Response to Reviewer 1 Comments

Börgel, Ruvalcaba Baroni et al.

General Response

We thank the reviewer for the thorough and constructive feedback. Below we provide our point-by-point responses (in blue) to each reviewer's comment (in red), followed by the corresponding changes implemented in the revised manuscript (in italics). Line/section numbers will be updated after final formatting.

Main points

Main point 1

Reviewer: Perhaps unavoidable for a multiple-authorship manuscript, some sections appear less consistent with the rest of the manuscript. Other sections read more as a listing of results, where the reader would more strongly benefit from an interpretation of those results into a coherent picture. This could be amended with little effort. I give some specific examples below.

Response:

We agree and will revise the affected sections to improve consistency in terminology, structure, and narrative style across the manuscript. In particular, we will add synthesis sentences to better interpret the findings of the study and link them to the overall teleconnection framework and the Baltic Sea system.

Main point 2

Reviewer: More effort, in my view, should, however, be placed into the Conclusion section. In a review paper, the conclusions section is probably more critical than in other types of manuscripts, and in this case it appears to me as too unspecific. After reading it several times, my take-home message was 'more needs to be done' and 'uncertainties still remain'. This is true for many fields of research, but a review manuscript should provide the reader with a more specific message. Perhaps the authors would like to restructure this section, including the grading of certainty. For instance, the section could be wrapped up with a paragraph of more certain findings, followed by less specific findings, and conclude with the questions that are still unresolved and really need targeted research.

Response:

We agree with the reviewer and we will revise the conclusions to provide clearer take-home messages. We will also extend it with concrete examples and improve it's structure. New text will read as follows:

Changes to the text: "The Baltic Sea is located at the confluence of Atlantic, Arctic and continental influences, with variability controlled primarily by large-scale atmospheric circulation over the North Atlantic-European sector, especially the North Atlantic jet and associated circulation patterns such as the NAO, East Atlantic, and Scandinavian patterns (e.g., Chafik et al., 2017; Comas-Bru and McDermott, 2014b). Their impacts on the Baltic Sea region are substantial (e.g., Rutgersson et al., 2022). For example, in winter the NAO explains about 87% of the surface air temperature variability at Stockholm (Meier and Kauker, 2003), accounts for about 29% of the year-to-year variance in annual maximum Baltic Sea ice extent (Omstedt and Chen, 2001), and correlates strongly with winter mean Baltic Sea level ($r = 0.63$ for 1825–1997 and $r = 0.74$ for 1902–1997; (Andersson, 2002)). On longer time scales, coupled ocean–atmosphere interactions linked to the AMOC, the SPG, and the AMV exert additional control (Årthun et al., 2017; Börgel et al., 2023; Yan et al., 2018): for instance, about 58% of decadal Baltic Sea SST variability has been linked to the AMV after removing the long-term warming trend (Kniebusch et al., 2019), and local winter SST responses can reach about 1.2 °C per standard deviation of AMV-related multidecadal variability (Börgel et al., 2023). However, quantifying the effect of the NAO on the past and future climate of the Baltic Sea region remains a challenge (Hurrell et al., 2003).

Across time scales, the literature uses different frameworks to describe large-scale circulation patterns and their variability, but many of these can be related to the weather-regime framework. For example, the Zonal and Greenland Blocking regimes are commonly interpreted as NAO-like states (Cassou, 2008; Vautard, 1990; Barrier et al., 2014; Fabiano et al., 2021). Similarly, the East Atlantic pattern has been linked to Atlantic Ridge and Atlantic Trough-like circulation anomalies (Barnston and Livezey, 1987; Carvalho-Oliveira et al., 2024), while the Scandinavian pattern resembles Scandinavian Blocking in its positive phase and Scandinavian Trough in its negative phase (Kauker and Meier, 2003; Comas-Bru and McDermott, 2014a). Thus, apparent differences across studies often arise from the framework and time scale used, rather than from entirely distinct circulation dynamics (Vautard, 1990; Grams et al., 2017).

