

RC2: '[Comment on egusphere-2025-5715](#)', Anonymous Referee #2, 25 Feb 2026 [reply](#)

Authors Response to the comments of two anonymous reviewer **#2** on the manuscript *egusphere-2025-5715*

„An ensemble of regional wind wave scenarios for the North Sea and the Baltic Sea: a revisit“ by Nikolaus Groll and Iris Grabemann

We would like to thank reviewer #2 for the comments, which helped us to improve the manuscript. The reviewer's comments are shown in blue below. The authors' response will appear below each comment, and any suggested changes to the text will be in orange and italics. The referred line numbers correspond to the line numbers in the original submitted manuscript.

The manuscript only includes CMIP3 and CMIP5 simulations, while CMIP6 is now widely used. (1) Why were CMIP6 projections not incorporated? (2) Even if unavailable, this limitation must be clearly justified and discussed. (3) A comparison with recent CMIP6-based wave studies would strengthen the manuscript.

We would like to thank the reviewer for raising this important point. When our simulations were carried out, regionalised atmospheric forcing based on CMIP6 was unavailable or only available to a very limited extent for the North Sea and the Baltic Sea. Sea state studies require high-resolution wind fields from regional climate models because global models do not adequately resolve complex coastal morphologies and local wind systems. Following a review of the literature, the authors are not aware of any peer-reviewed sea state studies for the North Sea and the Baltic Sea based on regionalised CMIP6 scenarios that have been published. Of the few CMIP6-based sea state studies available, those with a global scope (e.g. Meucci et al., 2024) and one using a machine learning approach for the Baltic Sea (Dubois et al., 2025) all use GCM wind fields directly, without regional downscaling. While it is difficult to draw regional conclusions from global studies a priori, the machine learning study shows a large range of possible changes in significant wave height (increase and decrease) depending on the GCM used for the forcing.

This shows that our study, which uses CMIP3/CMIP5-based regional forcing, can still make a valuable contribution to scientific knowledge about future sea state variability. We now address this more explicitly in the title and in the discussion, emphasising that future studies will benefit from CMIP6-based analyses as soon as the necessary regionalised forcing data are available and compare the results of the few existing CMIP6 studies with our findings.

Title: An ensemble of regional *CMIP3/CMIP5* wind wave scenarios for the North Sea and the Baltic Sea: a revisit

L309: *In the absence of regionalised atmospheric forcing based on CMIP6 simulations, which is required for regional wave analysis, global wind wave studies (e.g. Meucci et*

*al., 2023) cannot resolve evidence of changes to, or persistence in, significant wave height. However, Dubois et al. (2025) used a machine learning approach with global CMIP6 atmospheric forcing under the SSP2-4.5 scenario and showed a wide range of possible changes in significant wave height (increases and decreases) depending on the GCM used for the forcing.*

The ensemble includes 4 time-slice simulations and 10 transient simulations. The main Concerns are that these simulation types are methodologically different, with Time-slice experiments lacking transient internal variability representation. Secondly, Secodn the Mixing them in the same ensemble may introduce structural inconsistencies. The authors must justify combining both types (1) Assess whether results change when excluding time-slice runs.

We agree that combining time-slice and transient runs should be analysed with caution. However, given the available data for regional sea state projections, this is a pragmatic necessity also employed in other regional climate studies (Jacob et al., 2014, Grabemann et al., 2015). It is important to note that we are only comparing equivalent time periods. Déqué et al. (2012) demonstrate that time-slice and transient simulations produce comparable climate signals within specific time frames, while discussing also source of uncertainty. Additionally, when the individual time slice experiments are compared, they fall well within the range of the transient experiments (see Figures A1 to A3 in the Appendix). Based on this comparison, we have decided not to conduct an explicit analysis of changes with and without the time slice experiments. This methodological aspect has now been discussed more explicitly in the revised methods section, and the limitation has been made clear.

*L68: When combining time-slice experiments and transient simulations into one ensemble, it is important to use the same time period as defined by the time-slice experiments. Additionally, we only use time-slice experiments for the spatial comparison of 30-year mean statistical values. Therefore, the possible lack of transient internal variability can be neglected.*

*L345: It should be noted, when comparing the four time slice experiments (a2.e4rc, a2.h3rc, b2.e4rc and b2.h3rc) with the other ten transient simulations, their changes fell well within the range of the transient experiments.*

The manuscript states that all ensemble members are treated as equally plausible. Issues: (1) Different GCM–RCM combinations have varying skill. (2) No performance-based weighting is applied. (3) No evaluation of historical skill for CMIP5-driven runs is shown.

