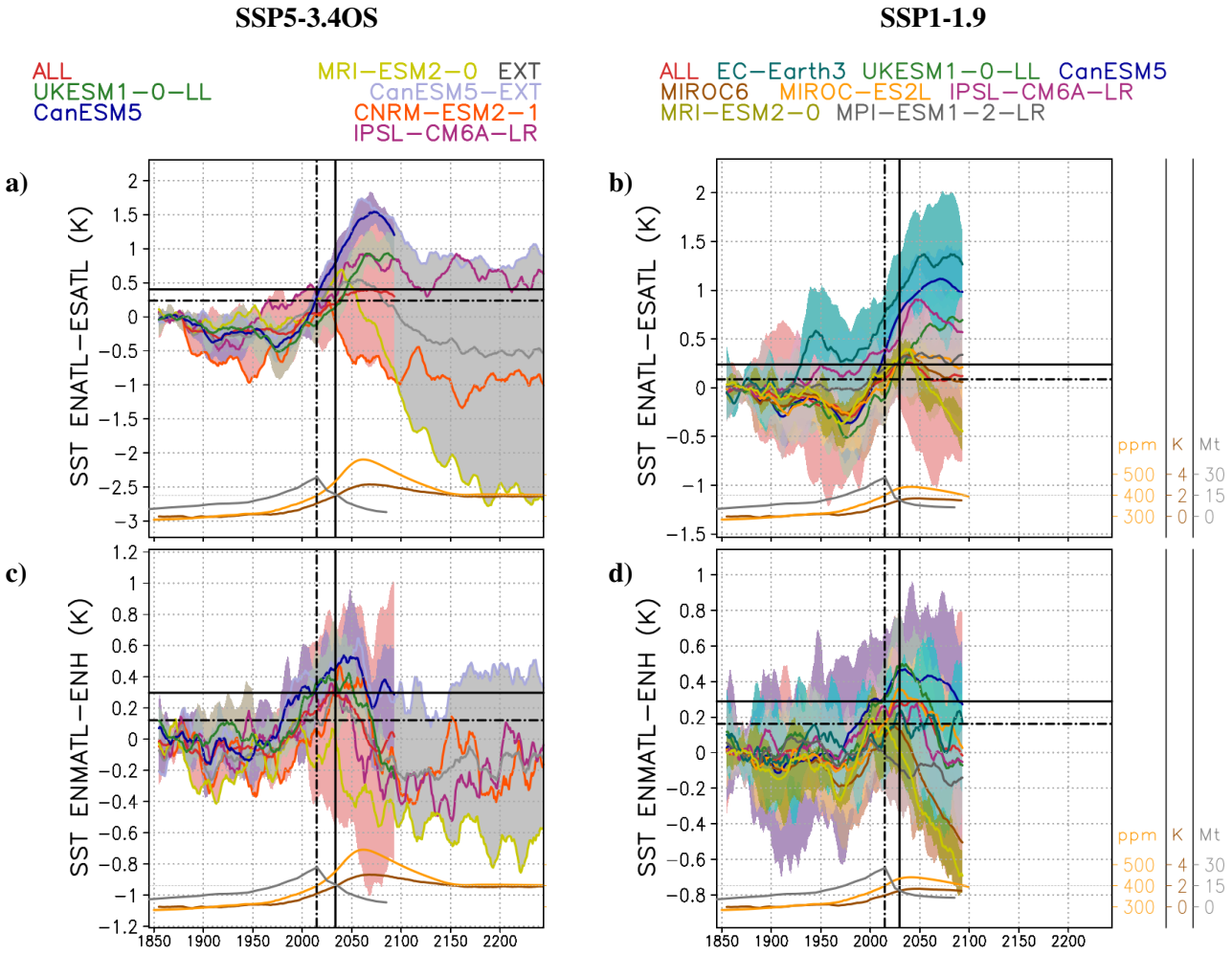
Figure A1:



R2C2

2. The SSP5-3.4OS ALL scenario generally produces results consistent with those of SSP1-1.9 ALL, although the magnitude differs due to the stronger and earlier CO_2 reduction in SSP1-1.9 ALL. Therefore, I recommend that the authors move the SSP1-1.9 figures to the supplementary materials, using them to support the main conclusions drawn from SSP5-3.4OS.

As discussed in the answers to comments R1C1 and R1C5 from the first round of review, 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 this reason, we prefer to keep them in the main text.

R2C3

3. The authors use both SSP5-3.4OS EXT and SSP5-3.4OS ALL to explore the temperature response to CO2 reduction. I would suggest the author highlight the differences of the two sets.

The differences between EXT and ALL ensembles are described in the methods section. To make it

more clear, we have modified the paragraph to clearly reflect the number of simulations, the covered period and the goal of each ensemble: “The ALL ensemble of SSP5-3.4OS contains 16 simulations from 8 models, covering the period from from 1850 to 2100, while the EXT ensemble of SSP5-3.4OS contains only 4 simulations from 4 models, but covering an extended period from 1850 to 2300. Both ensembles are then complementary, being the ALL ensemble mostly used to analyze the inter-model and the EXT ensemble mostly used to analyze the long-term stabilization after the overshoot.”