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17/06/2026

Re: MS No.: egusphere-2025-5400

Dear Editor,

We sincerely thank the reviewers for their thorough review and constructive feedback on our manuscript. The suggestions have been very helpful in improving the quality of the manuscript. Below, we provide a detailed, point-by-point response to all comments. For clarity, the reviewers' comments are shown in black, our responses are shown in blue, and the corresponding revisions made to the manuscript are shown in blue italics. The line numbers referred to below correspond to the revised manuscript.

Reviewer 1 comments:

This is a well written manuscript that investigates the relationship between surge/wave climate conditions and climate indices at a location (UK, North Sea). In comparison to previous studies covering the same subject, this study provides added insights by investigating a set of wave parameters (including sea and swell decomposition) with a well-stablished weather typing approach. This provides a better understanding of whether, and how, climate modes can impact waves and surges. While the study is applied to a single location, it seems that a similar approach could be followed for other locations, leading to improved understanding of these links for other areas as well. I do not have major comments and thus recommend the publication of the paper. However, I have a few suggestions that I encourage the authors to address or consider that can potentially help to improve the manuscript.

Response: Thank you for your positive comments and recommendation for the publication of the paper.

While I think the weather typing approach provides additional insights, in my opinion a fair portion of the additional insights derived in this study come also from the fact of analyzing the wave climate using a multivariate field and sea/swell partitions, which is not commonly done in previous similar studies. I suggest the authors state that, as not all the added value comes from the weather typing approach alone. In other words, some of the conclusions derived in this study could also be derived by just looking at the entire time series of events associated to each variable without dividing into weather patterns. The division of weather patterns surely provides additional information, but it is not the only key element.

Response: We thank the reviewer for this important clarification. We agree that the added value of the study does not arise from the weather-typing framework alone but from coupling that with a detailed multivariate analysis that links ocean-atmosphere teleconnections and local storm surge and sea and swell conditions. We revised the manuscript to acknowledge the value of using multivariate sea state conditions in Lines 413-416. These lines read:

'The added value of this study arises from combining weather typing with a multivariate characterization of sea state conditions, including the partitioning of the wave field into wind wave and swell components. The WT framework provides a probabilistic link between climate modes, synoptic circulation patterns, and local sea state distributions, while the partitioned wave analysis reveals response features that would not be evident from the combined wave fields.'

It could be informative to add Figure 4 as obtained from the mean wave period for the sea/swell partitions. Looking at Tp only can still mask some wind/swell events if the wind sea (or swell) partition is consistently the most energetic for certain weather types. Similarly, it would also be informative to see the same type of figure for Hs, with and without sea/swell separation (perhaps in the SM).

Response: We agree that the additional figures mentioned by the reviewer are worth being included in the manuscript. As such, we added the suggested figures in Appendix A. See Figures A1-A4, which present the empirical distributions of hourly Hs, and Tm associated with WTs that occur more frequently during each index phase (A1 and A2 respectively), as well as the corresponding distributions partitioned between sea and swell components in A3 and A4.