Our literature review highlights that, although still greatly underexplored, all three key biogeochemical parameters in the Baltic Sea are influenced by large-scale circulation patterns across all previously discussed time scales. These patterns affect biogeochemistry primarily by shaping the statistics of local physical processes such as stratification, water exchange, temperature, and advection, which then regulate nutrient availability, oxygen concentrations, species distributions, and phytoplankton abundance. However, quantitative and basin-wide evidence directly linking large-scale circulation variability to oxygenation, primary production, and ocean acidification in the Baltic Sea remains scarce. Important knowledge gaps persist, particularly regarding the spatial and temporal dynamics of total alkalinity (Kuliński et al., 2017). Likewise, although *the physical controls on primary-production variability, especially for the summer cyanobacterial bloom, are partly linked to large-scale variability (Kahru et al., 2020, 2025), a substantial fraction of the annual variability remains unexplained (Kahru et al., 2025).*

Similar to the physical controls, the NAO, the East Atlantic, and the Scandinavian pattern were identified as relevant. For example, a positive NAO can reverse the advection of oxygen-depleted water and remove hypoxia on inter-annual time scales in the Gulf of Finland, whereas strong heat fluxes during European Blocking can enhance stratification and exacerbate deep-water deoxygenation in the Gulf of Riga. Wind speed, light, and cloud cover have also been identified as potential triggers for initiating or ending phytoplankton blooms on synoptic scales. Importantly, the relative influence of these physical drivers varies with time scale. These findings underscore that understanding and predicting regional biogeochemical states requires explicit consideration of both large-scale atmospheric forcing and its time scale-dependent effects on the local physics.

This results in a system where large-scale circulation shapes the statistics of local processes. Yet, the attribution of their quantitative contributions, especially for biogeochemistry, remains challenging and understudied. Large-scale circulation patterns are non-stationary: their spatial structure and strength evolve with changes in the background climate, including, for example, Arctic amplification (Zappa and Shepherd, 2017), likely altering their relative importance for the Baltic Sea in the future. Thus, anthropogenic climate change as well as legacy nutrient loads set the stage for the biogeochemistry in the Baltic Sea upon which large-scale circulation patterns superimpose variability. Based on our review, we encourage future studies, in particular those on biogeochemistry, to include a more systematic quantification of dominant drivers, robust statistical assessments of relationships between connected processes, and a detailed analysis of time-scale dependence.

Robust attribution and causal disentanglement of large-scale circulation impacts on the Baltic Sea region remain difficult because externally forced signals and internal variability cannot easily be separated (e.g., Deser and Phillips, 2021). In addition, summer circulation patterns that drive variability on decadal and longer time scales are either less well resolved over Northern Europe or remain insufficiently studied. Possible predictability arising from the North Atlantic (e.g., SPG, AMV, AMOC) has not yet been systematically researched for the Baltic Sea region, as regional downscalings of decadal predictability experiments are not available. Finally, model fidelity is a limiting factor: common biases in jets, storm tracks, sea ice, subpolar gyre and the AMOC variability and likely incomplete coupling of physics and biogeochemistry do not yet allow for robust results (e.g., Palmer et al., 2023).

To advance our understanding on links between large-scale circulation patterns and local processes, we highlight the need for:

- *Regime-based diagnostics paired with in-depth process analysis to move beyond correlation. In addition, the nonstationarity of large-scale circulation patterns must be addressed, because their spatial structure and regional impacts may evolve over time. This can be investigated with coordinated multi-model ensembles, ideally complemented by initial-condition large ensembles which make it possible to separate internally generated variability from* *the externally forced response and to test the robustness of circulation–impact relationships across models and realizations.*

- *Fully coupled regional Earth-system models that resolve the complex topography of the Baltic Sea and can represent regional feedbacks among atmosphere, ocean, sea ice, and biogeochemistry more consistently.*
- *Targeted evaluation of the large-scale circulation and ocean state in the global parent model – including jets, storm tracks, the subpolar gyre, and the AMOC – because biases in these features can propagate into the regional model through the imposed boundary conditions and thereby affect the simulated Baltic Sea variability.*
- *Event-based modeling approaches for storms, atmospheric rivers and marine heat waves to quantify the biogeochemical responses on short time scales.*
- *Sustained high-frequency measurements of temperature, salinity, oxygen and other biogeochemical variables from coasts to deep basins to understand the impact of large-scale circulation patterns on biogeochemistry.*

The main barriers to robust attributions and predictions are their non-stationary nature and the limitation of currently available observations and models. Targeted observational, process-focused methods and fully coupled regional models together provide a credible route to near-term gains in understanding and to actionable guidance for the Baltic Sea region.

