'Pacific Decadal Oscillation modulates the Arctic sea-ice loss influence on the mid-latitude atmospheric circulation in winter'

<u>Review 1</u>

Summary

This paper used coupled and atmospheric-only model experiments to investigate the interaction of Arctic sea ice loss and the PDO. A range of sensitivity experiments were performed where sea ice was artificially reduced. It was shown that the mid-latitude and stratospheric response to sea ice loss was similar to the response to the warm phase of the PDO. A linear regression algorithm was used to determine that the effect of sea ice and PDO was not additive, and the atmospheric response to sea ice loss was dampened by the PDO.

Overall, I thought this was a well written paper with interesting results. I recommend publication with minor revisions. Mostly I have only minor comments and clarifications, however, I was unsure about the results in Figure 9 which seemed to contradict earlier key results.

We appreciate the reviewer's positive assessment of our work, and we are grateful for the time spent reviewing our manuscript and for providing constructive comments.

General comments:

Figure 9: If the combined effect of future sea ice and the PDO is not additive, and the PDO dampens the sea ice response (e.g. Figs. 3-7), why does Figure 9 not show a difference between the gradient of the lines in Fig. 9? For example, Fig. 4, bottom row, shows a difference in the combined Aleutian Low/PDO response between PD:PDO and FUT:PDO, since it's a linear regression would that also mean that the response of the PDO is dampened by reduced sea ice (apologies if I am misunderstanding this)? Which would imply that in PD should have a steeper gradient that FUT in Fig. 9.

We thank the reviewer for this comment. Indeed, Figure 9 was erroneous in the previous manuscript, as the points marked as PI, PD or FUT were in fact mixing the results of the three simulations. This was corrected in the revised manuscript. Figure 9, involving composite analysis, now clearly shows that the response of the PDO is dampened by the sea ice loss, except for the AO that the slopes are similar for both FUT and PD. We added to the figure the regression lines, to make a more straightforward comparison between the composite analysis and the regression analyses shown in previous figures.

We also reformulate and improve the description of the composite analysis. The legend of Fig. 9 was modified: "*Composites of the AO index (top-left; unitless), Aleutian low (top-right; in m) and polar cap 50 hPa geopotential height (bottom, in m), for members sorted following their PDO index in the PI (green lines), PD (blue lines) and FUT (red lines) ensembles. The dashed lines show the regression lines of the corresponding ensemble. The triangles indicate the value for each composite, constructed using* $PDO<Q_{1/3}$, $Q_{1/3}<PDO<Q_{2/3}$ *and* $PDO>Q_{2/3}$, *where the threshold are given by* $Q_{1/3} = -0.43$ *and* $Q_{2/3} = 0.43$, *the first and second tercile of a standard normal distribution. The error bar provides the 95% confidence interval.*"

We also modify the related text (Lines 496):
"*Therefore, we performed a composite analysis averaging members of the PI, PD and FUT ensemble simulating warm, neutral and cold phases of the PDO. The composites are built using members with a PDO index lower than -0.43 (cold phase), between -0.43 and 0.43*

(neutral phase) and higher than 0.43 (warm phase). The values of -0.43 and 0.43 are chosen as a threshold as they correspond to the first and second tercile of the standard normal distribution. For gaussian climate indices, this leads to a composite of approximately the same size."

My other general comment concerns the PDO in the experimental setup, if the experiments consist of 200 x 12 month periods, how can there be decadal variability?

The PDO pattern is commonly calculated from an EOF analysis based on yearly data. The resulting principal components then usually show large decadal variability. In our experiment, we perform the EOF with yearly data, but on the members dimension instead of the temporal dimension. This is equivalent to a classical EOF. As stated in Maher et al. (2018), ''When using the ensemble-dimension to compute EOFs (EOF-E), all time scales of variability are captured''. The pattern obtained by our analysis is well representative of the PDO. We also verify that a similar pattern can be obtained by a classical EOF using the preindustrial control run of the IPSL-CM6A-LR model (Fig. R1, left). Such a pattern is the PDO and is known to have an important decadal mode of variability. We verified that it is the case with our model IPSL-CM6A-LR, that found important decadal variability for the first principal component of the North Pacific SST (Fig. R1, right).