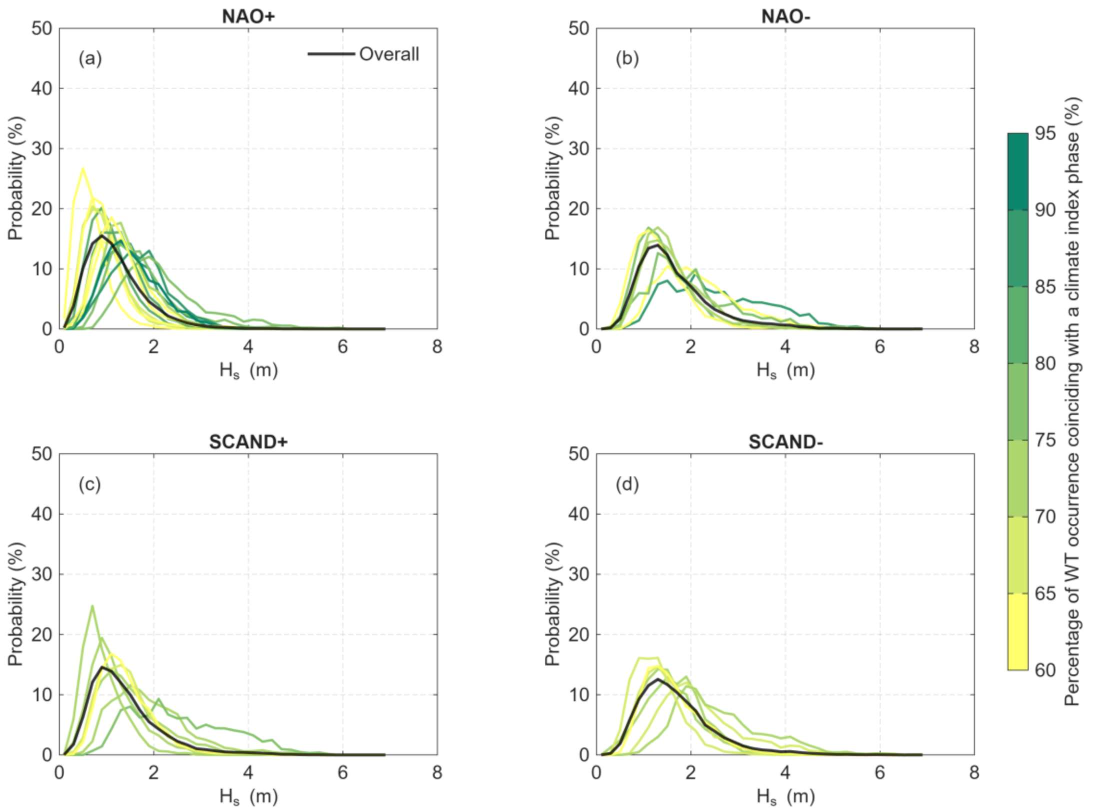

Figure A1. The empirical distributions of hourly H_s associated with WTs that occur more frequently during each climate index phase. Each coloured distribution is associated with an individual WT, with the colour representing the percentage of WT occurrence in particular NAO or SCAND phases in Table B1, thus indicating the strength of the association. The overall distributions (black) are derived from all hourly H_s values from WTs assigned to the same category of index phase.