We thank the reviewer for raising this important point. Our decision to use equal weighting aligns with the 'ensemble of opportunity' approach adopted in climate modelling (Tebaldi & Knutti, 2007; Knutti et al., 2010). Although weighting schemes have been developed based on historical performance, studies show that these do not necessarily lead to more robust future projections (Weigel et al., 2010), since future

model performance remains uncertain by its very nature. In the absence of clear evidence that specific model combinations are superior for sea state projections in the North Sea and the Baltic Sea, we consider equal weighting to be transparent and justifiable, as it reflects the entire spectrum of model uncertainty.

*L55: Following the approach from Tebaldi & Knutti (2007) and Knutti et al. (2010) of 'ensemble of opportunity', and studies showing that possible weighting of ensemble members based on the historical performance does not necessarily lead to more robust future projections (e.g. Weigel et al. 2010), hence we treat every member of the ensemble as equal plausible and introduce no kind of weighting.*

We agree that an evaluation of the CMIP5 runs would be valuable, the revised version includes a comparison of the distribution of yearly statistical values for the historical period. To avoid distracting from the main focus of this study, we have included this comparison in the appendix.

L79: Previous studies have shown *that for the CMIP3 simulations* the model is capable of representing the historical climate (e.g., Weisse and Günther, 2007; Groll et al., 2014a, 2017). *A verification of the CMIP5 simulations is presented in Appendix.*

#### *Appendix B. Distribution comparison of the significant wave height in historical period*

*To test the model's ability to reproduce the significant waves in the reference period, a distributional comparison between the model members and a reference dataset was done at two locations in the North Sea GBI and TYN (Figure B1), and two locations in the Baltic Sea, ARB and CBP (Figure B2). As reference dataset the regional wave hindcast coastDat3 (Groll 2024) was used. However, as the historical parts of the climate projections only incorporate greenhouse gas concentrations and no actual weather information, a direct comparison of the time series is not meaningful. Instead, the comparison is structured across three statistical metrics: Maximum values, 99<sup>th</sup> percentile and median, are displayed as density distributions for each location. The overall distributions of the climate models for the maximum, 99th percentile and median at the GBI location (Figure B1, upper panels) in the south-eastern North Sea show very similar distributions with minimal deviation from the hindcast distribution. This demonstrates that the wave conditions are reliably represented. At the TYN location in the western North Sea (see Figure B1, lower panels), the distribution ranges for the climate models are generally broader than the range for CoastDat3, with several models showing notably flatter distributions, particularly C20\_e5hi.3. While most climate models show a comparable distribution with an acceptable difference to the reference, model member C20\_e5hi.3 shows substantially higher 99th percentile and median values, representing a considerable difference in these wave conditions. As fewer climate simulations are available for the Baltic, only four historical simulations are compared with the hindcast coastDat3. At the ARB location in the western Baltic Sea (see Figure B2, upper panels), the distributions of the two CMIP5 models (hg.re and me.re) are within the range of the hindcast, while the distributions of the other two models are slightly shifted towards higher values. Nevertheless, all climate model simulations*

provide a generally reliable representation of the wave conditions. Finally, the maximum distributions at location CBP in the central Baltic (see Figure B2, lower panels) are notably broader than those at ARB. All four climate model distributions fall well within the range of the hindcast distribution. While the CMIP5 climate models demonstrate good overall agreement with the 99th percentile hindcast distribution, the other two climate model distributions are slightly broader and shifted towards higher values. All climate models show good agreement with the relatively narrow, well-defined median distributions. Although differences are observed between the absolute values from the climate model simulations and the hindcast data, particularly at location TYN, and the notable inter-model variability underscores the challenges of reproducing absolute wave climate characteristics using climate models, the overall conclusion is that the distributions from the climate models are in good agreement with the reference hindcast. However, due to the differences in absolute values, the main analysis focuses on the relative changes that occur between different time periods, rather than the absolute values themselves.