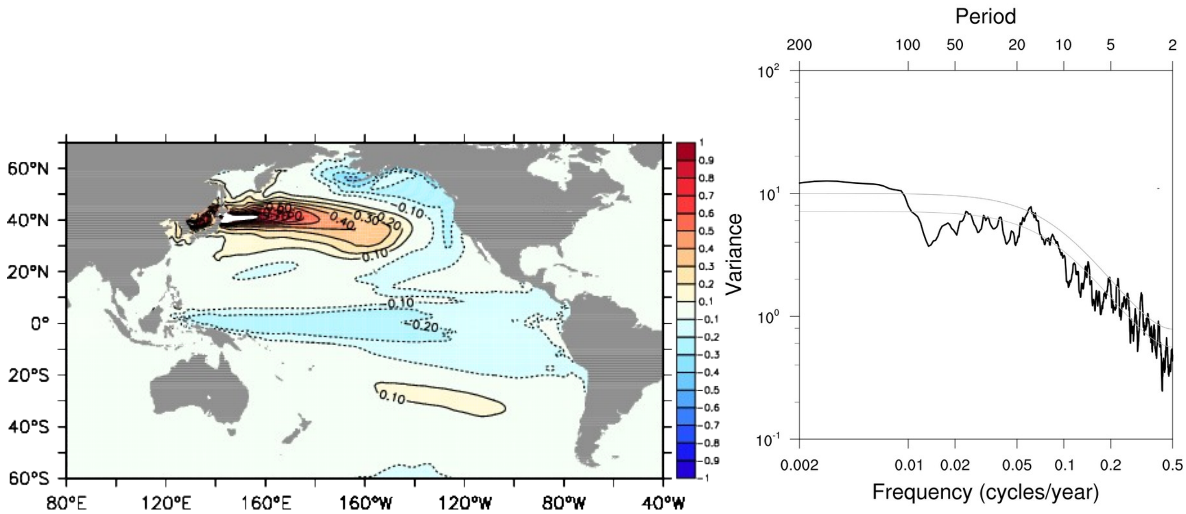

Figure R1. (Left) First EOF of the annual mean North Pacific SST (north of 20°N) with the preindustrial control simulation of the IPSL-CM6A-LR model. It explains 23.8% of the variance. (Right) Variance spectrum of the corresponding first principal component.

We now add a sentence L 238: "*Performing an EOF analysis using the member dimension instead of the time dimension allows capturing all time scales (Maher et al., 2018). It is equivalent to a classical annual EOF over the time dimension. We also verified that the same pattern can be found using the control simulations of the same model, as that the associated time series have important decadal variability.*"

Minor comments:

Line 32: North Atlantic Oscillation (NAO)

Done

Line 34: "while in the *stratosphere* the polar vortex weakens"

Done

Introduction: Is there a hypothesis for the mechanism for reduced sea ice -> negative NAO, and could that be briefly stated in the introduction?

We now provide more details L 75: "*Different physical mechanisms have been proposed to explain the reduced sea-ice and negative NAO relationship. It involves a tropospheric pathway, with a reduction of the equatorward-to-pole lower tropospheric temperature gradient weakening the eddy activity, followed by feedback related to the eddy-mean flow interactions (Smith et al. 2022). A stratospheric pathway was also found, where upward propagating planetary waves into the stratosphere are intensified with sea-ice loss. Such waves lead to a weakening of the polar vortex propagating downward into an Arctic-Oscillation (AO) pattern. "*

Line 74: "late *autum*"

Done

Line 227: Why were concatenated outputs used for the EOF analysis? Taking the second EOF as a physical mode can be problematic (e.g. Dommenget & Latif, 2002 https://doi.org/10.1175/1520-0442(2002)015%3C0216:ACNOTI%3E2.0.CO;2) and, as stated in the text, the first EOF is due to the reduced sea ice, so would taking the EOF from each experiment first and combining them be better

We thank the reviewer for the interesting suggestion. We followed this suggestion, and performed three separate analyses using the outputs of each of the PI, PD and FUT ensembles. The first EOF obtained in each ensemble is indeed similar to the second EOF calculated using the concatenated outputs (see Fig. R2). However, there are also differences among the three EOF1 obtained. Therefore, as proposed, one has to combine the three patterns, and then calculate an index using a projection onto the combined pattern.

As the patterns obtained when taking the EOF from each experiment are similar to EOF2 of concatenated output, it is unlikely that such pattern is associated with little climate physics, as illustrated in Dommenget and Latif (2002). For the sake of simplicity, we decided to not conduct such an analysis.

We added in the manuscript L 257: ''*Although this pattern appears here as the second EOF, a very similar pattern is found as the first EOF conducting separate EOF analysis for each of the PI, PD, and FUT, or using the 2000-yr preindustrial control simulations of the same model (not shown). We also verified that the associated time series have prominent decadal variability in a preindustrial control simulation.*''