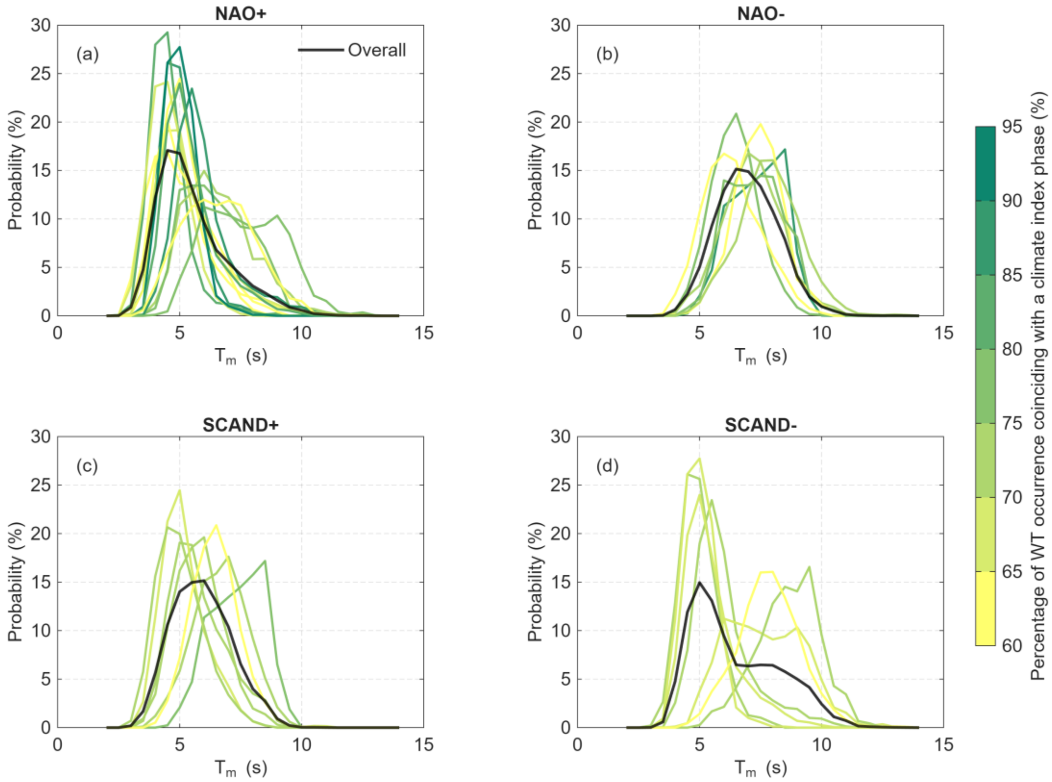

Figure A2. The empirical distributions of hourly T_m associated with WTs that occur more frequently during each climate index phase (similar to Fig. A1).

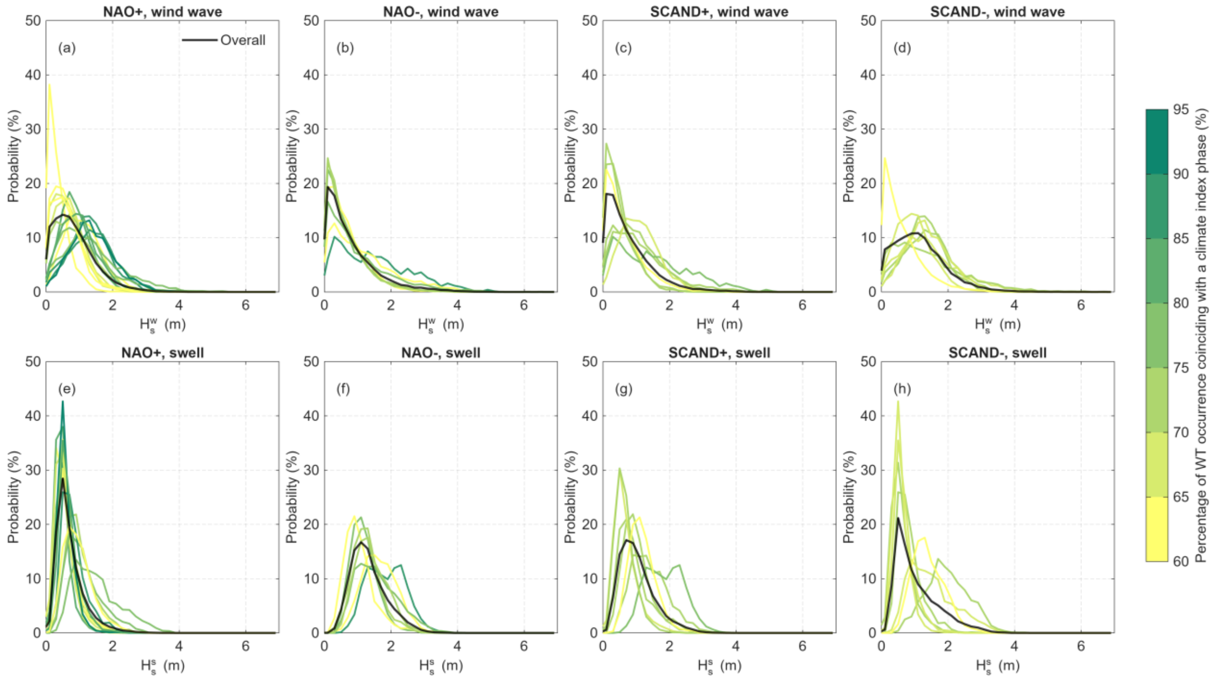

Figure A3. The empirical distributions of hourly H_w^s and H_s^s associated with WTs that occur more frequently during each climate index phase (similar to Fig. A1).