Main point 2b (internal variability vs external forcing)

Reviewer: Another point that sometimes confused me is the emphasis on 'internal variability'. This would, per se, not be wrong, but the reader is then prompted to expect a section on the impact of external forcing, either on the large-scale drivers, on the Baltic Sea itself, or on teleconnections. However, this does occur. I honestly did not see the need to highlight 'natural variability' in the manuscript. The only external forcings that are discussed in the manuscript are the rise in temperatures due to anthropogenic climate change and authentication. Both are very weakly related to 'teleconnections', if at all.

Response:

We thank the reviewer for highlighting this point regarding the terminology of "internal variability" versus "natural variability" and the scope of external forcing. We agree that clarity on these definitions is essential for the reader, as well as a good description of the scope of the manuscript.

Note that we base our manuscript around the IPCC definitions for these terms:

- Internal Variability: Noise generated inside the system (e.g., ocean-atmosphere interactions).

- Natural Variability: The combination of internal variability and natural external forcing (everything not human-induced).
- External Forcing: A push from outside the system (e.g., increase of greenhouse gases, volcanoes, changes in solar radiation).

Base on this definitions, we will 1) revise the manuscript to explicitly align our terminology with the IPCC Sixth Assessment Report (AR6) definitions, 2) specify, in the introduction, that the focus is on natural variability and 3) improve the scope description of this manuscript, which is to treat large-scale modes (e.g., NAO, AO) primarily as expressions of internal atmospheric-ocean coupling that drive Baltic Sea variability, rather than focusing on how these modes themselves might be altered by external forcing.

Furthermore, our analysis focuses on the recent evolution of the Baltic Sea. During this time frame, external forcings other than anthropogenic greenhouse gases have played a negligible role in long-term trends. Consequently, we place our analysis under a context of climate change only.

Specifically, we will (i) define what we mean by natural variability and internal variability in subsection 2.2, (ii) highlight the relevance of large-scale patterns in modulating regional natural variability in the introduction and (iii) clarify the scope of the manuscript, also in the introduction.

Changes to the text:

(i): "Natural variability refers to climatic fluctuations that occur without any human influence, that is, internal variability (i.e., noise generated within the system) combined with the response to external natural factors such as volcanic eruptions or changes in solar activity (Arias et al., 2021)."

(ii): "Large-scale Euro-Atlantic circulation variability has been shown to impact the Baltic Sea ecosystem by modulating the statistics of local forcing (e.g., Hänninen et al., 2000; Dippner et al., 2019; Gröger et al., 2024). However, the effects vary regionally as coastal and sub-basin dynamics respond differently to changes in local forcing (e.g., winds, heat fluxes, freshwater input, or vertical mixing) (Eremina et al., 2012; Lehtoranta et al., 2017; Dietze and Löptien, 2021; Gröger et al., 2021; Stoicescu et al., 2022; Löptien and Dietze, 2022; Polyakov et al., 2023; Dabulevičienè and Servaitè, 2024). In the Baltic Sea, such differences can emerge as changes in coastal upwelling and cross-shore transport, shifts in riverine freshwater and nutrient supply, or altered stratification, deep-water ventilation, and oxygen depletion in the central basins. Disentangling these sources of internal variability from anthropogenic trends is therefore essential for understanding how regional biogeochemistry is linked to large-scale circulation variability. This review represents a first attempt to synthesize these links for the Baltic Sea region, identify key knowledge gaps, and clarify how large-scale circulation patterns and their variability influence both physical processes in the Baltic Sea and biogeochemical responses. Improved understanding of these links may also support future advances in predictability, although this prospect is currently much more developed for physical variables than for biogeochemical

processes."

(iii): "This review synthesizes current understanding of how large-scale atmospheric Euro-Atlantic circulation variability relates to local forcing over the Baltic Sea region (here defined as the Baltic Sea and its surrounding catchment area; Figure **??***) across time scales ranging from synoptic to multidecadal. It also examines how the resulting hydrodynamic variability is linked to oxygen dynamics, primary productivity and ocean acidification. We focus specifically on the recent evolution of the Baltic Sea, during which anthropogenic climate change has become the dominant long-term external driver. Against this background, we examine how variability in Euro-Atlantic circulation patterns governs local forcing over the region and critically assess how these large-scale atmospheric influences interact with ongoing climate change."*

Particular points

Point 3

Reviewer: 'from the climatological reference state appear as geopotential height anomalies that can persist for up to 3 or 4 weeks.'