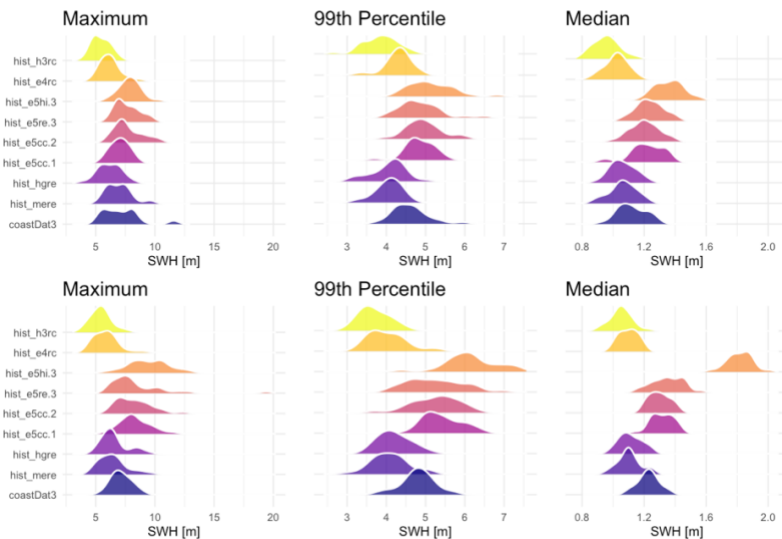


Figure B 1: The density distribution maximum, 99th percentile and median SWH for the historical simulation (hist\_) and the hindcast simulation (coastDat3) for two locations in the North Sea (GBI in the upper panels and TYN in the lower panels). The abbreviation after 'hist\_' indicates the respective ensemble member, as shown in Tabel 1.

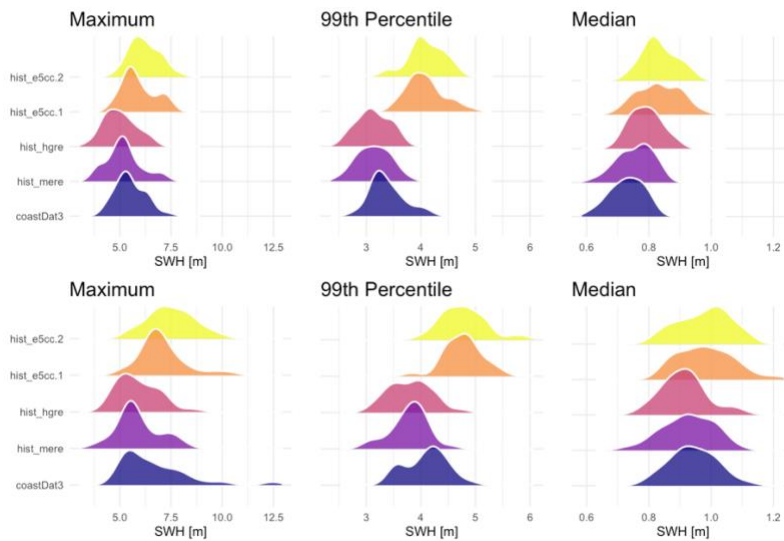


Figure B 2: The density distribution maximum, 99th percentile and median SWH for the historical simulation (hist\_) and the hindcast simulation (coastDat3) for two locations in the Baltic Sea (ARB in the upper panels and CBP in the lower panels). The abbreviation after 'hist\_' indicates the respective ensemble member, as shown in Tabel 1.

While spatial patterns are described, physical mechanisms are only briefly discussed. Provide the detailed wind field change diagnostics, NAO influence discussion, Storm track shifts, Changes in cyclone intensity, Fetch and directional wave energy changes.

Comprehensive documentation of the underlying atmospheric changes in NAO, storm tracks and cyclone activity and the resulting changes in the wind climate of the North Sea and the Baltic Sea under CMIP3/CMIP5 scenarios and they are already available (e.g. Feser et al., 2015; Meier et al., 2022).

Pinto et al. (2007) noted for the underlying CMIP3 GCM simulations using the A1B and B1 projections, a shift towards stronger westerly winds is consistent with a shift towards more positive North Atlantic Oscillation (NAO) phases. They also demonstrated the multi-decadal variability of the NAO index throughout the twenty-first century. Analysing 12 GCM simulation under CMIP5 scenarios in the North Sea, de Winter et al. (2013) show generally that no significant changes in extreme annual winds are projected, however the two GCMs used in the presented study show a tendency towards an increase in the North Sea region. Zappa et al. (2013) predict an extension of the North Atlantic storm track towards Europe in winter, which would lead to slight increase of the wind intensity in the area from the British Isles into the Baltic Sea.