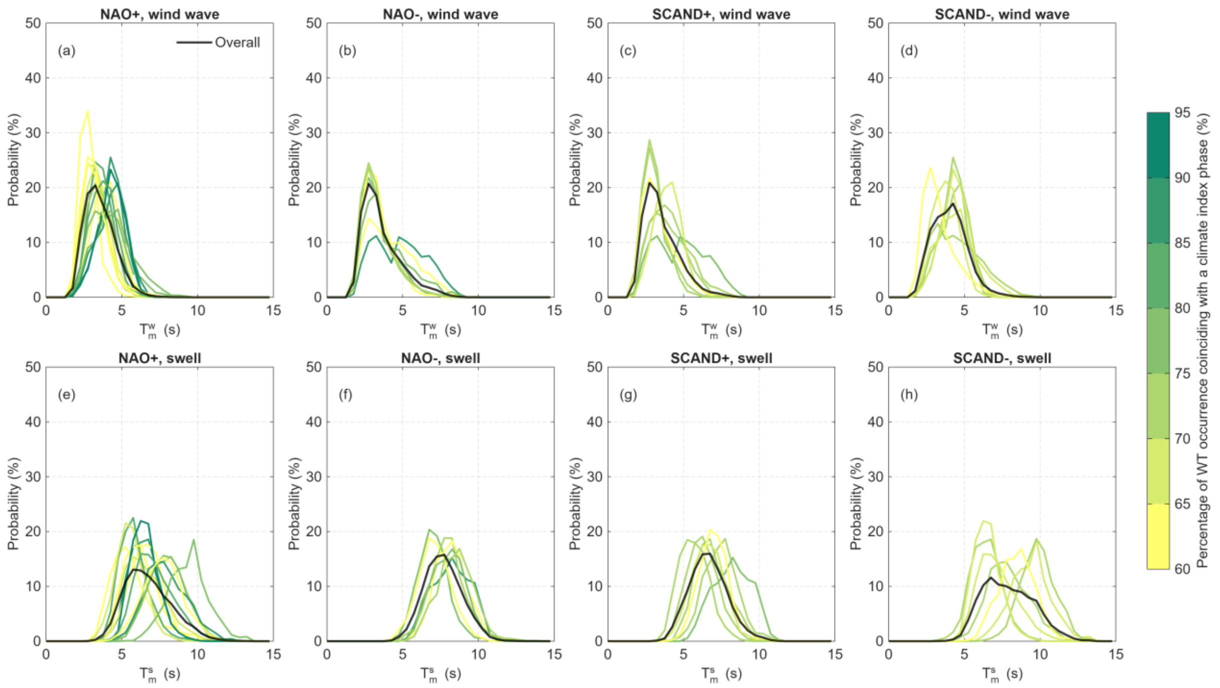

Figure A4. The empirical distributions of hourly T_w^m and T_s^m associated with WTs that occur more frequently during each climate index phase (similar to Fig. A1).

Finally, considering that the authors analyze both waves and surges, it could be interesting to investigate the impact of climate indices to compound surge-wave events. I understand that a comprehensive analysis in this regard might be out of the scope of this study, but they could provide some preliminary results, such as the correlation between surge and waves associated to different weather types and climate indices. This could increase the added value of the paper, especially in the relevance of nowadays' compound analysis frameworks.

Response: We agree that there is great value of conducting compound wave-surge analysis but this is currently out of scope for this study and is a potential avenue to explore in future work. A robust assessment would require more than comparing simple correlations, particularly because compound hazards depend on the joint distribution, temporal concurrence, event definition, and potentially tidal conditions as well as non-linear feedback mechanisms between these processes. We therefore consider that a comprehensive compound analysis would be better addressed in a dedicated study rather than added as a preliminary analysis here.