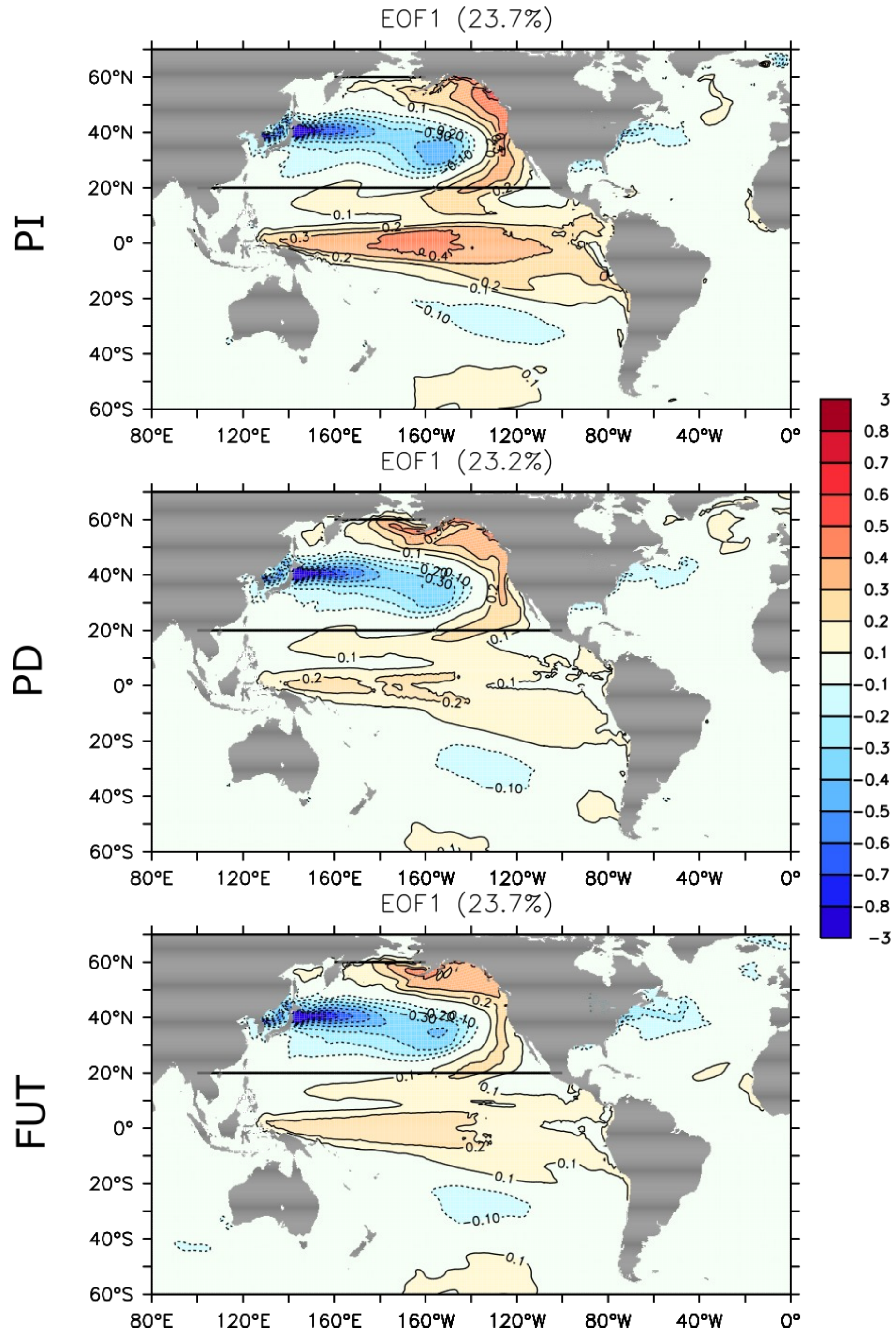

Figure R2. First EOF of the annual mean North Pacific SST (north of 20°N) using separated EOF analyses conducted on the (first line) PI, (second line) PD and (third line) FUT ensembles.

Line 228: "This EOF analysis uses the member dimension instead of the time dimension, as classically used" Since each member is one year, I assume it's equivalent to using annual means, is that right? Could that be briefly specified.

Yes, exactly. The EOF uses yearly SST on the member dimension, so it can be seen as equivalent to using annual means on the temporal dimension.

See the response to the second major comment.

Line 252: "... winter, defined as the 3-month mean in December-February-March" Is that meant to be Dec-Jan-Feb, or is there a reason for excluding January from the winter mean?

We correct it to December-January-February.

Line 269 and 273: "β_{PD} is the regression coefficient determining the effect of the sea ice in PD (FUT) when compared to PI (same for β_{FUT} with FUT);". To make it easier to read, I recommend separating the description of β_{PD} and β_{FUT} into two sentences rather than using parentheses.

Done.

Line 455: Define DCPP

Done.

Line 477: "Concerning the amplitude of the response to sea ice loss". The amplitude of what?

We removed this part of the sentence and now say (L 520): "*Observational studies estimate that winter Arctic sea-ice loss could have led to a much larger NAO-like anomaly than the one found here*"