This seems to me to be a very long duration for a blocking situation. Please, check and eventually include a reference.

Response:

Thank you for spotting this error. We corrected and rephrased accordingly.

Changes to the text: Atmospheric circulation variability over the Baltic Sea region spans a broad range of time scales, from synoptic to multidecadal, and reflects the interplay of atmospheric, oceanic, and terrestrial factors. At shorter time scales, departures from the climatological reference state often take the form of large-scale geopotential height anomalies that persist from several days to about two weeks (Kautz et al., 2022).

Point 4

Reviewer: 'Traditionally, weather regimes are defined for winter and classified by four patterns..'

Do the authors consider weather regimes to be different from weather patterns or synoptic patterns? Perhaps a clarification would be helpful here. A search of 'seasonal weather regimes' yields a large number of published papers, so the authors may want to qualify the sentence.

Response:

We will change the wording so that this becomes more clear. In our manuscript, weather regimes refers to statistically identified, recurrent and quasi-stationary large-scale circulation states. We will also make sure that the wording is consistent through the manuscript. Rather than stating that weather regimes are "defined for winter," we now state that the canonical Euro-Atlantic four-regime framework is most commonly formulated and applied for boreal winter, while seasonal and year-round regime classifications also exist.

Changes to the text: "Traditionally, the canonical Euro-Atlantic weather-regime classification refers to the four recurrent large-scale circulation regimes most robustly identified in boreal winter (Vautard, 1990; Cassou, 2008; Barrier et al., 2014; Falkena et al., 2020). In this manuscript, weather regimes refer to statistically identified, recurrent large-scale circulation states, rather than to individual synoptic weather patterns. "

Point 5

Reviewer: 2.3.3 Sea level

'The sea level has a pronounced seasonal cycle with higher sea levels in autumn and winter than in summer and spring (Stramska, 2013)'

This sentence, while true, is oddly placed. The section is about interannual variations and how the Kattegat straits filter this variability. Then this sentence suddenly states that the most considerable variations (the annual cycle) are generated within the Baltic Sea itself (probably due to runoff).

Response:

We agree and this sentence should have been the start of the next paragraph. This will be corrected and also rephrased as follows:

Changes to the text: "Sea level in the Baltic Sea exhibits a seasonal cycle, with higher levels in autumn and winter than in spring and summer (Stramska, 2013). Against this seasonal background, interannual sea-level variability has been found to correlate with the NAO, especially in winter, although the strength of the relationship varies in time and across the Baltic Sea region. "

Point 6

Reviewer: 'Surface Air Temperature and Sea Temperatures Low winter SST is associated with negative NAO.... This wave train...'

what wave train?

Response:

We agree, that this was unclear and did not add important information. Hence, we will delete this statement and rephrase.

Changes to the text: "On decadal and longer time scales, positive AMV phases are associated with higher Baltic Sea SSTs, but this response is strongly seasonal and spatially heterogeneous rather than uniform throughout the year. Previous work estimated that about 58% of the decadal Baltic SST variability can be linked to the AMV after removing the global warming signal (Kniebusch et al., 2019). More recent work further showed that the linear annual-mean SST response to the AMV is relatively weak, on the order of 0.2°C*, whereas the influence is strongest in winter, when up to 40% of regional SST variability can be associated with multidecadal variability closely linked to the AMV, corresponding locally to about 1.2* °C *per standard deviation of the AMV(Börgel et al., 2023). This influence is thought to be mediated partly through the NAO and partly through a subpolar atmospheric wave train that links North Atlantic SST anomalies to Northern European climate (Borchert et al., 2019; Monerie et al., 2021; Börgel et al., 2020). In the Baltic Sea region, this influence appears to be expressed primarily through changes in large-scale pressure patterns, westerly flow, and oceanic inertia (Börgel et al., 2023) and aerosol forcing (Barghorn et al., 2025)."*

Point 7

Reviewer: '385 January and March, negative NAO phases (NAO ¡ -0.5) are linked to substantially larger mean annual ice extent (259,000 kmÂš),'

The units did not render correctly when converting to pdf. This incorrect rendering of special symbols also occurs for some references, e.g., Matthäus, W. and Franck, H., 1992; Meier et al., 2022; Ostrowska et al., 2019; Patrizio et al., 2023. Please check the reference list carefully in the pdf file produced by the submission system.