Furthermore, as the significant wave height does not show significant relationships with climate index phases, we suspect that any climate-related modulation of compound wave-surge events may be weak or expressed through other wave characteristics. As such, Hartlepool might not be a suitable location for clearly demonstrating such an effect. Nevertheless, we revised the discussion (Lines 424-428) to identify compound wave-surge analysis as a valuable future application of the framework. The lines read:

'It would also be interesting to examine whether climate indices also modulate the probability of compound wave–surge events. In addition, the local tidal range varies from around 1 to 5 m. Incorporating tidal variability into such an analysis might further clarify whether extreme coastal water levels during particular climate index phases arise from the concurrence of multiple drivers or from the dominance of a single component. A comprehensive compound analysis of waves, surge, and tide is, however, beyond the scope of the present study.'

Reviewer 2 comments:

"Linking large-scale climate oscillations to local wave climate and storm surge: insights from a weather typing approach" by Zhong et al. describes the relationships between wave and storm surge properties and climate oscillations near Hartlepool, UK, and how these can be tied to specific weather regimes. This paper is technically sound and uses appropriate data and analysis techniques. Rather than how the chosen analysis method has been implemented, my main question is why that analysis method was chosen. Whilst I don't believe it was the intention of the authors, the paper reads like the purpose was to use a specific analysis method, rather than answering a specific question and using the most appropriate method to do that.

After reading the paper, I was not convinced of the need to use weather types as in intermediary for explaining the relationship between climate oscillations and surges/waves. I was expecting to see strong statements like (for example) "NAO- is associated with larger period waves because the more common WTs associated with it are where storms are further offshore, and hence, waves have larger fetch" (Figure 4) and "NAO+ is associated with larger storm surges because the more common WTs associated with it are where storms are closer to shore, and hence, there is lower pressure and stronger winds at Hartlepool" (Figure 7). To me, this is why you would use weather types to explain the relationship between climate drivers and wave/surge, rather than present two separate analyses – one that looks at weather types and wave/surge response and one that looks at climate oscillations and wave/surge response.

Response: We thank the reviewer for their valuable comments. We agree that the original manuscript could have explained the role of WTs more clearly and better demonstrated the added value of considering them. Our intention is not to use WTs primarily to identify climate--sea-state relationships, but rather to provide an intermediate, physically interpretable layer between climate modes and local sea-state variability. We have therefore revised the manuscript to clarify how WTs provide a physically interpretable by showing how climate phases alter the occurrence probabilities of synoptic circulation patterns and their associated atmospheric forcing:

- Lines 67-70 (introduction), we highlight the distinct role of weather type:
  'While direct correlation analyses can identify whether climate indices are associated with wave or surge variability, they provide limited information on the synoptic-scale atmospheric conditions through which these associations develop. In this research, we use weather types as an intermediate layer linking interannual climate modes to daily-scale atmospheric circulation and, ultimately, to local sea state variability.'

- Lines 352-355 (discussion), we reiterate the purpose of introducing weather types as a means of interpreting how relationships between climatic index phases and sea state arise develop.
  'The direct correlation analysis identifies which climate indices are statistically related to local sea state variability at Hartlepool, whereas the WT analysis helps interpret how these relationships arise. In this sense, WTs are not used primarily to detect climate--sea state relationships; rather, they provide a probabilistic link between climate modes, atmospheric circulation patterns, and local wave and surge distributions.'

- Lines 381-393 and 405-411 (discussion), we specifically discuss how the synoptic information provided by weather types can explain the identified climate-sea state relationships for wave climate and storm surge, respectively. These revisions provide the type of statements suggested by the reviewer.
  'The WT analysis helps interpret why these phase-dependent wave responses arise, by showing how climate modes alter the occurrence probabilities of synoptic circulation patterns that favour different combinations of remote swell generation and local wind forcing. During NAO+/SCAND-, it is more likely to observe WTs characterized by intense low pressure systems centred near Iceland, the Norwegian Sea, or the Scandinavian Peninsula. These regions also correspond to areas of enhanced storm activity and are relatively distant from Hartlepool, allowing remotely generated waves to develop longer periods before reaching the site. Meanwhile, most of these WTs are also characterized by strong local south-westerly wind forcing across the UK, contributing to more energetic wind wave conditions. In comparison, WTs that occur more frequently during NAO-/SCAND+ are characterized by low pressure systems located at lower latitudes, mainly around the British Isles. Under these conditions, the North Sea becomes a more

important source region for swell generation. Because this source region is closer to Hartlepool, the resulting swell is likely to have shorter propagation distances and therefore less time to develop into distinctly long-period waves. At the same time, the distribution of low pressure systems of these WTs is less spatially concentrated. This leads to larger variability in the orientation of pressure gradient, which favours less consistent wind wave directions.'

