Reply to Referee 2: egusphere-2025-3140

A. Zhao *et al.*

Correspondence: yyhu@pku.edu.cn

We would like to thank the reviewer for reviewing our manuscript and providing constructive comments. We already aim to revise the text and improve the readability and clarity, as suggested by reviewers. Specifically, we will restructure the introduction to mechanisms of the NAO, and we will avoid referring to the LGM as a predominantly GHG-driven change whilst further emphasising the orographic steering effects. Additionally, we will use better topic sentences as suggested. We
5 will also tighten the references and address the presentational issues. Blue text below is our response to the referee's comments (reproduced in black).

Referee 2

Review of "North Atlantic Oscillation (NAO) in the Paleoclimate Modelling Intercomparison Project (PMIP)" by Zhao, et al.
The authors investigate how the mean state of the European climate and the NAO change in three simulated past climate and
10 one idealised future warming climate. Their results highlight that the NAO is sensitive to GHG-forcing-induced temperature change but not the orbital configurations. They also show consistent changes between the amplitude of the NAO and the precipitation.

A key strength of this paper is the comparison of NAO responses to two distinct types of forcings. The results carry important implications for understanding the NAO response to global warming
15 However, several issues need clarification. In particular, some statements differ from previous studies without sufficient discussion, there are mismatches between text and figures, and the organization of paragraphs could be improved.

Massive thanks. We are happy to make the revisions suggested.

Major points:
20 Line 64-68: The mean state change in the NAO index shows spreads among models. However, the reason summarized in the text is not correct, because most models predict a reduced temperature gradient at lower-level as well as an enhanced temperature gradient at upper-level (see Fig. 3 Harvey et al, 2015). Actually, as shown by McKenna et al, 2021, this "large spread" is mainly due to internal variability.

- McKenna, C. M., & Maycock, A. C. (2021). Sources of uncertainty in Multimodel Large Ensemble projections of the
25 winter North Atlantic Oscillation. Geophysical Research Letters, 48, e2021GL093258. https://doi.org/10.1029/2021GL093258

We will also add in a discussion of internal variability. Thankfully internal variability is less of a factor in the present work, as we can average over substantially longer periods. We were not aware of McKenna & Maycock (2021), so thank you for

bringing it to our attention. It would appear to suggest that internal variability explains only 1/3 of the spread, rather than being the main source of it.

30

Line 43-48: Changes in the NAO index can be partitioned into changes in its mean state (shift in the NAO index distribution) and changes in its variability (changes in the shape of the distribution), see Liu (2025) and O'Brien and Deser (2023). The last sentence in this paragraph is unclear.Why are these two aspects difficult to separate in paleoclimate reconstructions but "easy to distinguish" in paleoclimate simulations? Further clarification is needed.

35 – Liu, Quan, et al. "More extreme summertime North Atlantic Oscillation under climate change." Communications Earth & Environment 6.1 (2025): 474.

–

– O'Brien, J. P. and C. Deser, 2023: Quantifying and understanding forced changes to unforced modes of atmospheric circulation variability over the North Pacific in a coupled model large ensemble. J. Climate, 36, 17-35, doi: 10.1175/JCLI-
40   D-22-0101.1.

Fundamentally, palaeoclimate records consist of individual timeseries at relatively low temporal resolution (annual at best) and often uncertain spacing between the data-points. This alone makes the decomposition between changes at two different timescales challenging. The direct chronological connection between of records at different locations with an accuracy sufficient to be sure they represent the same individual season is not possible. This means that spatial patterns of inter-seasonal
45 variability is out-of-reach.

Line 196 / Line 215 consistency: The midHolocene and lig127k experiments show weaker meridional temperature gradients than the PiControl. According to Line 64, this should lead to a negative NAO-like mean-state change. Yet Line 215 states that the mean state exhibits a positive NAO-like pattern. Do you have an explanation?

50 We apologize for this inconsistency, which may have arisen from the insufficient distinction between the concept of changes in the NAO. The NAO index in future simulations (Lines 61-68) is defined as the difference in DJF zonal mean sea level pressure at fixed latitudes, and "positive/negative" refers to the signal of anomalies considered as the difference in index between the averages from the end of the 21st century under SSP scenarios and averages from 1995–2014. In our study, Line 215 describes the change in sea level pressure. The spatial NAO patterns in the midHolocene and lig127k experiments are indistinguishable
55 from the piControl. The meridional temperature gradients weaken in the midHolocene and 127k experiments compared to the piControl, slightly reducing the magnitude of the positive NAO pattern, but do not reverse its spatial structure (Section 5). Both experiments still exhibit a positive NAO-like pattern. We will revise the text to eliminate the inconsistency.

Line 352: The figure reference is incorrect. Fig. 2a shows temperature changes, not sea-level pressure. Moreover, the text
60 claims "models do not capture a positive NAO-like pattern," but Figs. 2c and 2f clearly display such a pattern. Please reconcile the text with the figures.

"models do not capture a positive NAO-like pattern" comes from the finding of Mauri et al. (2014) as cited in manuscript. We will revise the text during revision.

65   Figure 4: although the caption notes that "the horizontal locations of dots in a does not have any meaning", it's easier for readers to understand if the black dots are in the shaded side (right side) of the distribution, as in Figure 5.
Thanks for the suggestion. We will update the figure.

Section 6 title ("remote effects"): I am wondering if "remote effects" is a good title for section 6. It suggests a focus on
70   NAO impacts on remote climates, but much of the section (e.g., Line 349) discusses NAO amplitude changes under different mean-state backgrounds. A more precise title would improve clarity.
Thanks for the suggestion. We will produce a new title for section 6.

The visibility of the paper could be improved with clearer writing, particularly in the way paragraphs are structured. I noticed
75   that some paragraphs cover multiple topics, and topic sentences are not always clearly stated. For example, in the paragraph starting at line 192, the first sentence is intended as a topic sentence, but it is actually a technical statement that belongs in the methods section (and could be deleted here). Instead, the sentence at line 195 would serve much better as the topic sentence.Another example is the paragraph starting at line 250. It begins with the NAO pattern, then moves on to explained variance, and finally to the magnitude of the NAO index. It would be much clearer if this paragraph were split into separate
80   ones, each focused on a single topic, with a strong topic sentence each. That way, the subsequent discussion of these three aspects (a new paragraph in your manuscript) could be integrated into the corresponding new paragraphs.
Thanks for the suggestion. We will improve the writing.

Minor points:
85   Line 85-88 I suggest to remove the very vague description from "State-of-the-art" to "in different scenarios". Line 175 NAO pattern is a dipole pattern, with negative anomaly at the northern center of action, and positive anomaly at the southern center of action. Therefore, the pattern is always "positive" and the phase is given by the sign of the NAO index. if the EOF gives a "negative" pattern, then both the "eof" and the "pc" should be multiplied by -1. "simulated pattern shows a positive phase" is misleading and should be revised. Line 235 to be more concise, "uncertainty in producing the location of the jet stream, arising
90   from both model bias and internal variability". Line 294 I suggest to remove the vague sentence "The NAO is a variation in the atmospheric pressure differences between the Icelandic Low and the Azores High."
Many thanks for listing the points. We will revise the text as suggested during the revision.