Response:

Thank you for spotting this. We will correct the unit encoding (km^2) and reviewed the manuscript and reference list for character-encoding issues, especially for diacritics and special symbols.

Point 8

Reviewer: 'but correlations can be of comparable magnitude to those of the Atlantic Oscillation,'

North Atlantic Oscillation

Response:

Thank you for spotting this. We will correct the term to "North Atlantic Oscillation (NAO)" for precision and consistency.

Point 9

Reviewer: ‘For the 20th century, common power ...’

common spectral power

Response:

We thank the reviewer for spotting this; we will correct the wording.

Changes to the text: “common power” will be replace by “common spectral power”.

Point 10

Reviewer: ‘about 20-40% of the shortwave variability’

shortwave radiation variability

Response:

We thank the reviewer for the suggestion; we will in fact rephrase the whole paragraph, also in response to reviewer #2 (comment for line 425):

Changes to the text: “A recent modeling study suggested that the PDO accounts for about 20–40% of the unforced year-to-year shortwave-flux variability in Northern Hemisphere continental averages, mainly through cloud redistribution. For Europe, the modeled response is weaker, with anomalies of about $\pm 2\ Wm^{-2}$*, and negative PDO phases are associated with reduced atmospheric shortwave reflectivity. However, the signal is strongest in spatially aggregated averages and is difficult to distinguish from atmospheric noise over most of Europe, so its relevance for the Baltic Sea region remains uncertain (Chtirkova et al., 2024).”*

Point 11

Reviewer: The following two paragraphs appear inconsistent: First, it states that ‘Wind conditions did not show a strong relationship with how often cyanobacteria blooms occurred, although winds mainly influenced variations from year to year (Kahru et al., 2020, their Figure 9)’

Then, later: ‘However, sea surface temperature and wind speed play a significant role in modulating decadal cyanobacteria blooms (Kahru et al., 2018)’.

What should the reader interpret from these results? Is wind responsible or not for cyanobacteria variability?

Perhaps wind is not responsible for individual blooms but, somewhat, indirectly affects the conditions that modulate decadal variability; this needs an explanation.

Response:

We agree that these sentences are confusing. What we mean is that phosphorus is clearly the primary driver for cyanobacteria blooms but that wind and temperature also play a role in determining the timing of the blooms. We will rephrase them as follows:

Changes to the text: "Kahru et al. (2020) showed that the frequency of cyanobacteria in the Baltic Proper at decadal time scales is primarily correlated with phosphorus abundance and bottom-water anoxia (Figure **??***). However, sea surface temperature and wind speed also play a significant role in modulating decadal cyanobacteria blooms and their initiation (Kahru et al., 2018, 2025)."*

Point 12

Reviewer: This is an example of somewhat inconsistent writing.

'Yet, clear links between primary productivity and large-scale patterns, the relative importance of teleconnections on primary productivity and future primary productivity responses under an acceleration of warming remain unclear in the Baltic Sea.#'

Clear links remain unclear ?

Response:

We agree this sentence was internally inconsistent. We will rephrase is as follows:

Changes to the text: "Yet, in the Baltic Sea, the links between large-scale circulation patterns and primary productivity remain poorly understood and largely unquantified; consequently, the relative importance of these links and the future response of productivity to accelerated warming are even less certain. "

Point 13

Reviewer: 'Because primary productivity forms the base of the marine food web, understanding its link to natural variability and large-scale patterns is important to better predict its future and implications.'

But large-scale patterns are part of the natural variability or do the authors mean something else, like natural variability of the food web itself?

Response:

Thank you for the clarification request. We will explicitly distinguish between large-scale atmospheric/oceanic circulation patterns (teleconnections) and intrinsic variability within the Baltic Sea ecosystem. We will revise the sentence accordingly.

Changes to the text: "Because primary productivity forms the base of the marine food web, understanding its link to natural variability and large-scale patterns is important to better predict its future and implications. "

Closing

Response:

We again thank the reviewer for the helpful comments, which improved the clarity, consistency, and synthesis of the manuscript.

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