'The response patterns of μ_{SS} and σ_{SS} are related to the effects of local atmospheric pressure and wind stress, both of which are modulated by large-scale climate modes. During NAO+/SCAND-, WTs characterized by negative pressure anomalies over Hartlepool and stronger winds occur more frequently. Similar synoptic conditions have been reported in previous studies (e.g., Gleeson et al., 2019; Scott et al., 2021). These conditions contribute to the increase in μ_{SS} and σ_{SS}, producing SS distributions that are more widely spread and shifted toward positive values. In comparison, WTs occurring more frequently during NAO-/SCAND+ are generally associated with positive pressure anomalies and weaker winds over the study region. These conditions favour lower μ_{SS} and reduced σ_{SS}, resulting in SS distributions that are more narrowly centred around zero.'

- Lines 476-482 (conclusion), the interpretation of climate-sea state relationships through weather types is summarised.
  'Our analysis suggests that WTs that occur more frequently during NAO+/SCAND- are characterized by stronger westerly winds, enhanced storm activity at higher latitudes, and more negative local pressure anomalies. These conditions favour a combination of locally generated wind waves, remotely generated longer-period swell, and storm-surge distributions with higher means and greater variability. In contrast, WTs occurring more frequently during NAO-/SCAND+ are generally associated with weaker and more variable local winds, storm activity concentrated closer to the North Sea, and more positive pressure anomalies. These conditions favour a greater relative contribution from swell generated nearer to the site and storm surge distributions with smaller means and reduced variability.'

I have a few suggestions for how these changes could be implemented in a revised manuscript:

1. Follow the logic set out in the final sentence of the introduction. First, talk about climate oscillations which have a significant/important/notable relationship to wave/surge. Second, describe what the wave/surge response is. Third, explain how WTs can explain why oscillations elicit the responses that they do. I would consider combining methods and results for these sub-sections to make it clear that WTs are only relevant for the third part. This includes re-doing figures.

Response: We thank the reviewer for the structural suggestion. We have revised the manuscript to follow this three-step logic more explicitly. The revisions are made mainly in Sections 4.1 and 4.2, where the discussion of the identified response pattern (objective 2) and the interpretation based on WTs (objective 3) are more clearly separated. We also emphasize that the consideration of WTs is more relevant for objective 3 in following lines.

Lines 305-308: 'The third objective of this study is to investigate the atmospheric processes linking climate modes to the corresponding sea state responses. At this stage, WTs become particularly relevant, as they provide an intermediate, physically interpretable layer for identifying the synoptic-scale atmospheric conditions through which climate modes influence local sea-state variability. These conditions are examined in terms of wind forcing, storm activity, and atmospheric pressure anomalies.'

Lines 352-355: 'The direct correlation analysis identifies which climate indices are statistically related to local sea state variability at Hartlepool, whereas the WT analysis helps interpret how these relationships arise. In this sense, WTs are not used primarily to detect climate–sea state relationships; rather, they provide a probabilistic link between climate modes, atmospheric circulation patterns, and local wave and surge distributions.'

We retained separate Methods and Results sections rather than combining them, as we consider this structure clearer for presenting the analytical procedures and corresponding findings. Besides, we think the ambiguity surrounding the relevance of WTs in the original manuscript arose primarily because their purpose was not sufficiently explained or clearly distinguished from the direct correlation and sea-state response analyses, rather than from the overall section structure. This is now addressed through the amendments made in response to the reviewers' comments. This issue is closely related to the reviewer's preceding comment, and the corresponding revisions are summarized in our response above.