The changes in wind conditions over the Baltic Sea examined in the CMIP3 projections used have already been discussed in Groll et al. (2017) showing a small to moderate increase of the annual wind statistics. Christiansen et al. (2022) showed that, for a larger CMIP5 ensemble, there was little agreement on possible changes. However, slight positive changes in 75 percentile wind speeds under RCP 8.5 towards the end of

the 21st century can be detected, which are more pronounced in northern regions (in supplement section of Christiansen et al. (2022)).

The changes in sea state that we discussed are consistent with the documented wind patterns. A detailed analysis of the wind climate would exceed the scope of this study. However, we have included a section in the discussion that contextualises our results within the framework of studies on the wind climate.

*L277: Pinto et al. (2007) identified in the underlying CMIP3 GCM simulations using the A1B and B1 projections, a shift towards more positive North Atlantic Oscillation (NAO) phases, which lead to a shift towards more westerly winds. They also showed multi-decadal variability of the NAO index throughout the twenty-first century. Also, Zappa et al. (2013) using 19 CMIP5 GCM simulations predicted an extension of the North Atlantic storm track towards Europe in winter, which would lead to slight increase of the wind intensity in the area from the British Isles into the Baltic Sea. Ruosteenoja et al. (2019), among others, found that, the strong westerly winds are projected to occur more often in CMIP5 experiments. In contrast, a decrease of easterly winds is evident. Studies using a larger ensemble and CMIP3 and CMIP5 experiments indicate no robust change in the wind field over the North Sea and Baltic Sea regions (e.g. Feser et al., 2015; Meier et al., 2022). De Winter et al. (2013), using 12 GCM CMIP5 simulations, also show that generally no significant changes in extreme annual winds are projected. However, the two GCMs used in the presented study indicate an increasing trend in the North Sea region. Christiansen et al. (2022) demonstrated that, for a larger CMIP5 ensemble, there was little agreement on possible changes for the Baltic Sea. Nevertheless, slight positive changes in 75th percentile wind speeds under RCP 8.5 towards the end of the 21st century can be detected, which are more pronounced in the north.*

*L 314: Additionally, initial CMIP6 studies on wind changes (Wohland, 2022; Carvalho et al., 2021) show significant discrepancies with CMIP5 results for Northern Europe. Unlike CMIP5 projections, CMIP6 projections do not predict an increase in annual wind resources but show a notable redistribution across seasons. Krieger and Weisse (2025) analysed storm activity in the German Bight using a multi-model approach with CMIP6 global simulations and found that, although the frequency of westerlies is likely to increase, overall storm activity will probably decrease, while the most extreme storms may become more frequent. The impact of these changes on the wave climate is still uncertain and should be addressed once regionalised CMIP6 atmospheric data becomes available. Incorporating these future wave scenarios will enable projections to be refined further and sources of uncertainty to be addressed more precisely.*

NOTE:

While working on the revised version of the manuscript to address the reviewers' comments, we found inconsistencies in the calculation of the 30-year running means for some ensemble members (e5cc\_a1b\_1, e5cc\_a1b\_2, e5cc\_b1\_1 and e5cc\_b1\_2) at location GBI. Consistent calculations of the time series of 30-year running means for these four ensemble members led to slight changes in the ensemble medians for high

and low emission scenarios. While the overall conclusion remains the same, the description of Figure 4 in the submitted manuscript has been adapted as follows:

L204: Although neither exhibits a consistent upward trend throughout the 21st century, both ensemble medians show an increase towards the end. *The high-emission sub-ensemble also showed a statistically significant increase in the middle of the simulation period, demonstrating a rise of over 8%. Both ensembles showed an increase of around 5% towards the end of the simulation period, but only the increase for the high-emission sub-ensemble was statistically significant.*

L207: The median for the high-emission sub-ensemble again shows a larger and statistically significant increase of *more than* 5 % by the end of the century.

L211: By contrast, the sub-ensemble for low-emission scenarios exhibits *no significant changes*, suggesting that changes in the 99th percentile SWH at GBI are less robust.

L215: Neither the median SWH *for the high- and low-emission sub-ensembles, nor the maximum and 99th percentile SWH for the low-emission sub-ensembles*, shows statistically significant changes, implying that any trends are either too small to detect or are masked by substantial internal ensemble variability.

L288: The time series analysis for the location in the German Bight shows, that the high-emission scenarios exhibit stronger and more consistent increases over time than low-emission scenarios. ~~., although statistically significant trends are primarily confined to the 99th percentile.~~

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