2. Be clear about why you want to investigate climate oscillations. Presumably it is around the multi-year predictability of NAO that just doesn't exist in synoptic timescales. This paper and the references therein may be helpful (https://www.nature.com/articles/s41612-025-01027-7), although I note I am not as familiar the UK context as you likely are being based in the UK.

Response: We thank the reviewer for highlighting the predictability of NAO and providing this relevant reference. We have added a paragraph in Lines 437-443 to discuss the implications of this research for seasonal-to-decadal prediction of climate and sea state conditions. The paragraph reads:

'Investigating the influence of climate modes through weather types is also relevant from a predictability perspective. Individual synoptic weather systems have limited predictability beyond weather-forecast timescales, whereas slowly varying climate modes may contain predictable components on seasonal to decadal timescales (Dunstone et al., 2016; Athanasiadis et al., 2020), although the level of skill varies among prediction systems and remains sensitive to the representation of North Atlantic Ocean–atmosphere interactions (Patrizio et al., 2025). Establishing how such climate modes alter the occurrence probabilities of synoptic circulation patterns and associated local sea states could therefore provide a basis for translating large-scale climate predictions into probabilistic information on coastal wave and storm surge conditions.'

3. Be clear about all relationships being probabilistic rather than deterministic: a specific WT may load the dice towards a specific hazardous wave and surge condition occurring, and specific climatic condition may load the dice towards a specific WT occurring. I would discourage the use of phrases that imply there is a deterministic relationship (e.g., "For WTs associated with NAO+" – Line 240). Therefore, the main value in considering WTs is why the observed relationship between oscillations and wave/surge exist, not as a means of identifying the relationship (there would be a stronger signal if one simply looked at the relationship directly).

Response: Indeed, the relationships are probabilistic rather than deterministic, and we agree that the original wording can be misleading. We have revised the manuscript throughout to avoid wording that implies a one-to-one correspondence. For example, phrases such as "WTs associated with NAO+" have been replaced with expressions such as "WTs occurring more frequently during NAO+" or "WTs with higher occurrence probabilities during NAO+." We have also added an explicit statement in Lines 179-182, clarifying that WTs assigned to a given climatic index phase may still occur during the opposite phase, but at lower frequencies. The lines read:

'It should be noted that the association between WTs and climate modes is probabilistic rather than deterministic. In other words, WTs associated with a given climate index phase tend to occur more frequently during that phase, but they can also occur during the opposite phase, albeit at lower probabilities.'

4. Consider tides and how this impacts risk of extreme water levels at the Hartlepool Power Station. For example, Whitby has a tidal range of ~ 5 metres. Hence, whether a storm surge or large wave event occurs at a spring tide or neap tide is critically important. At a minimum I think the following question should be answered and its implications discussed: Are the times of year when climate oscillations most likely to lead to high waves and large surges also the times of year when tides are highest?

Response: We thank the reviewer for emphasizing the importance of tides in determining extreme total water levels and coastal risk at Hartlepool. We agree that the timing of high waves and storm surges relative to the tidal phase is critical. Having said that, the present study is designed to investigate how large-scale climate oscillations influence meteorologically driven wave and storm-surge conditions through changes in WT occurrence. Astronomical tides differ fundamentally from these variables because they are predominantly deterministic and are not generated or directly modulated by synoptic WTs. Therefore, we are concerned that the WT-based framework used here is not, by itself, the most appropriate method for such an analysis. It would perhaps require a dedicated event-based analysis of total water level, including the temporal dependence and potential nonlinear interactions among tide, storm surge, and waves. We therefore consider incorporating tide into the current analysis to be beyond the scope of the present study. To acknowledge these comments, we added this analysis as potential future research in Lines 424-428, which read:

'It would also be interesting to examine whether climate indices also modulate the probability of compound wave-surge events. In addition, the local tidal range varies from around 1 to 5 m. Incorporating tidal variability into such an analysis might further clarify whether extreme coastal

water levels during particular climate index phases arise from the concurrence of multiple drivers or from the dominance of a single component. A comprehensive compound analysis of waves, surge, and tide is, however, beyond the scope of the present study.'

Many Thanks,

Zehua Zhong, on behalf of all the authors